Minimizing Technical Risks in Photovoltaic Projects

Recommendations for Minimizing Technical Risks of PV Project Development and PV Plant Operation

Merged Deliverable D1.2 and D2.2 (M16)

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Foreword

The photovoltaic (PV) sector has overall experienced a significant growth globally in the last decade, reflecting the recognition of PV as a clean and sustainable source of energy. Project investment has been and still is a primary financial factor in enabling sustainable growth in PV installations. When assessing the investment-worthiness of a PV project, different financial stakeholders such as investors, lenders and insurers will evaluate the impact and probability of investment risks differently depending on their investment goals. Similarly, risk mitigation measures implemented are subject to the investment perspective. In the financing process, the stakeholders are to elect the business model to apply and be faced with the task of taking appropriate assumptions relevant to, among others, the technical aspects of a PV project for the selected business model.

The Solar Bankability project aims to establish a common practice for professional risk assessment which will serve to reduce the risks associated with investments in PV projects. The risks assessment and mitigation guidelines are developed based on market data from historical due diligences, operation and maintenance records, and damage and claim reports. Different relevant stakeholders in the PV industries such as financial market actors, valuation and standardization entities, building and PV plant owners, component manufacturers, energy prosumers and policy makers are engaged to provide inputs to the project.

The technical risks at the different phases of the project life cycle are compiled and quantified based on data from existing expert reports and empirical data available at the PV project development and operational phases. The Solar Bankability consortium performs empirical and statistical analyses of failures to determine the manageability (detection and control), severity, and the probability of occurrence. The impact of these failures on PV system performance and energy production are evaluated. The project then looks at the practices of PV investment financial models and the corresponding risk assessment at present days. How technical assumptions are accounted in various PV cost elements (CAPEX, OPEX, yield and performance ratio) are inventoried. Business models existing in the market in key countries in the EU region are gathered. Several carefully selected business cases are then simulated with technical risks and sensitivity analyses are performed.

The results from the financial approaches benchmarking and technical risk quantification are used to identify the gaps between the present PV investment practices and the available extensive scientific data in order to establish a link between the two. The outcomes are best practices guidelines on how to translate important technical risks into different PV investment cost elements and business models. This will build a solid fundamental understanding among the different stakeholders and enhance the confidence for a profitable investment.

The Solar Bankability consortium is pleased to present this report which is one of the public deliverables from the project work.

Other Publications from the Solar Bankability Consortium

Description	Publishing date
Snapshot of Existing and New Photovoltaic Business Models	August 2015
Technical Risks in PV Project Development and PV Plant Operation	March 2016
Review and Gap Analyses of Technical Assumptions in PV Electricity Cost	July 2016
Minimizing Technical Risks in Photovoltaic Projects	August 2016
Financial Modelling of Technical Risks in PV Projects	September 2016
Best Practice Guidelines for PV Cost Calculation	December 2016
Technical Bankability Guidelines	February 2017

Proceedings from the Project Advisory Board and from the Public Workshops

Description	Publishing date
1st Project Advisory Board closed meeting	June 2015
2nd Project Advisory Board closed meeting	December 2015
First Public Solar Bankability Workshop - Enhancement of PV Investment Attractiveness	July 2016
3rd Project Advisory Board closed meeting	February 2017
Solar Bankability Final Workshop - Improving the attractiveness of solar PV investment	February 2017

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Project Information

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Glossaries & Abbreviations

CDF	Cumulative Distribution Function
CPN	Cost Priority Number
DiffHI	Diffuse Horizontal Irradiance
EPC	Engineering Procurement and Construction
EL	Electroluminescence imaging
EYP	Energy Yield Prediction
FiT	Feed-In Tariff
FMEA	Failure Modes and Effects Analysis
GHI	Global Horizontal Irradiance
GTI	Global Tilted Irradiance
IEA	International Energy Agency
IR	Infrared imaging
LCOE	Levelised Cost of Electricity
O&M	Operation & Maintenance
PLR	Performance Loss Rate
POA	Plane of Array
PPA	Power Purchasing Agreement
PR	Performance Ratio
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
RCE	Retail Cost of Electricity
RPN	Risk Priority Number
RMF	Risk Mitigation Factor
STC	Standard Test Conditions

Executive Summary

In the project report “Technical Risks in PV Projects” (Moser et al., 2016), technical risks were identified and categorised for components and phases of the value chain of a PV project. The technical risks were broadly divided into risks to which one can assign an uncertainty to the initial yield assessment and risks to which one can assign a Cost Priority Number (CPN). While failures arising from technical risks belonging to the first group have an impact on the overall uncertainty of the energy yield, failures with a CPN have a direct impact on the annual cost of running a PV plant caused by economic losses due to downtime (utilisation factor) and component repair or substitution (OPEX) and it is given in Euros/kWp or Euros/kWp/year. The CPN methodology was thus developed to assess the economic impact of technical risks occurring during the operation and maintenance phase (O&M) of a PV project. The analysis summarized in the report “Technical Risks in PV Projects” was linked to a failure database over a portfolio of more than 700 PV plants, 420 MWp, ~2,000,000 modules, ~12,000 inverters, etc. for a total of ~2.4 million components (status March 2016). Although the database already includes PV plants from various market segments and countries, the comparison of the CPNs for various technical risks (e.g. quantifiable failures during O&M) was carried out on an annual basis for all plants. This is a shortcoming of the database and not of the methodology.

The overall methodology was created to allow the estimation of the economic impact of failures on the levelized cost of electricity (LCOE) and on business models of PV projects. Not all the technical risks fit into the two groups mentioned above: some risks can be defined as precursor of a risk propagating along the value chain or have an indirect impact on the CPN of various risks in terms of occurrence, time to detect, time to repair, etc. Thus, the overall technical risk framework in the *Solar Bankability* project has been developed to determine the economic impact of a failure but also to be able to assess the effectiveness of mitigation measures.

Mitigation measures must be identified along the value chain and assigned to various technical risks. Some failures can be prevented or mitigated through specific actions at different project phases as, for e.g., for potential induced degradation (PID) the use of a different encapsulant or glass during the product manufacturing phase, or a PID box in case of reversible PID during the operation/maintenance phase. Others can be prevented or mitigated through a more generic action. For example, the monitoring of performance or visual inspection can be considered as generic mitigation measures that can have a positive impact on the reduction of the CPN of many failures. In practice, it is important to understand how mitigation measures can be considered as a whole to be able to calculate their impact and thus assess their effectiveness.

It is not the aim of this report to provide a set of specific mitigation measure for each technical risk as this would entail failure specific cost-benefit analysis. At this stage, the *Solar Bankability* project objective is to create a framework of well-defined mitigation measures, which have an impact on the global CPN (given as sum of CPNs of all technical risks). The cost-benefit analysis can then include the combination of various mitigation measures and derive the best strategy depending on market segment and plant typology. In addition to this, it is important to assess in the CPN analysis who bears the cost and the risk to derive considerations not only on the overall economic impact of the technical risks, but also on cost and risk ownership.

In order to evaluate the effectiveness of mitigation measures into the framework for the assessment of the economic impact of technical risk (Moser et al., 2016), two main categories of mitigation measures are here defined:

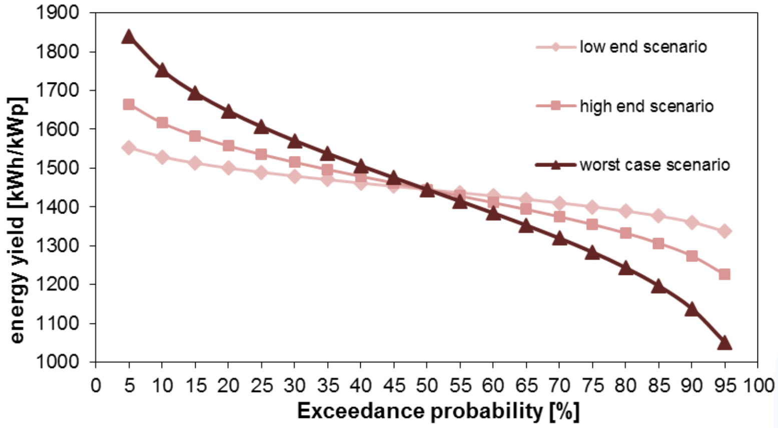
Category 1 (before) represents all the preventive measures, which are applied before the risk occurs in order to prevent it from happening.

Category 2 (after) represents the corrective measures, which reduce higher losses and costs, if the risk has already occurred. The costs are mostly related to the OPEX due to the later implementation during the operation and maintenance phase.

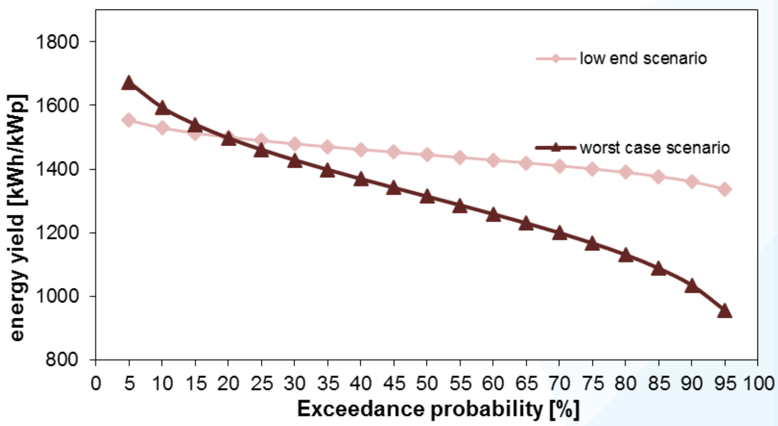
Some of the risks related to a PV project, already identified in (Moser et al., 2016) and included in a Risk Matrix, have an economic impact in terms of uncertainty. In particular, the uncertainty can be related either to the expected yield during the planning phase, or to the actual yield during the operational phase. It is interesting to highlight that not all the components of a PV systems are involved, and that uncertainties related to the assessment of the actual yield might also originate from phases preceding the operation. In order to analyze the variability of the uncertainty of the outputs of a generic PV model, several uncertainty scenarios have been defined. Typically, a normal distribution function is assumed for the various components. A more precise analysis during the planning phase would benefit from the use of an empirically established probability distribution. Unfortunately, there is not always a sufficiently large dataset available to establish the cumulative distribution function (CDF) from which to interpolate exceedance probabilities. Nevertheless, for some elements involved in the calculation of the long-term expected yield as, e.g. the solar resource, this method can be applied. With the availability of more data for other elements, also other secondary effects can be included in the methodology as not normally distributed.

The results show that there is a group of cases assuring a low level of uncertainty (4.55% to 8.70%). They all refer to the use of long series of either ground- or satellite measurements of insolation. The range of the available insolation data seem therefore to be the most important factor affecting the uncertainty of the yield estimation. Among the analysed scenarios, the best case corresponds to the use of 20 year of measured values of Global Tilted Irradiance (GTI), showing also that a lower uncertainty is ensured when a) ground measurement are used in place of satellite measurements and b) time series of plane-of-array irradiance is available without the need to apply transposition models. Results show also that using a combination of long time series of satellite data with a short series of measured data is recommended than just using satellite data. In the case a PV plant is to be installed in a location with high insolation variability, the uncertainty of the yield estimation is also negatively affected. Amongst the parameters not related neither to insolation variability nor to solar resource, the uncertainty related to shading and soiling effects, and to the use of the right transposition model, plays a role in the uncertainty of the final yield. In general, the uncertainty of the final yield of the PV plant used in the analysis can range from 4.5% to 14.9%. The latter becomes a 16.6% in the eventuality that the planner has the worst information quality available.

The cumulative distribution functions are shown in the figure below for the low-end scenario (σ=4.6%), a high-end scenario (σ=9.3%) and the worst-case scenario (σ=16.6%).



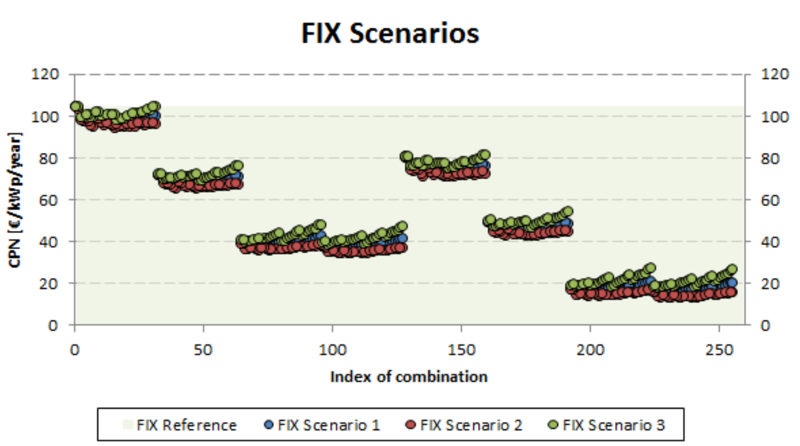
The use of shorter time series can also lead to an underestimation (or overestimation) of the mean specific value depending if the tails of the distribution are present or not. As an example, when compared to a low-end scenario (4.6% uncertainty), the reduction in P90 for the worst-case scenario (16.6% uncertainty and underestimation of the mean specific energy yield value) is 22% (see Figure below).



Besides the technical risks associated with uncertainties during project planning phase, the second group of risks has a direct economic impact during operation. These risks were already identified and evaluated in (Moser et al., 2016). The methodology of quantification was also introduced in chapter 5 of the mentioned report and the results were based on two different scenarios: i) a FIX scenario and ii) a never detected scenario. The overall sum of the CPNs for all components was around 120 Euros/kWp/year.

The methodology has been further developed for the evaluation and effectiveness of the identified mitigation measures. Risk Mitigation Factors (RMF) are introduced which quantify the reduction of costs for fixing the failures (i.e. repair of existing component, substitution by spare component, substitution by new component).

The new CPN (CPN_{new}) value arise from the cost-benefit analysis by adding the CPN after mitigation with the cost of the mitigation measures. The Figure below shows the results of calculating the FIXING costs for selected failures when applying combinations of eight selected mitigation measures listed in Table 5.3. The index of 256 combinations can be found in Annex 3. The costs related to FIXING the failures result from the sum of the costs of repair/substitution, the costs of detection, the costs of transport, and the cost of labour. The selection of failures was based on experts' panels and include the top 20 PV module failures, top 20 inverter failures, failures of mounting structure, combiner boxes, cabling as well as failures of transformer station as listed in Annex 2 of this report.



Preventive measures have the highest impact on CPN_{new} e.g. Qualification of EPC will bring down CPN_{new} to 75 €/kwp/year. E.g. Design review will further reduce to CPN_{new} to 40 €/kwp/year. Corrective measures have less impact on CPN_{new} e.g. Basic and advanced monitoring and visual and advanced inspection. In general, mitigation measures which reduce the failure occurrence have the highest impact due to the related reduction in substitution costs. For 99% of all mitigation measure combinations the scenarios will result in economic benefit by reducing the CPN_{new} to values lower than the reference one (104.75 €/kWp/year) as shown in the Figure above. The highest savings for all three cost scenarios can be achieved by applying the three preventive measures (component testing + design review + qualification of EPC). The savings may reach 90 €/kWp/year for the best combinations of selected mitigation measures.

The report presents the results of the identification and categorisation of mitigation measures before and after the operational phase of a PV project.

In Chapter 2, two main categories for the description of mitigation measures are introduced together with their relation to CAPEX and OPEX.

In Chapter 3, several fact sheets describe specific mitigation measures, their cost and the impact.

In Chapter 4, we describe the methodology used to assess the impact for mitigation measures affecting technical risks related to the uncertainty of the energy yield and technical risks to which we can assign a CPN. The methodology for the calculation of the CPN is extended to include the impact of preventive and corrective mitigation measures.

In Chapter 5, the results of the analysis are given together with a prioritization of mitigation measures.

Finally, Chapter 6 describes the link of the present report with the work carried out within the Solar Bankability project in terms of gap analysis and impact on the LCOE and on the business models.

1 Introduction on Mitigation Measures

In the project report “Technical Risks in PV Projects” (Moser et al., 2016), technical risks were identified and categorised for components and phases of the value chain of a PV project. The technical risks were broadly divided into risks to which one can assign an uncertainty to the initial yield assessment and risks to which one can assign a Cost Priority Number (CPN). While failures arising from technical risks belonging to the first group have an impact on the overall uncertainty of the energy yield, failures with a CPN have a direct impact on the annual cost of running a PV plant. The latter are caused by economic losses due to downtime (reduction in the utilisation factor) and component repair or substitution (Operational Expenditures, OPEX) and it is given in Euros/kWp or Euros/kWp/year. The CPN methodology was thus developed to assess the economic impact of technical risks occurring during the operation and maintenance (O&M) phase of a PV project. The analysis presented in the report “Technical Risks in PV Projects” was linked to a failure database over a portfolio of more than 700 PV plants, 420 MWp, ~2,000,000 modules, ~12,000 inverters, etc. for a total of ~2.4 million components (status March 2016). Although the database already includes PV plants from various market segments and countries, the comparison of the CPNs for various technical risks (e.g. quantifiable failures during O&M) was carried out on an annual basis for all plants. This is a shortcoming of the database and not of the methodology. In fact, the methodology already allows for the following analysis (among others):

- Market segment analysis (e.g. residential, commercial, industrial, utility scale)
- PV plants at different climates
- Differentiation between module type (e.g. crystalline silicon vs thin-film)
- Differentiation between inverter type (e.g. centralised vs string inverter)
- PV in different countries (e.g. labour costs)
- Distribution of failures over the years
- Assignment of an exceedance probability to the CPN (e.g. by using the energy yield at P50 or P90)
- Assessment of the economic impact of mitigation measures (e.g. reduction of failure occurrence and time to detect).

The overall methodology was created to allow the estimation of the economic impact of failures on the levelised cost of electricity (LCOE) and on business models of PV projects. Not all the technical risks fit into these two groups: some risks can be defined as precursor of a risk propagating along the value chain or have an indirect impact on the CPN of various risks in terms of occurrence, time to detect, time to repair, etc. Thus, the overall technical risk framework in the *Solar Bankability* project has been developed to determine the economic impact of a failure, but also to be able to assess the effectiveness of mitigation measures. To this extent, it is important as a next step to create failure flow maps to understand how failures propagate, to check for consistency, to assign liabilities, identify mitigation measures and assess their effectiveness in terms of reduction of uncertainties and CPNs.

In a PV project, costs for correction of defects increase exponentially with a factor of 10 by each step along the value chain from the product idea to the handover to the customer (Klute, 2016). Defect prevention instead of defect correction should thus be considered as a first mitigation option with an effective risk management strategy during system design and planning. The reduction in occurrence of failures during the planning phase has in fact a direct positive consequence in terms of reduction in occurrence of failures during the operational phase, resulting in a lower CPN. Mitigation measures as defect correction will also have a cost. Therefore, the balance between the increased capital expenditure during planning must be countered by an effective decrease of operational (monetary) losses caused by downtime, component replacement or repair. It is important to this extent to analyse how risks propagate from one step of the value chain to the next: this allows us to identify mitigation measures and to understand if, for some specific failures, an effective mitigation measure is already in place (see Figure 1.1). For the latter, it means that a failure present during an early step of the value chain is not detected during the operational phase.

Product testing	Planning	Transportation / installation	O&M	
7. Visually detectable hotspots - cells are overheating, which has a negative impact on the energy production of the module (module degradation).			1. Hotspot - overheating of cells etc. can cause burn marks. Temperature difference between neighbour cells should not be over 30°C. Infrared cameras can be used for imaging the defects of the modules. Hotspots can also identified by visual inspection from the rear side of the module.	CPN
8. Incorrect power rating (flash test issue) - sorting of the modules by performance will not be possible, PV modules mismatch losses undefined. High uncertainty of the nominal power of the PV plant and thus uncertainties of specific yield and performance ratio (PR).	3. Modules' mismatch - caused by interconnection of solar cells or modules without identical electrical properties or conditions (due to soiling, shadow, etc.).			uncertainty
	5. Flash test report not available or incorrect - sorting of the PV modules not possible, mismatch losses undefined.			uncertainty
9. Uncertified components or production line - life cycle, reliability and quality of PV modules can be significantly reduced.	4. Modules not certified - no quality warranty, modules of unknown origin			indirect impact
	8. Quality of module production unclear (lamination, soldering, etc.)			indirect impact
	1. Soiling losses - less energy production due to soiling caused, amongst others, by pollution, bird droppings, and accumulation of dust and/or pollen. Its impact is strongly site dependent.		4. Soiling losses - due to operational conditions: e.g. smog, sand particles, bird droppings, etc. Its impact is strongly site dependent.	CPN

Figure 1.1: Example of failure flows along the value chain of a PV project for some module related technical risks. The number relates to the list of technical risks as presented in the Report (Moser et al., 2016)

Typically, during the design of a PV project, a component qualification process is put in place. This is applicable for the main components (module, inverter, mounting structure) and contains compatibility check, risk analysis, supplier audit, and lessons learnt. It entails different complexity according to the project configuration (e.g. technology, country, region, climate).

As previously mentioned, the cost of mitigation measures needs to be included in a cost benefit analysis, which has to consider the expectations of the stakeholders that are involved in a PV project (Bächler, 2016). Investors are seeking for long defect warranty periods, performance guarantees, reasonable low CAPEX and OPEX, high long-term plant performance and lifetime (ideally above the initial prediction). Banks have requirements similar to those of the investors which are looking for projects with a 10-15 year financing period and PV plant performance which can also be slightly below prediction. Insurers try to limit their liability to failures with an external root cause based on PV plants, which meet technical market standards and are maintained on a regular basis. On the contrary, EPC contractors will look for short defect warranty periods, minimum of additional guarantees and warranties, high sale price with low OPEX showing a very different time horizon compared to the investors.

As a consequence of the different needs between the key actors, O&M operators are in a difficult position to manage all these conflicting requirements for a long period of time. The best condition for O&M operators is in fact in the presence of long defect warranty period and low sale price to allow for higher OPEX. Recent trends in the PV market have put a lot of pressure on the O&M price which is reported to be as low as 8 Euros/kWp/year in Germany in 2016 (Bächler, 2016). A large share of these costs is labour intensive (i.e. site keeping and inspection, preventive maintenance, monitoring and reporting). It is therefore of extreme importance to identify what O&M scope is obligatory vs what is optional and the required reaction time depending on the severity of the failure by assessing the cost of various mitigation options during the operational phase which can be part of an effective O&M strategy.

Mitigation measures must be identified along PV the value chain and assigned to various technical risks. Typical mitigation measures during the design phase are linked to the component selection (e.g. standardised products, products with known track record), O&M friendly design (e.g. accessibility of the site, state of the art design of the monitoring system), LCOE optimised design (e.g. tracker vs. fixed tilt, central vs. string inverter, quality check of solar resource data). Mitigation during the transportation and installations are linked to the supply chain management (e.g. well organised logistics, quality assurance during transportation), quality assurance (e.g. predefined acceptance procedures), grid connection (e.g. knowledge of grid code) (Herzog, 2016). These mitigation measures positively affect the uncertainty of the overall energy yield, increase the initial energy yield and reduce the cost of O&M during the operational phase (e.g. faster replacement of components, lower cost of site maintenance, lower occurrence and severity of defect, etc.).

Mitigation measures during the O&M phase are linked to maintenance (e.g. preventive maintenance, visual inspection, spare parts management), monitoring and data quality (e.g. state of the art measurement equipment and software, performance evaluation, predictive monitoring), outsourcing (e.g. in-sourcing can reduce costs and dependency from suppliers), remote monitoring (e.g. video surveillance, defined workflow to reduce replacement time). These mitigation measures directly affect the CPN of failures occurring during the operational phase by reducing the time to detect defects, the time to repair/substitute defects, etc.

Compared to many other power generating technologies, PV plants have reduced maintenance and service requirements. However, a continuous O&M programme is essential to optimise energy yield and maximise the lifetime and viability of the entire plant and its individual components. Many aspects of O&M practices are interrelated and significantly affect the performance of all the components in the generation chain and project lifecycle. The PV technical risks were defined in the Project Report "Technical Risks in PV Projects" (Moser et al., 2016) in terms of downtime, production performance, operational costs and time to complete the required activities. It is important that risk ownership is also considered to better understand which key actor is responsible for the action of mitigating the risk. These risks can then be turned in opportunities to meet or even exceed the expectations of the developers and owners in terms of return on the investment. In particular, suitable planning, supervision and quality assurance actions are critical at all stages of a PV project in order to minimise the risk of damages and outages, optimise the use of warranties, avoid non optimal use of resources and ultimately optimise the overall performance of the PV plant.

The scientific PV community has thoroughly investigated some specific failures and drawn recommendations on how to mitigate the economic impact for, e.g. soiling (Bengt Stridh, 2012; Mani and Pillai, 2010; Qasem, 2013), grid integration (Appen et al., 2013), PID (Pingel et al., 2010). General recommendations on the mitigation measures to reduce the impact of technical risks are also found in more general publications given by companies active in the field as EPC contractors, consultants, and O&M operators (Iban Vendrell et al., 2014; Lowder et al., 2013). Some failures can be prevented or mitigated through specific actions at different project phases (e.g. for PID, a different encapsulant or glass during product manufacturing phase, a PID box in case of reversible PID during the operation/maintenance phase); others can be prevented or mitigated through a more generic action. For example, the monitoring of performance or visual inspection can be considered as generic mitigation measures that can have a positive impact on the reduction of the CPN of many failures. In practice, it is important to understand how mitigation measures can be considered as a whole to be able to calculate their impact and thus assess their effectiveness. It is not the aim of this project to provide a set of specific mitigation measure for each technical risk as this would entail failure-specific cost-benefit analysis. At this stage, the Solar Bankability project objective is to create a framework of well-defined mitigation measures, which have an impact on the global CPN (given as sum of CPNs of all technical risks). The cost-benefit analysis can then include the combination of various mitigation measures and derive the best strategy depending on market segment and plant typology. In addition to this, it is important to assess in the CPN analysis who bears the cost and the risk to derive considerations not only on the overall economic impact of the technical risks, but also on cost and risk ownership.

The core goal is to create tools for determining the intrinsic values of a PV project based on cost factors.

2 Description of Categories of Mitigation Measures

In the previous chapter, we have introduced the need for mitigation measures with a very broad overview using several examples. Furthermore, as part of the project, all common and not so common mitigation measures were collected. In order to evaluate the effectiveness and to implement one or more of those into the framework for the assessment of the economic impact of technical risk (Moser et al., 2016), the two main categories are defined here and the relevant mitigation measures are described in Annex 1.

Category 1

Category 1 (before) represents all the **preventive measures**, which are applied before the risk occurs in order to prevent it from happening. The costs are mostly related to the CAPEX due to the earlier implementation during an earlier project phase (e.g. during PV plant planning and design). In this category we have all the mitigation measures that have an impact on the overall uncertainty for the calculation of the energy yield. As we will see in the following chapters, a reduction in uncertainty can lead to higher values of the energy yield at high exceedance probability, e.g. at P90.

In addition to the aforementioned uncertainty related technical risks, this category of mitigation measures - according to our mathematical model - influences the parameter n_{fail} (number of detected failures). These measures have a great influence in the CPN value of the risks. For instance, in cases of failures such as “wrong installation” the number of failures can be drastically reduced by 90%. The parameter *number of failures* is of great interest as it influences the losses due to downtime, the losses due to repair time and cost of substitution.

For this reason, preventing the occurrence of failures can improve the attractiveness of PV projects despite the fact that initial investment might be higher. On the other hand, the added value of the PV plant after these measures must also be considered, especially in cases such as resale of the PV plant. In Chapter 5.1 and Chapter 5.2 the impact of the preventive actions on the reduction of uncertainties and on the total CPN value of the risks is described as well as the costs of these actions.

The following mitigation measures typically belong in this group:

- Component testing
- Design review and construction monitoring
- Qualification of EPC

Each action influences different groups of failures and different components. However, in some cases the detected number of failures (n_{fail}) can be minimized due to the combination of mitigation measures by e.g. applying design review and qualification of EPC, which will significantly reduce the risk of failures during the installation phase due to low-qualified personnel.

Category 2

Category 2 (after) represents the **corrective measures**, which reduce higher losses and costs, if the risk has already occurred. The costs are mostly related to the OPEX due to the later implementation during the operation and maintenance phase.

Actions that influence the parameters such as time to detect $\mathrm{t_{td}}$, time to repair $\mathrm{t_{tr}}$, substitution time $\mathrm{t_{ts}}$ belong in this group of mitigation measures.

In particular cases, e.g. monitoring system, the mitigation measure cannot be assigned to a single category and both characteristics in terms of impact and costs must be taken into account.

The effective mitigation measures, both preventive and corrective measures, are described in Annex 1.

2.1 CAPEX related Mitigation Measures and Preventive Measures

According to the analysis presented in the technical report “Technical Risks of PV Projects” and the statistical data most of the failures can be avoided.

Specifically, suitable planning, supervision and quality assurance activities are critical at every phase of the PV project in order to reduce the risk of failures and outages, optimize the use of warranties, avoid not-optimised used of resources and ultimately optimize the overall performance of the PV plant.

2.1.1 Design Verification and Description of Mitigation Measures

There are two main reasons that highlight the importance of this type of mitigation measure. The first is the *Factor of 10* which means that in design phase mistakes are costly, and the longer it takes to discover a problem, the more costly it becomes. According to Dr. David M. Anderson (Anderson, 2014), it costs 10 times more to find and repair a defect at the next stage of the plant, and then it costs 10 times more at each subsequent stage of the project. Applying this methodology in PV plants, we can assume the following:

Table 2.1: The factor of 10 applied in PV plants. Every phase of the plant has a different cost factor regarding the same failure

Project Phase	Cost
The component itself	1 X
Design phase	10 X
Procurement phase	100 X
Installation phase	1000 X
Final commissioning	10000 X

Table 2.1 demonstrates the importance of mitigating the failure in the design phase.

The second reason is that failures occurring during the design or installation phase will typically be detected if a third independent party will review the design or inspect the PV plant. This was learnt from the large failure database used for the technical report “Technical Risks of PV Projects”. Most regrettably, in many cases the EPC or the installer did not have the expertise to know how to avoid possible failures that may occur during the design and installation phase. In other cases, third party design verification of the PV plant is carried out after the warranty period (often 2 years) offered by the EPC of the PV plant. During the warranty period, the EPC is responsible for the performance of the PV plant and has little interest that others may interfere. In these cases, the owner cannot claim any refund due to possible energy losses or repair works without charge.

For these reasons, the expertise of the EPC or the inspection of the design phase from a third independent party might increase the overall CAPEX, but it will significantly lower the risks of failures of the PV plant at an early stage. Table 2.2 shows an example of a failure due to wrong design and the actual costs incurred to repair it.

Table 2.2: Example of a failure due to wrong sizing of the inverters and the financial impact (Klute, 2016)

Failure		**Photographic demonstration**
Risk	Wrong sizing of the inverters	
Description	Optiprotect switches fail due to higher currents and temperatures than expected	
Performance losses	100%	
Mitigation	Inspection during the design and planning phase	
Detection method	Monitoring	
Reparation method	Redesign and reconstruction with less strings per optiprotect channel	
Cost of repair	28 €/kWp	
Cost of mitigation measure	10 €/kWp	

2.2 OPEX related Mitigation Measures and Corrective Measures

PV plants are not maintenance free. However, comparing the CAPEX and OPEX indexes used in PV industry, the cost of O&M is relatively low compared to other similar technologies. The OPEX consists of two main categories of mitigation measures (T.J. Keating et al., 2015):

1. Preventive actions
2. Corrective actions.

The first category includes all the actions in order to ensure the profitability of the PV plant. Preventing a failure in PV plants is essential, especially regarding the failures related to PV plant components. For instance, a failure of the medium voltage transformer due to soiling can cause high losses in the produced energy. Furthermore, the cost to substitute the transformer is also relatively high as procurement, availability, transportation, installation and commissioning must be taken into account. Thus, maintenance instructions provided by the manufacturer must be followed concerning all components of the PV plants. The most sensitive parts, concerning maintenance, of the PV plant are:

1. Tracking system
2. Combiner boxes
3. Data acquisition system
4. Inverters
5. Medium and low voltage cabinets
6. Transformers.

The second category of mitigation measures are the corrective actions. Unfortunately, these actions take place after the occurrence of the failures. According to the mathematical model that is used to calculate the CPN value of each failure, such actions do not reduce the number of detected failures. However, they influence the time to detect and time to repair a failure. The most critical characteristics of such actions are the availability of the components (spare parts) and response time of the operator. For instance, if a failure occurs in the medium voltage cables the losses due to the downtime of the PV plant depends on the time to repair the failure and the availability of the cable. Repairs should be delayed only if there is an opportunity to do the repair more efficiently in the near future. Response time for alerts or corrective action for the O&M function should be specified as part of the O&M.

2.2.1 Operation & Maintenance

As the plant becomes older, O&M becomes more and more important for improving the performance of the plant. An effective O&M programme will enhance the likelihood that a system will perform at or above its projected production rate and cost over time. It therefore reinforces confidence in the long-term performance and revenue capacity of an asset. Most essential parameters of an O&M contract are:

1. Documentation – before O&M
    a. As-built files
    b. List of all responsible parties (e.g. off-taker of power, owner etc.)
    c. Performance prediction
    d. Malfunctions or errors in the PV plant
    e. Chronological records of failures

2. Preventive O&M
    a. List of preventive measures to maintain the warranty of the components
    b. Vegetation management (trimming)
    c. Cleaning of the modules
    d. The schedule and cost of the preventive measures
    e. Procedure of responding to alerts
    f. Inventory of spare parts
    g. Reports after inspection or visit of the PV plant
    h. Availability and performance guarantee.

3 Fact Sheets for Mitigation Measures

In the following chapter, five selected samples of mitigation measures and the corresponding parameters are described in detail. Such a method aims to show the process of weighing mitigation actions for the failures described in the Solar Bankability project. The list of all mitigation measures with description can be found in Annex 1. The selected measures that are described here are:

a. Component testing - PV modules
b. PV plant planning
c. Design review and construction monitoring
d. Basic and advanced monitoring system
e. Reducing uncertainties (irradiance)

3.1 Parameters of the Fact Sheet

For every example the following parameters are described:

Category of the mitigation measure
The measures have been derived into two main categories - preventive and corrective. Preventive measures include actions before the failure occurs and corrective measures include actions after the occurrence and detection of the failure.

Short description
For every mitigation measure a short description is given. This way the purpose or the scope of the described mitigation measure will be clear. Thus, it will help to understand the suggested actions.

Actions
Every measure contains a number of actions. For every action the following parameters are given:

- Uncertainty:
  In addition to reducing the risk of the PV plant an action can reduce the uncertainty regarding the energy yield.
- Cost:
  The cost of every action is given in €/kW. This value is an approximation according to statistical data and case studies.

Table 3.1: Fact Sheet on Mitigation Measure - Component Testing – PV Modules

Name	Component Testing – PV modules	Preventive	X
		Corrective	X
Short description			
High-quality photovoltaic modules are subject to a number of requirements. First, they have to deliver the guaranteed rated power reliably, while withstanding an extremely wide range of environmental conditions. They must also be safe and durable, ensuring the system high yield over the long- term period. However, with testing actions the quality of the modules can be fully certified.			

Actions	Short description	Uncertainty	Cost
PID Testing	PID refers to potential induced performance degradation in crystalline silicon photovoltaic modules. It occurs when the module voltage potential and leakage current cause ion mobility within the module. The degradation accelerates with exposure to humidity, temperature and voltage potential. PID tests simulate the practical conditions in the PV system, and verify the module performance and power output under high voltage.		0.5 – 1 €/kW
Insulation measurement	A typical module would have a structure of glass–EVA–cell–EVA–tedlar back sheet. Apparent physical deteriorations of modules under long-term field-exposure have been observed. This measurement ensures the quality of the materials in order to ensure the insulation of the module.		0.2 – 0.7 €/kW
STC Power Measurements	Measurements under standard test conditions for determining IV and electrical output. Measurement conditions (STC): 1000 W/m², AM 1.5, 25°C.		0.3 – 0.8 €/kW
EL Imaging	Electroluminescence (EL) imaging is a quality assessment tool for both crystalline silicon and thin film solar modules. It is able of accurately detecting numerous failures and ageing effects e.g. cracks and breakages, in some cases defective edge insulation, shunts etc.		0.5 – 1 €/kW
IR inspection	The infrared imaging (IR) inspection of photovoltaic systems allows the detection of potential defects at the cell and module level as well as the detection of possible electrical interconnection problems. The inspections are carried out under normal operating conditions and do not require a system shut down.		0.5 – 1 €/kW

Table 3.2: Fact Sheet on Mitigation Measure – PV Plant Planning

Name	PV Plant Planning	Preventive	X
		Corrective	
Short description			
The planning of a PV plant requires the assignment of a set of input parameters in order to predict its final yearly energy production and its lifetime performance. This is usually done using specific software. Each input has a given uncertainty, depending on the availability and quality of the information that the planner has. PV projects simulations run in a context of low information on the input parameters have the highest uncertainties of the output values, and therefore are less attractive for investments (the values for the uncertainty reduction are given in absolute term and are based on the analysis carried out in Chapter 4.1).			
Actions	Short description	Uncertainty	Cost
Insolation variability	Use long time series of irradiance data (around 20 years). Ensure the quality of the available data.	>5% reduction (compared to 5 years)	
Solar Resource	i) Using ground measured insolation data assures a lower level of uncertainty in the estimation of the energy yield of a PV plant than using satellite measurements. Ii) When only satellite measures are available, consider combining it with short series (8 to 12 months) of ground measurements.	i) 1.5-2.0% reduction ii) 1.5-2.0% reduction	
Plane-of-array (POA) insolation	The use of insolation data (measured or estimated) on the same plane of the planned PV plant is preferable than the use of global horizontal and diffuse horizontal (alternatively, direct normal irradiance) irradiance. In fact, the use of POA transposition models is avoided in this case.	1.5-2% reduction	
POA transposition model	Choose POA models with highest accuracy for the specific location from available literature (Moser et al., 2016).	>2% reduction	
Ambient temperature variability	Use long time series (at least 20 years) of ambient temperature data from ground measurements.	>0.2% reduction	
Temperature coefficients	Use temperature coefficients or Ross coefficients from laboratory measurements or extrapolated from existing plants in similar conditions. When applying models to translate the available series of ambient temperature, use models that take also the influence of wind on module performance into consideration.	>0.1% reduction	

Degradation	Consider available research results on typical values of degradation rates and long-term behaviour according to technology and climate.	>0.2% reduction	
Shading	Use appropriate equipment for the measurement of the horizon at the chosen site. Consider the presence of surrounding obstacles and the variation of shading during the year (e.g. vegetation).	>1% reduction	
Soiling	Consider available research results on typical values of soiling according to climate and regional conditions.	>1% reduction	
Spectral effect	Consider available research results on typical values of spectral effects according to the technology and climate.	>0.5% reduction	
Nominal power	Use values of nominal power from measurements under Standard Test Conditions from accredited laboratories. Consider stabilized values of nominal power, especially for those technologies that are susceptible to initial metastable effects (light induced degradation (LID), light soaking). Sort modules with similar nominal power to minimize module mismatch.	>0.2% reduction	
PV array and inverter model	Ensure that the software meets the requirements, in particular that it allows the user to set the whole set of parameters influencing the energy production. Consider which sub-models (temperature, POA transposition models) are implemented within the software.		
Tracker accuracy	Ensure to consider the right tracker accuracy in the calculations.		

Total cost of the mitigation	Uncertainty before the mitigation	Uncertainty after the mitigation	.
Typical cost of a yield assessment	16.58% (worst case) 8.7% (base case)	4.55%	

Table 3.3: Fact Sheet on Mitigation Measure - Design Review and Construction Monitoring

Name	Design Review and Construction Monitoring	Preventive	X
		Corrective	
Short description			
The total number of detected failures due to wrong design or installation in our database highlights the importance of this measure. In order the PV project to meet the expectations of the investors regarding the profitability and life expectancy a number of actions have to be taken. Risks such as underperformance, warranty coverage, delay, cost overrun etc. are minimized after the application of this measure.			

Actions	Short description	Uncertainty	Cost
Site suitability	Ensure that a geo-technical assessment (clay, rock, porosity, stability) is undertaken to confirm ground stability and ability to support the solar PV installation Ensure slope stabilization and good drainage if applicable		€/kW
Grid code compliance	To ensure that the design of the PV plant is in compliance with the grid code. The EPC contractor has experience meeting grid operator commissioning requirements. Moreover, confirm that commissioning is in line with grid code is a contractor obligation.		€/kW
Design review	To guarantee robustness of warranty and the correct and efficient sizing of the components. In addition to ensure that specifications comply with international and local standards and requirements.		0.5 – 1 €/kW
Construction monitoring	To avoid failures during the construction of the PV plant. Especially mistakes due to lack of know-how. Designs and installation must be in line. To conduct electrical and mechanical measurements in order to identify possible failures of the components.		0.5 – 1 €/kW
Performance prediction	To ensure that the meteorological data and software used for the energy analysis of the PV plant meet the requirements. Ensure that shading is considered in performance calculation assessment. Furthermore, potential current and future sources of dust are taken into consideration as well as potential risks of grid outage.		€/kW

Table 3.4: Fact Sheet on Mitigation Measure – Basic and Advanced Monitoring System

<table>
<tr><td rowspan="2">Name</td><td rowspan="2" colspan="2">Basic and Advanced Monitoring System</td><td>Preventive</td><td>X</td></tr>
<tr><td>Corrective</td><td></td></tr>
<tr><td colspan="5">Short description</td></tr>
<tr><td colspan="5">A basic monitoring system typically allows the monitoring on plant level including device alarm collection and notifications. Furthermore, aggregation functionality on plant level for energy, irradiation and performance ratio are typically provided.

An advanced monitoring system allows the early detection and diagnosis of faults. Early detection and diagnosis of faults during PV plant operation are essential in order to obtain and maintain the energy yield high. Early remediation of faults not only restores generation promptly but also avoids the occurrence of additional component failures and leads to reduction of O&M costs. The benefit of advanced monitoring is built up through reduced operational costs on one hand and additional revenues resulting from a higher performance ratio and higher availability on the other hand.</td></tr>
<tr><td>Actions</td><td colspan="2">Short description</td><td>Uncertainty</td><td>Cost</td></tr>
<tr><td>Basic monitoring</td><td colspan="2">A basic monitoring system allows to the user, among others, to follow-up the key performance indicators such as e.g. PR. Furthermore, the user may receive notifications coming from device alarms, which can allow the timely detection of a fault. However, the user does not receive information on the root cause of the problem.</td><td></td><td>0.5 €/kW</td></tr>
<tr><td>Advanced monitoring</td><td colspan="2">The application of advanced monitoring techniques helps identifying several operational issues and design flaws. Amongst others, the following issues may be identified through advanced monitoring: irradiation sensor issues, string failures, bypass diode failures, partial shading, potential induced degradation (PID), unintentional power loss caused due to inverter sizing or incorrect inverter settings, etc.</td><td></td><td>2 €/kW</td></tr>
</table>

Table 3.5: Fact Sheet on Mitigation Measure – Reducing Uncertainties (Irradiance)

Name	Reducing Uncertainties (Irradiance)	Preventive	X
		Corrective	

Short description
Some of the main technical risks in lifetime energy yield calculations arise from the uncertainties related with the solar resource quantification and its long-term behaviour. These uncertainties affect directly the business plan and the investment decision can be compromised. Therefore, reducing these uncertainties can help to make the investment of the PV system attractive.

Actions	Short description	Uncertainty	Cost
Site adaptation	The use of site adaptation techniques potentially mitigates one of the highest risks related with the lifetime energy yield by minimizing the risk of an over-estimation of the solar resource in the initial assessment during project development. An over-estimation of energy yield will lead to under-estimation of the project LCOE and thus could mislead an investment decision. In addition, if the actual energy production does not meet the initial estimates the investment returns are impacted.	e.g. a reduction from 4% down to 2% can be achieved if satellite bias is constant over the year and more than 8 months of local measurements are used.	3-5 €/kW
Long-term variability and trends	The use of more advanced methodologies to account for the effect of long-term variability and trends can mitigate the risk associated with the long-term solar resource behaviour. The uncertainty for cash flow analysis (uncertainty of single years) can be reduced by using off-the-shelf algorithms. However, for valuation analysis (uncertainty of multiple year sums), the approach is more complex and a clear methodology needs to be derived. More information about these methods can be found in [Reff to D3.1].	e.g. a reduction from ca. 6% down to 5% can be achieved in the Netherlands.	€/kW

4 Methodology

4.1 Definition of Best and Worst Uncertainty Scenarios

Some of the risks related to a PV project, already identified in (Moser et al., 2016) and included in the risk matrix, have an economic impact in terms of uncertainty. In particular, the uncertainty can be related either to the expected yield and performance indicators during the planning phase, or to the actual yield and/or performance indicators during the operational phase. Figure 4.1 shows a list of technical risks with impact on the uncertainty during the *PV plant planning phase*. It is interesting to see that not all the components of a PV system are involved, and that also uncertainties related to the assessment of the actual yield originate from phases preceding operation and maintenance.

In particular, this section focuses on defining several uncertainty scenarios of the input parameters used for the design of a PV plant, with a focus on how these uncertainties propagate to the expected yield and performance ratio. Therefore, it is first of all necessary to define a general model that describes the relation between input parameters, and between input parameters and output quantities. In Figure 4.2 a possible structure of such a model is shown. The PV array model receives input from the temperature and irradiance models, and generates the expected array yield by also taking several array losses into account. Finally, the yield is fed into the PV inverter model in order to estimate the final yield of a PV system. In Figure 4.2, all risks that have an impact in terms of uncertainty on the model are reported in different colours depending on the PV plant component related to it. It is worth to note that some of the uncertainties associated to a risk can have a direct impact on a model or sub-model, while others can also affect the uncertainty of other risks. For example, an incorrect estimation of the power rating has a direct impact on the PV array model (wrong nominal power inserted in the simulation software), but might also lead to an incorrect sorting of the modules right before their installation, which in turn may cause losses in the energy generation due to power mismatch of modules.

UNCERTAINTY

Planning of PV Plants

EXPECTED YIELD AND PERFORMANCE INDICATORS

Component	Project phase	Risk
A. MODULES	Product testing / development	8. Incorrect power rating (flash test issue
A. MODULES	PV plant planning / development	1. Soiling losses
A. MODULES	PV plant planning / development	2. Shadow diagram
A. MODULES	PV plant planning / development	3. Modules' mismatch
A. MODULES	PV plant planning / development	5. Flash test report not available or incorrect
A. MODULES	PV plant planning / development	7. Incorrect assumptions of module degradation
A. MODULES	PV plant planning / development	9. Simulation parameters (low irradiance, temperature, etc.) unclear
B. INVERTERS	PV plant planning / development	1. Inverter wrongly sized
B. INVERTERS	PV plant planning / development	5. Inverter wrongly sized - excessive derating.
B. INVERTERS	PV plant planning / development	6. Inverter exposed to direct sunlight - Derating
B. INVERTERS	PV plant planning / development	9. Simulation parameters (low irradiance, temperature dependencies, etc.) unclear
C. MOUNTING STRUCTURES	PV plant planning / development	7. Overestimation of tracker accuracy
K. MISCELLANEOUS	PV plant planning / development	2. System documentation incomplete

Assessment of PV Plants

ACTUAL YIELD AND/OR PERFORMANCE INDICATORS

Component	Project phase	Risk
G. WEATHER STATION & COMMUNICATION & MONITORING	PV plant planning / development	1. No monitoring system
G. WEATHER STATION & COMMUNICATION & MONITORING	PV plant planning / development	2. Shadow and soiling of irradiance sensors
G. WEATHER STATION & COMMUNICATION & MONITORING	PV plant planning / development	3. Inadequate or non-existent module temperature measurements or temperature assessment
G. WEATHER STATION & COMMUNICATION & MONITORING	PV plant planning / development	4. Inadequate or non-existent monitoring of DC voltage and current
G. WEATHER STATION & COMMUNICATION & MONITORING	PV plant planning / development	5. Inadequate data logger
G. WEATHER STATION & COMMUNICATION & MONITORING	PV plant planning / development	6. Missing weather sensors, inadequate or non-existent irradiance, ambient/module temperature and wind speed sensors
G. WEATHER STATION & COMMUNICATION & MONITORING	Transportation / installation	1. Misalignment between the solar irradiation sensor and PV array
G. WEATHER STATION & COMMUNICATION & MONITORING	Transportation / installation	2. Sensors not calibrated
G. WEATHER STATION & COMMUNICATION & MONITORING	Transportation / installation	3. Erroneous data and/or missing information implemented in the monitoring system
G. WEATHER STATION & COMMUNICATION & MONITORING	Transportation / installation	4. Wrong information supplied to monitoring platform

Figure 4.1: List of the risks having an economic impact in terms of uncertainty of either estimated or actual yield of a PV plant. Numbers are taken from the list of risks presented in (Moser et al., 2016)

The schematic model in Figure 4.2 is a general overview of the PV energy conversion chain and the inter-relation of the different steps (input parameters and models) involved. Several software tools implement irradiance, temperature, PV array and PV system models with different characteristics (i.e. number and type of input parameters, type of sub-models used) and different levels of complexity. In general, two methodologies are typically used to estimate the uncertainty propagation: the Monte Carlo technique and the classical law of propagation of errors ("JCGM 100:2008(E)," 2008). The Monte Carlo approach allows reconstructing the Probability Density Function (PDF) of the errors of a model starting from the information on the PDF of the errors of its input quantities. This way, if a high (i.e. statistically significant) number of values of each input parameter is generated according to the distribution of its error, and the corresponding number of simulations is run, the resulting model outputs can be statistically analyzed in order to reconstruct the PDF of their error and calculate their uncertainty. The Monte Carlo technique is particularly useful and reliable when applied to models described by complex equations, in which also correlations between input parameters may occur. In this case, the application of classical law of propagation of errors might become a difficult task. In order to overcome this problem, some approximations can be introduced. As reported by Thevenard et al (Thevenard and Pelland, 2011) it is possible to represent a PV model with a good approximation as the product of linear factors:

$$\textit{output} = \textit{input} \times \textit{proportionality factor} - \textit{offset}$$

where the offset is relatively small compared to the phenomenon itself. If a quantity X is the product of N independent variables $X_1, X_2, ..., X_N$ and can be expressed as $X=c*X_1*X_2*...*X_N$, where c is a constant and $\sigma_1, \sigma_2, ..., \sigma_N$ are the uncertainties (corresponding to the standard deviations), then the so-called *rule of squares* can be applied and the combined relative uncertainty of X becomes:

$$\frac{\sigma_X}{X} = \sqrt{\left(\frac{\sigma_1}{X_1}\right)^2 + \left(\frac{\sigma_2}{X_2}\right)^2 + \dots + \left(\frac{\sigma_N}{X_N}\right)^2} \quad (4.1)$$

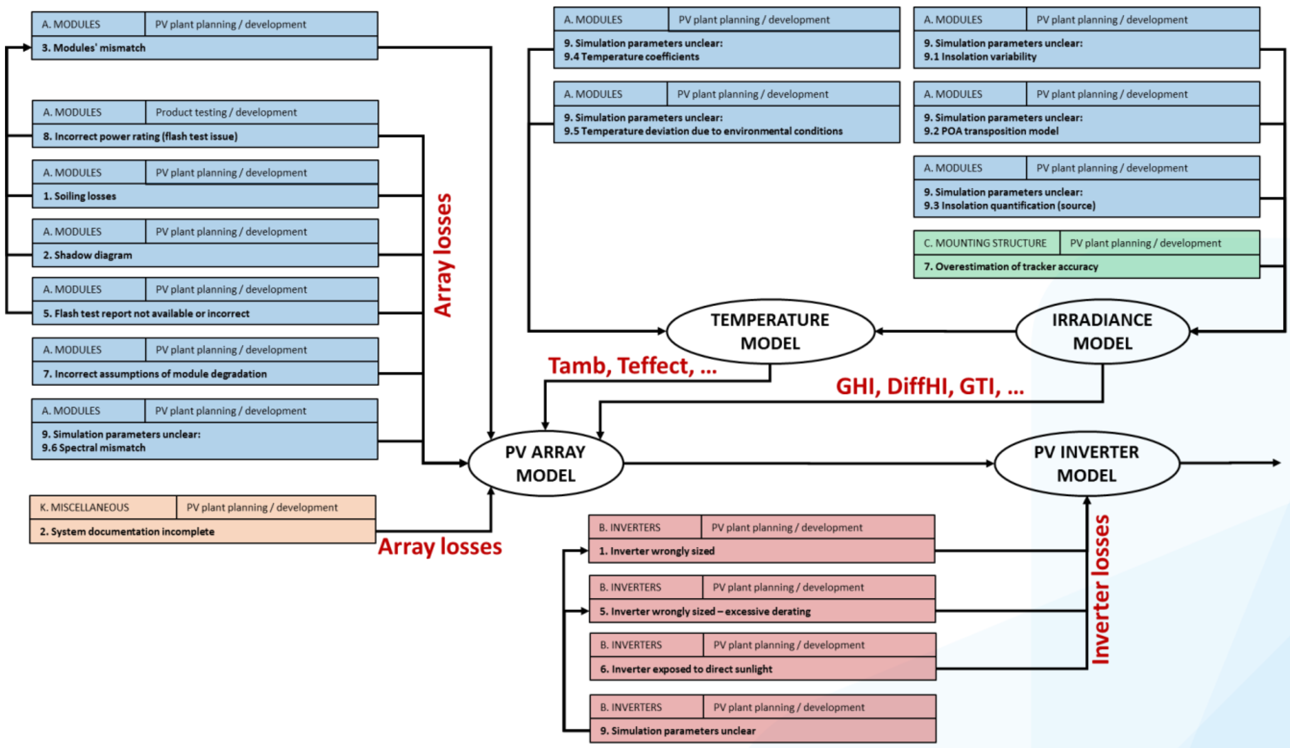


Figure 4.2: General schematic of a model for the estimation of the yield of a PV system. Risks generating uncertainty are reported with a representative value of associated uncertainty, and colored depending on the related component. Mutual influences are indicated by arrows.

In order to compare the two methodologies, both are applied to estimate the uncertainty related to the planning of a 4kWp PV system in Bolzano (South Tyrol, Italy). The main characteristics of the PV plant and the input parameters involved in the calculations are presented in Table 4.1. The information on the uncertainty of the input parameters, i.e. the distribution characteristics of their errors is presented in Table 4.2, and refers to a **base uncertainty scenario**. These values have been assigned on the basis of the information on the PV plant and on the site that is really available, and in particular on a 20-year period of meteorological data (i.e. global horizontal irradiance, diffuse horizontal irradiance, ambient temperature and wind speed) from satellite estimates. In order to apply the Monte Carlo technique, a number of *1000* values (N) was generated for each considered input parameter, according to the PDF of their errors as reported in Table 4.2. The software used for this exercise is Statistics101 (“Statistics101 - Grosberg,” 2016).

The selected number of draws is estimated sufficient to have statistical significance for this exercise. In the next step, the 1000 generated values of each input parameter were combined in 1000 input vectors, and fed into the simulation software PVSyst (“PVSyst,” 2016). The software therefore calculated 1000 values of global tilted irradiance (*GTI)*, array yield (*Ya)*, final yield (*Yf)* and Performance Ratio (*PR)* for the considered PV plant.

Figure 4.3 shows the frequency distributions and the cumulative frequency distributions of the error of Ya, Yr and PR that seem to resemble the normal distribution with a good approximation. By calculating the standard deviation of the error distribution, we finally calculated the uncertainty of these parameters as shown in Figure 4.4. In the same figure, also the uncertainty calculated with the rule of squares is reported. It is interesting to see that the values of uncertainty of GTI, Ya and Yf are similar for the two methodologies (though values generated with the rule of squares are slightly lower than that calculated with Monte Carlo), thus confirming the validity of the assumption made in order to apply the classical law of propagation of errors. An exception rises for PR, where the uncertainty of 5.77% from the rule of squares is much higher than the 0.78% with the Monte Carlo technique. A reasonable explanation for this comes from the expression of PR (“IEC 61724 : Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange and Analysis,” 1998):

$$PR = \frac{Y_f}{Y_r} \quad (4.2)$$

Since PR is a function of two highly correlated variables (Yf depends on Yr), here the assumption previously made (PV yield model as a product of independent variables) is not valid anymore and the rules of squares is not adequate.

Table 4.1: Main characteristics and settings of the simulated PV system in Bolzano

Module type	210Wp (crystalline Si)
Nominal power	3.8 kWp
Number of modules	18 polycrystalline-silicon
N. modules x n. strings	9 x 2
Inverter type	4000 W nominal power
Tilt and orientation	30° tilt, 188° azimuth
Soiling losses	0.5%
Module quality loss	1%
Thermal factor	29 W/ (m^2 K)
Meteo file	22 years of satellite data

Table 4.2: Parameters describing the frequency distribution of the errors of the input parameters used for the 1000 simulations with PVSyst. Only the base uncertainty case scenario is reported.

Parameter	Insolation variability	Temp. variability	Temp. effects (thermal factor Uc)	Soiling losses	Nominal power
Shape	normal (calculated)	normal (calculated)	normal (calculated)	normal (assumed)	normal (assumed)
Relative uncertainty (standard deviation)	3.31% GHI 2.24% DiffHi (k=1)	0.43% (k=1)	0.14% (k=1)	0.49% (k=1)	0.98% (k=1)

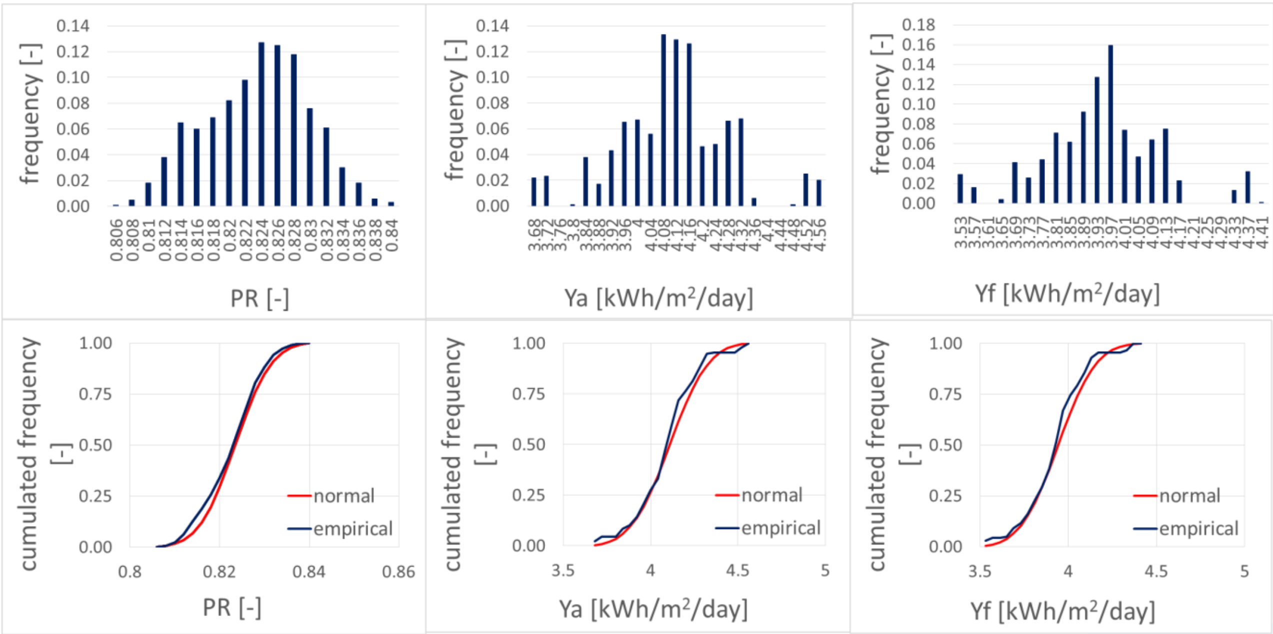


Figure 4.3: Frequency distribution and cumulative frequency distribution of the parameters array yield (Ya), final yield (Yf) and performance ratio (PR), generated from 1000 simulations with PVSyst using input parameters errors distributed according to Table 4.2. Red line represents the corresponding normal distribution with empirical mean (μ) and standard deviation (σ). Only the base uncertainty scenario is represented.

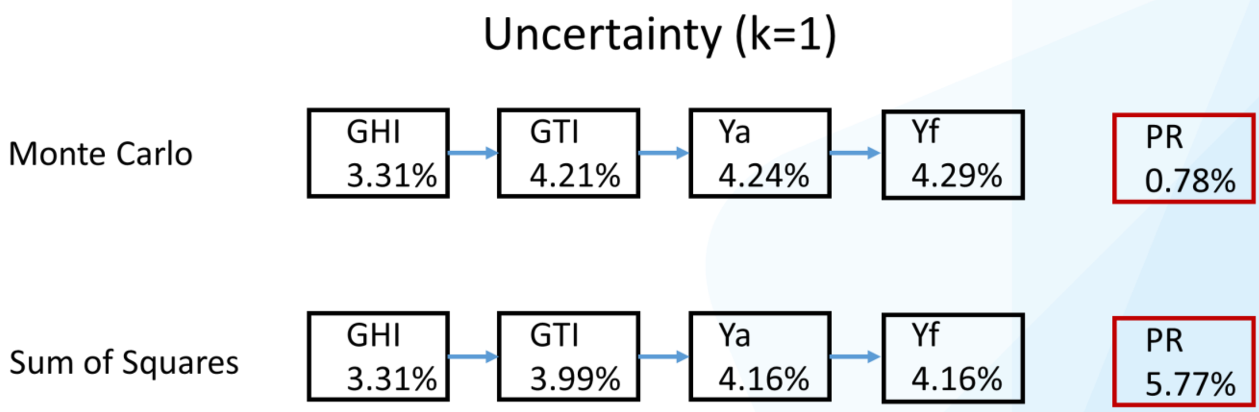


Figure 4.4: Propagation of the uncertainty from the simulation software (PVSyst) input to the different output parameters, using the Monte Carlo technique and the rule of square. Only the base uncertainty scenario is considered.

Further scenarios – best and worst-case

When planning a PV system, the available information can be different from case to case affecting also the value of the associated uncertainty. For example, when considering the solar resource parameter, which accounts for the most quote of the energy yield uncertainty as shown e.g. in (Caroline Tjengdrawira and Mauricio Richter, 2016), the planner could have:

- Different time series ranges, i.e. different insolation variability: e.g., 1, 5, 20 etc. years of available data
- Different insolation resources: e.g. measured, satellite-retrieved, or a combination of long-term satellite data and short-term series of measured data (Achim Woyte et al., 2016; Gueymard and Wilcox, 2009; Polo et al., 2016)
- Datasets of irradiance on the plane of array, or the need to use plane-of-array transposition models from global and diffuse horizontal irradiance.

Further information is needed to define the value and the uncertainty of, among the most important, the ambient temperature variability, the temperature coefficients or temperature effects, the performance loss rate, the soiling losses, the shading losses, the spectral mismatch gain/losses, the module nominal power and the inverter efficiency.

In order to analyse the variability of the uncertainty of the outputs of a generic PV model, several uncertainty scenarios have been defined. These scenarios differ from the base uncertainty scenario previously introduced:

- **case 1: base uncertainty scenario (22 years of satellite-derived GHI and DiffHI in Bolzano)**
- case 2: 5 years of measured GHI and DiffHI in Bolzano
- case 3: 20 years of measured GHI and DiffHI in Bolzano
- case 4: combination of long-term satellite-derived GHI and DiffHI and short-term (1 year) series of measured GHI and DiffHI
- case 5: 5 years of satellite-derived GHI and DiffHI in Bolzano
- case 6: 20 years of measured GHI and DiffHI in a site with high insolation variability
- case 7: 20 years of satellite-derived global tilted irradiance (GTI) in Bolzano
- case 8: 5 years of measured GTI in Bolzano
- case 9: 20 years of measured GTI in Bolzano
- case 10: combination of long-term satellite-derived GTI and short-term (1 year) series of measured GTI
- case 11: 5 years of satellite-derived GTI in Bolzano
- case 12: 20 years of measured GTI in a site with high insolation variability
- case 13: worst transposition model for Bolzano
- case 14: high uncertainty of temperature effects (e.g. choice of temperature model not accounting for wind effect)
- case 15: high variability of ambient temperature
- case 16: high uncertainty of performance loss rate

- case 17: high uncertainty of shading effect (e.g. mountainous region, no measurement of the horizon)
- case 18: high uncertainty of soiling effect (e.g. desert area, no estimation of soiling in the region)
- case 19: high uncertainty of spectral mismatch effect (e.g. use of technology with narrow spectral responsivity such as amorphous silicon)
- case 20: high uncertainty of nominal power
- case 21: high uncertainty of inverter efficiency
- case 22: worst-case (highest uncertainty for each input parameter).

The additional cases (2 to 22) have the same set of uncertainties of the base scenario, except for the uncertainty of one single parameter (e.g. insolation variability, or solar resource, etc.), which can be either higher or lower.

A complete list of all considered uncertainty scenarios, reporting the values of uncertainty associated to each input parameter and the uncertainty of the PV model outputs calculated with the rule of squares, is found in Appendix 5. Table 4.3 contains an overview of the uncertainties used for each input parameter in the base and additional uncertainty scenarios, with a short explanation regarding the choice of the values. It is worth to notice that all the uncertainty values of Table 4.3 refer to the uncertainty on the energy yield. For example, the uncertainty on energy yield due to soiling effect is 0.49%, which is calculated considering an average value of Ya of 4.13 kWh/kWp/day (calculated with PVSyst), a value of soiling loss of 0.5% (see Table 4.1) and an uncertainty of 2% on this value.

A ranking list of the considered cases, based on the value of the uncertainty calculated on the final yield of the 4 kWp PV plant in Bolzano with the rule of squares is reported in Table 4.4. The value of uncertainty reported for the base uncertainty scenario does not correspond to that reported in Figure 4.4, because the uncertainty propagation of more input parameters is involved in the calculation. The results of Figure 4.4 refer to the propagation of a limited number of uncertainties types, reflecting the limited number of input parameters that can be modified in the batch mode of PVSyst. This issue will be further discussed in Section 4.3. In general, the following considerations can be made:

There is a group of cases assuring a low level of uncertainty (4.55% to 8.70%). This includes the base case and the alternative cases with lower uncertainties than the base case. **They all refer to the use of long time-series** of either ground measurements or satellite estimates of insolation. The temporal range of the available insolation data seem therefore to be the most important factor affecting the uncertainty of the yield estimation. There is for example a 5% improvement when using 20 years instead of 5 years of GTI data, which increases up to 7.6% when GHI and DiffHI data are used.

The best case corresponds to the use of 20 years of measured values of GTI, showing also that a lower uncertainty is assured when a) **ground measurements are used in place of satellite estimates** and b) **time series of plane-of-array irradiance is available without the need to apply transposition models**. In the first case there is, for example, a 1.9% improvement when using long series of measured GTI data, which increases up to 2.9% when using long series of measured GHI and DiffHI data. Results show also that using a combination of long time series of satellite data with a short series of measured data is recommended than just using satellite data.

In the case a PV plant is to be installed in a location with high insolation variability, the uncertainty of the yield estimation is also negatively affected. For example, if the same considerations made for Bolzano were applied for London, at least an additional 3% should be added in the final yield uncertainty.

Besides the insolation variability and the solar resource quantification uncertainty**, the uncertainties related to shading and soiling effects and to the use of transposition models play also a role** in the overall uncertainty of the final yield.

In general, the uncertainty of the final yield of the 4kWp plant installed in Bolzano ranges from 4.5% to 14.9%. The latter becomes a 16.6% in the eventuality that the planner has the worst information quality available.

Table 4.3: List of uncertainties assumed for the different input parameters, both in the base uncertainty scenario and in the alternative uncertainty scenarios

	Scenario	Description	Rel. unc. (st.dev, k=1)	Note
Insolation variability	Base	20 years of data	3.31%	calculated from the weather files. Same value for GHI, DiffHI, GTI
	Alternative	5 years of data	9.00%	Same value for GHI, DiffHI, GTI
	Alternative	20 years of data, high variability due to location	7.10%	Same value for GHI, DiffHI, GTI
Solar resource	Base	satellite estimates	5.00%	from Suri et al. (Suri et al., 2007) and Richter et al. (Richter, M et al., 2015)
	Alternative	ground measurements	2.00%	supposing to use a secondary standard pyranometer
	Alternative	combination of long-term satellite data and short-term series of measured data [ref 3E]	3.00%	from Gueymard et al. (Gueymard and Wilcox, 2009)
Transposition model	Base	good transposition model	2.00%	proven to be good for the specific location
	Alternative	bad transposition model	5.40%	(Cameron et al., 2008)
Ambient temperature variability	Base	20 years of data	0.43%	calculated from the weather files
	Alternative	highest reported by SB deliverable	2.00%	highest value (Moser et al., 2016) [Technical Risks in PV Projects, page 50]
Temperature effect	Base	best temperature model	0.14%	using a temperature model that accounts for wind effect (e.g. Koehl (Koehl et al., 2011)), proven to be good for the considered location (Schwingshackl et al., 2013)
	Alternative	worst temperature model	1.15%	using a temperature model that does not account for wind effect (e.g. NOCT formula), proven to be bad for the considered location
Performance loss rate	Base	low uncertainty	0.50%	
	Alternative	high uncertainty	2.00%	highest value (Moser et al., 2016) [Technical Risks in PV Projects, page 50]
Soiling effect	Base	low uncertainty	0.49%	calculated from 2% uncertainty of soiling losses
	Alternative	high uncertainty	4.00%	highest value according to Reich et al., 2015 (Reich et al., 2015)
Shading effect	Base	low uncertainty	2.00%	
	Alternative	high uncertainty	5.00%	
Spectral mismatch effect	Base	low uncertainty	0.20%	
	Alternative	high uncertainty	2.00%	
Nominal power of the modules	Base	low uncertainty	0.98%	
	Alternative	high uncertainty	2.00%	highest value (Moser et al., 2016) [Technical Risks in PV Projects, page 50]
Inverter efficiency effect	Base	low uncertainty	0.20%	
	Alternative	high uncertainty	0.50%	highest value (Moser et al., 2016) [Technical Risks in PV Projects, page 50]

Table 4.4: Ranking list of the base and alternative uncertainty scenarios based on the calculated value of uncertainty on the final yield of the 4 kWp PV system installed in Bolzano

Relative Uncertainty on Yf	Case Number	Description
4.55%	9	20 years of measured GTI in Bolzano
5.07%	10	combination of long-term satellite-derived GTI and short-term (1 year) series of measured GTI
5.80%	3	20 years of measured GHI and DiffHI in Bolzano
6.45%	7	20 years of satellite-derived GTI in Bolzano
6.61%	4	combination of long-term satellite-derived GHI and DiffHI and short-term (1 year) series of measured GHI and DiffHI
7.76%	12	20 years of measured GTI in a site with high insolation variability
8.70%	1	base uncertainty scenario (20 years of satellite GHI and DiffHI in Bolzano)
8.71%	21	high uncertainty of inverter efficiency
8.77%	14	high uncertainty of temperature effects (e.g. choice of temperature model not accounting for wind effect)
8.87%	20	high uncertainty of nominal power
8.91%	16	high uncertainty of performance loss rate
8.92%	15	high variability of ambient temperature
8.92%	19	high uncertainty of spectral mismatch effect (e.g. use of technology with narrow spectral responsivity like amorphous silicon)
9.53%	8	5 years of measured GTI in Bolzano
9.56%	18	high uncertainty of soiling effect (e.g. desert area, no estimation of soiling in the region)
9.83%	17	high uncertainty of shading effect (e.g. mountainous region, no measurement of the horizon)
10.04%	13	worst transposition model for Bolzano
10.57%	11	5 years of satellite GTI in Bolzano
10.89%	6	20 years of measured GHI and DiffHI in a site with high insolation variability
13.41%	2	5 years of measured GHI and DiffHI in Bolzano
14.89%	5	5 years of satellite-derived GHI and DiffHI in Bolzano
16.58%	22	worst-case (highest uncertainty for each input parameter)

4.2 CPN Reduction by Different Mitigation Measures

Besides the technical risks associated with uncertainties during project planning phase, the second group of risks has a direct economic impact during operation. These risks were already identified and evaluated in “Report Technical Risks in PV Projects” (Moser et al., 2016). The methodology of quantification was also introduced in chapter 5 of the mentioned report.

The developed method is now applied on the evaluation of the effectiveness of the identified mitigation measures. To this extent, Risk Mitigation Factors (RMF) are introduced which quantify the reduction of costs for fixing the failures (i.e. repair of existing component, substitution by spare component, substitution by new component). Therefore, three new parameters are defined as risk mitigation factors. Depending on the category of mitigation, the impact is:

(α) mitigation of number of failures

(β) mitigation of time to detection

(γ) mitigation of time to repair.

The quantitative impact is given by a number between 0 - 1. If a mitigation measure has no impact on a certain failure, the related risk reduction factor is 1. If the risk parameter is completely eliminated after the mitigation, the risk mitigation factor becomes 0. This means that with **α** of 0.5 the number of failures can be reduced to 50% and with **β** of 0.5 the time to detection can be reduced to 50% of the time without mitigation.

Thus, the mitigated number of failures is calculated as follows:

$$n_{fail,mit} = \alpha \cdot n_{fail}$$

The mitigated time to detection is calculated as follows:

$$t_{td,mit} = \beta \cdot t_{td}$$

and the mitigated time to repair/substitution is calculated as follows:

$$t_{tr/ts,mit} = \gamma \cdot t_{tr/ts}$$

When several mitigation measures with impact on the same risk mitigation factor are considered, the individual risk mitigation factors are multiplied with each other and the risk is further reduced. The risk mitigation factor **α,** respectively **β** and **γ,** is then calculated as follows:

$$\alpha = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \ldots = \prod_{i=1}^{n} \alpha_i$$

Implementing the new mitigation factors into the CPN model leads to the following mitigated downtime costs (€):

$$C_{down,mit} = C_{down,td,mit} + C_{down,tr/ts,mit} + C_{down,fix,mit}$$

- mitigated downtime costs to detection:

$$C_{down,td,mit} = \alpha \cdot n_{fail}/n_{comp} \cdot \beta \cdot t_{td}/t_{ref} \cdot PL \cdot M \cdot PPA \cdot Y = \alpha \cdot \beta \cdot C_{down,td}$$

- mitigated downtime costs to repair/substitution:

$$C_{down,tr/ts,mit} = \alpha \cdot n_{fail}/n_{comp} \cdot \gamma \cdot t_{tr/ts}/t_{ref} \cdot PL \cdot M \cdot PPA \cdot Y = \alpha \cdot \gamma \cdot C_{down,tr/ts}$$

and mitigated downtime costs during repair/substitution:

$$C_{down,fix,mit} = \alpha \cdot n_{fail}/n_{comp} \cdot t_{fix}/t_{ref} \cdot M \cdot PPA \cdot Y = \alpha \cdot C_{down,fix}$$

In addition to downtime costs, the costs for fixing the failures is the second main parameter. It considers the costs of repair and substitution of parts ($C_{rep/sub}$), costs of transportation (C_{trans}), labour costs (C_{lab}) and also the costs of detection and mitigation depending on the applied mitigation measures ($C_{det/mit}$). It is calculated as follows:

$$C_{fix,mit} = \alpha \cdot n_{fail} \cdot [C_{det/mit} + C_{rep/sub} + C_{trans} + (C_{lab} * t_{fix})] = \alpha \cdot C_{fix}$$

The calculation of the mitigated CPN is then given by:

$$CPN_{mit} = C_{down,mit} + C_{fix,mit}.$$

4.3 Critical Aspects of the Proposed Approaches

4.3.1 Error Propagation in Yield Uncertainty for Failures during Planning

In Section 4.1 the Monte Carlo technique has been used to calculate the propagation of uncertainty of the input parameters of a PV simulation software or model to its outputs (generated energy, performance indexes etc.). This methodology is preferable when the model to which it is applied is made up of non-linear and not differentiable equations, as prescribed by GUM ("BIPM - Guide to the Expression of Uncertainty in Measurement (GUM)," n.d.) . In this case, the Monte Carlo is expected to be more rigorous and correct than the classical rule of squares. As demonstrated in Section 4.1, the application of the two methodologies to the estimation of the energy yield of a PV plant generates similar results, with the exception of the Performance Ratio index. Therefore, in this case the use of the Monte Carlo technique would be preferable to the rule of sum of squares.

However, some critical aspects can be highlighted in the application of this methodology. First of all, Monte Carlo is a statistical technique that requires a high number of simulations in order to assure that the results have statistical significance. Therefore, a significant level of computational resources must be guaranteed. Another aspect concerns the current available software for the calculation of the of energy productivity of a PV plant. An ideal software should allow the user a) to set a sufficient number of input parameters needed to perform a reliable uncertainty propagation analysis; and b) to give the possibility to run simulations in batch mode, i.e. to execute scripts. Unfortunately, to the authors' knowledge, the implementation of both features has not been done yet in any of the available commercial software, or only partially.

4.3.2 CPN methodology and mitigation measures

Mitigation measures as described in the methodology have an impact limited to the number of failures, time to detection, and time to repair/substitution through the Risk Mitigation Factors. Some specific mitigation measures could have an impact also on other parameters included in the CPN methodology but not fully exploited in this report. For example, the availability of spare parts could also have an impact on the cost of repair and substitution: when the failure occurs, a specific product might not be available on the market anymore (e.g. module from a specific manufacturer or with a certain nominal power) or available only at higher costs.

Other issue is represented by the complexity of carrying out a comprehensive analysis of the effect of combined mitigation measures. In this report, mitigation measures have been grouped with a broad scoped. The impact of specific mitigation measures such as video surveillance, effective insurance cover, predictive monitoring, just to name a few, are to some extent included in the analysis but each individual contribution is not specified. This was the results of a trade-off between the need to analyse various mitigation measures and the complexity of the analysis.

It has to be stressed that the methodology already allows or can be easily modified to include the aforementioned analysis.

5 Analysis and Results

5.1 Impact on Initial Energy Yield Prediction and Exceedance Probability for the Defined Scenarios with Reduced Uncertainties

As also covered in the report “Review and Gap Analyses of Technical Assumptions in PV Electricity Cost” (see chapter 3.1.2) (Tjengdrawira and Richter, 2016), a common way to quantify the technical risks arising during the PV planning phase, is to calculate the exceedance probability as, e.g., P50/P90. Typically, for the various elements concurring to the final uncertainty of the energy yield, a normal distribution is assumed. In section 4.1 of this report, instead of relying on a normal distribution, we have opted for an empirical method based on a Monte Carlo analysis. The result is an empirical cumulative distribution function from which the exceedance probabilities can be interpolated.

The use of empirical methods can thus be regarded as the most advanced mitigation measure in reducing the risks in the initial yield assessment as it allows the inclusion of data which might not be normally distributed.

Figure 5.1 shows the comparison between the results of the Monte Carlo analysis and a normal distribution with a mean (μ) specific energy yield value of 1445 kWh/kWp and standard deviation (σ) of 4.6% (k=1) as taken from Chapter 4.1.

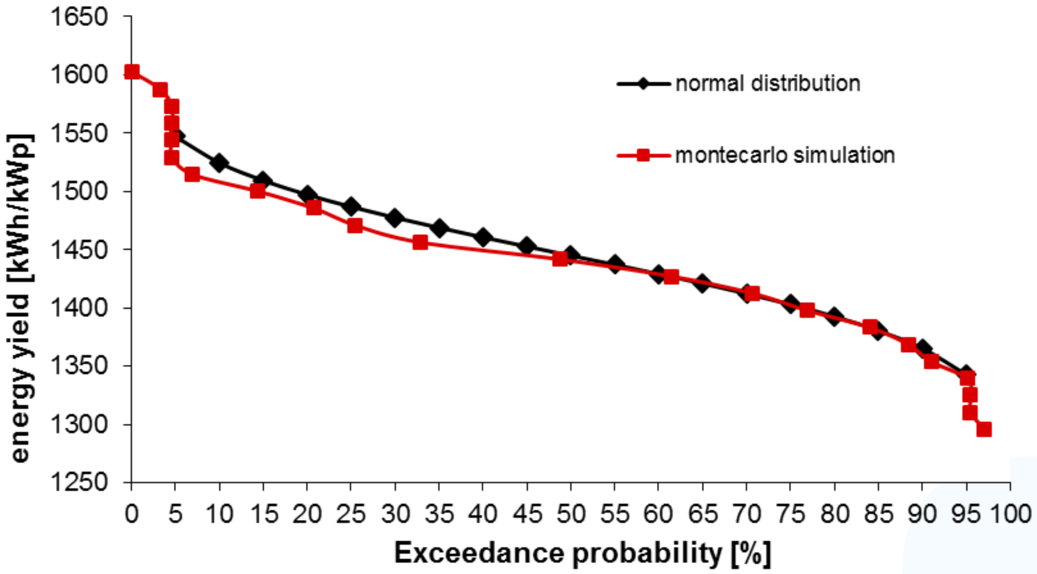


Figure 5.1: Comparison of the cumulative distribution function for a normal distribution with σ=4.6% (k=1) (black curve) and the results from a Monte Carlo analysis (red curve)

It is by coincidence that the P90/P50 ratio is very similar for both distributions (94.4%). What differs are the absolute values of P50 and P90 (-0.35% for the empirical distribution). The empirical distribution is positively skewed and shows important differences for values <P50 (e.g. -6.6% at P10 for the empirical distribution). In addition, extreme scenarios (e.g. P99) can largely be affected by the use of normal distribution yielding unrealistic results. Similar results were obtained for the analysis of the long-term solar resource as presented in deliverable D3.1 of the Solar Bankability project (Tjengdrawira and Richter, 2016), where it is shown that assuming a normal distribution for the solar resource uncertainties may not be the most correct approach.

Unfortunately, there is not always a sufficiently large dataset available to establish the CDF from which to interpolate exceedance probabilities. Nevertheless, for some elements involved in the calculation of the long-term expected yield as, e.g. the solar resource, this method can be applied. With the availability of more data for other elements, also other secondary effects can be included in the methodology as not normally distributed.

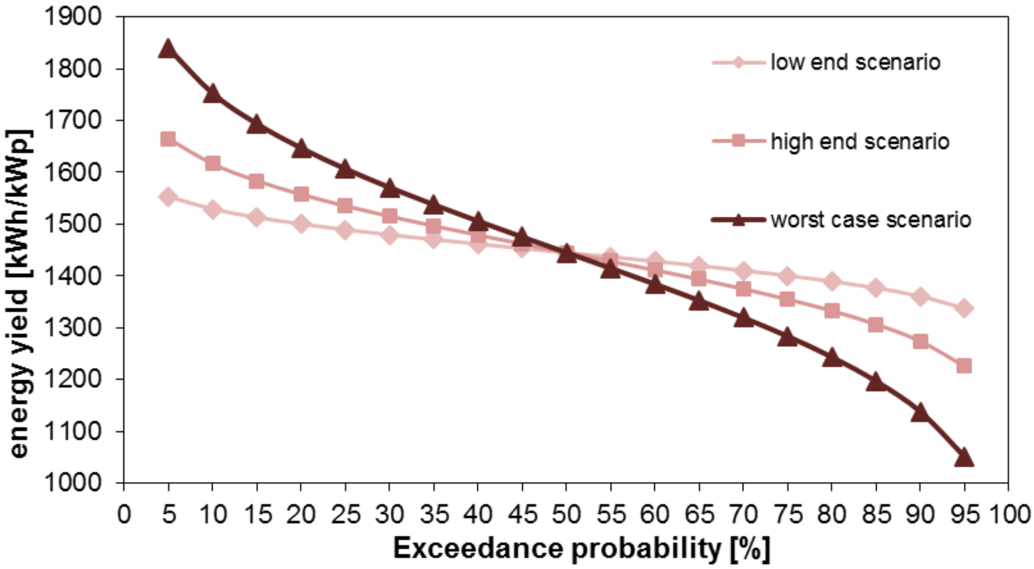


Figure 5.2: Comparison of the three scenarios assuming a normal distribution

The possibility of running a full-scale Monte Carlo analysis requires knowledge on the distribution of each element contributing to the overall uncertainty of the energy yield. If we restrict the analysis on normally distributed energy yield, we can look at the effect of the results obtained in section 4.1 for the various cases (see also Annex 5). For the 22 cases, the uncertainty varies between 4.6% (here defined as the low-end scenario) and 16.6% (here defined as the worst-case scenario). A high-end scenario was defined as the average without the outliers resulting in a σ=9.3%. The low end and high end scenarios are thus representative for the range given in (Moser et al., 2016) of 5-10% overall uncertainty of the energy yield. Here the impact of the uncertainty on the CDF is evident and the resulting P50, P90 and P90/P50 values are summarised in Table 5.1 and shown in Figure 5.2. The P90 values decrease respectively by -6% and -15% when compared to the low-end scenario.

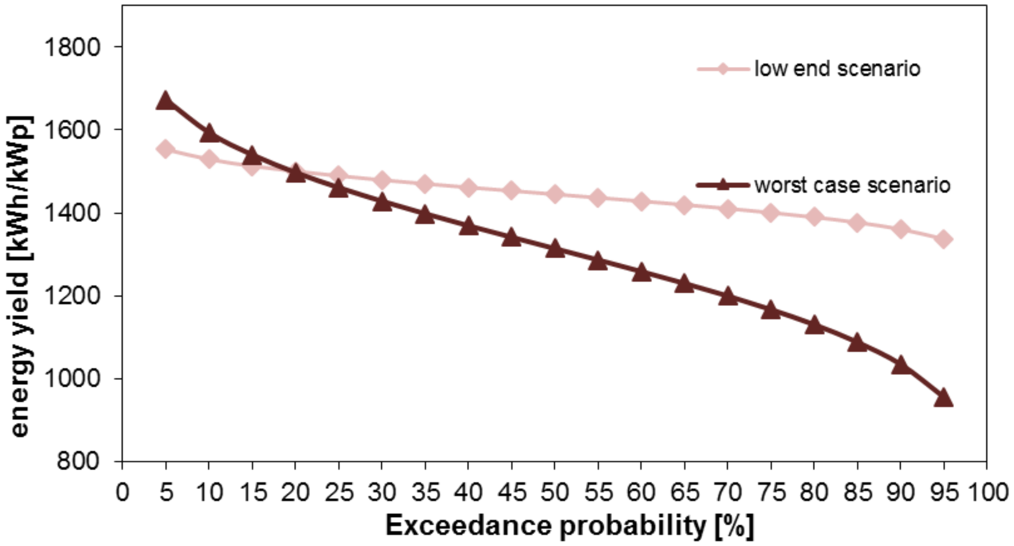


Figure 5.3: Comparison of the worst case scenario with different mean values of the normal distribution with σ=16.6%

Another important parameter which affects the overall analysis is the mean value of the energy yield (P50 if normally distributed). The main source of error is related to the solar resource assessment. Figure 5.2 shows the results for the worst-case scenario with a mean value of 1314 kWh/kWp instead of 1445 kWh/kWp. These values come from a solar resources assessment based on 5-year-measured data and 20-year-satellite-derived data, respectively. The use of shorter time series can clearly lead to an underestimation (or overestimation) of the mean value depending if the tails of the distribution are present or not. When compared to the low-end scenario, the reduction in P90 for this specific case is 22%.

Table 5.1: Summary of the exceedance probability values for various scenarios

	σ (k=1)	**P50 (kWh/kWp)**	**P90 (kWh/kWp)**	**P50/P90 (P50 reference case)**
Reference case (PVSYST, not all contributions included)	4.3%	1440	1360	94%
Ref. case (sum of squares)	**8.7%**	**1445**	**1283**	**89%**
Low end scenario	4.6%	1445	1365	94%
High end scenario	9.3%	1445	1273	88%
Worst case scenario	16.6%	1445	1138	79%
Worst case scenario (different mean value)	16.6%	1314	1034	72%

To deepen the analysis and understand how initial yield assessments relates with actual data during operation, the *Solar Bankability* project compared the initial long-term yield estimates against the actual production over a portfolio of 41 PV plants. This analysis is presented in (Caroline Tjengdrawira and Mauricio Richter, 2016). Results show that the dispersion (nRMSE) across the portfolio between initial yield estimates and actual production over the first years is around 4.4%. This lies towards the low-end scenario as presented in this analysis. However, for some extreme cases within the portfolio the difference is around 8 to 10%, lying more towards the reference case and high-end scenario.

Once the CDF of the yield is assessed for a specific plant or for a portfolio of PV plants, the exceedance probability values of the yield can be used as input for the parameter "Severity" as included in the CPN methodology (defined as the yield of a PV plant or a portfolio of PV plants unaffected by failures during operation). This would lead to a calculation of the distribution of CPNs with the possibility of assessing the risk related also to Cost Priority Numbers in terms of CPN_{50} and CPN_{90}.

The methodology presented in 4.1 and the results shown in this section can then be directly linked to the CPN methodology to provide an overall framework for the analysis of the economic impact of technical risks.

5.2 Impact of Applied Mitigation Measures on and Ranking of CPN

The economic impact of various mitigation measures are here reviewed and quantitatively evaluated based on the described methodology. In addition, the measures with the highest cost to benefit ratio are identified in order to facilitate the selection of suitable measures and their combinations.

The following eight of the already introduced mitigation measures are assessed. The pre-selection was made after research of the most common measures as defined in the gap analysis presented by (Tjengdrawira and Richter, 2016) and a representation of measures influencing the three parameters described n_{fail}, t_{td} and t_{tr} / t_s.

Table 5.2: List of most significant measures, their mitigation factors and affected parameters

Mitigation Measure	Risk Mitigation Factor	Affected Parameter
Component testing – PV modules	α	number of failures
Design review + construction monitoring	α	number of failures
Qualification of EPC	α	number of failures
Advanced monitoring system	β	time to detection
Basic monitoring system	β	time to detection
Advanced inspection	β	time to detection
Visual inspection	β	time to detection
Spare part management	γ	time to repair/substitution

The implementation of the measures is performed based on a reference scenario, limited to the utility scale segment of the database described in (Moser et al., 2016). The downtime is based on the "never detected" scenario without mitigation measures (the never detected scenario was defined with a 12 months lead-time to detection), here referred as LOSS scenario. The FIX scenario instead is dedicated to the cost of fixing the failure.

The total CPN is calculated from the sum of the individual CPN of all failures. The new CPN is the sum of the mitigated CPN including the costs incurred for the mitigation measures. The benefit of the combination of the measures resulting from the difference between total CPN and new CPN is then given by:

$$CPN_{new} = CPN_{mit} + Cost_{mit}$$

The applied costs of the mitigation measures are defined in Table 5.3 where three different cost scenarios are introduced: medium cost scenario (1), low cost scenario (2) and high cost scenario (3). They mark the lower and upper range of the applied costs for the new CPN calculations.

Table 5.3: List of mitigation measures with medium, low and high cost scenarios

Mitigation measure	**Defined costs** Scenario 1 (medium costs)	**Defined costs** Scenario 2 (low costs)	**Defined costs** Scenario 3 (high costs)
Component testing – PV modules	3 €/kWp (0.15 €/kWp/year)	1 €/kWp (0.05 €/kWp/year)	10 €/kWp (0.5 €/kWp/year)
Design review + construction monitoring	20 €/kWp (1 €/kWp/year)	10 €/kWp (0.5 €/kWp/year)	40 €/kWp (2 €/kWp/year)
Qualification of EPC	3 €/kWp (0.15 €/kWp/year)	1 €/kWp (0.05 €/kWp/year)	10 €/kWp (0.5 €/kWp/year)
Advanced monitoring system	2 €/kWp/year	1 €/kWp/year	3 €/kWp/year
Basic Monitoring system	0.5 €/kWp/year	0 €/kWp/year	1 €/kWp/year
Advanced Inspection	2 €/kWp/year	1 €/kWp/year	3 €/kWp/year
Visual Inspection	1 €/kWp/year	0.5 €/kWp/year	2 €/kWp/year
Spare part management	10 €/kWp (0.5 €/kWp/year)	2 €/kWp (0.1 €/kWp/year)	20 €/kWp (1 €/kWp/year)

The exact cost can vary depending on the type of project. A range of typical costs is given in Chapter 3.

The influence of the mitigation measures was ranked by the risk mitigation factor for each failure and each of the eight mitigation measures in the following four impact classes (Table 5.4). The overall classification of all failures was carried out in the context of a panel of experts composed by the project participants and is given in Annex 2 (An example of the combination of mitigation measures is given in Table 5.5.

Table 5.4: Definition of impact classes with respect to risk mitigation factor (RMF)

Impact Classes	RMF (α,β,γ)
High	99.5 %
Medium	50.0 %
Low	25.0 %
No	0.0 %

Table 5.5: Example of combination of mitigation measures

Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management
1	1	1	0	0	0	1	0

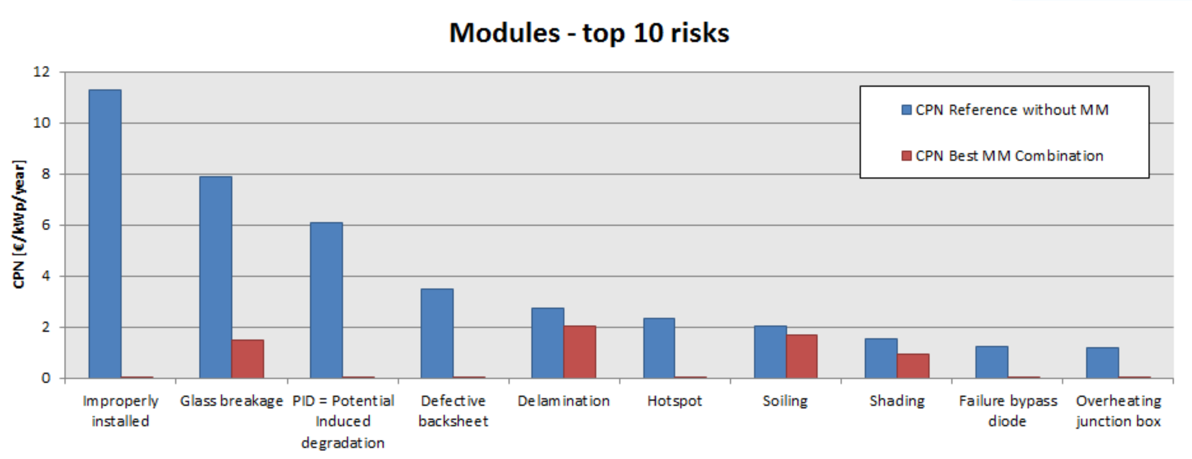


Figure 5.4: Top 10 risks of PV modules with and without mitigation measures in CPN

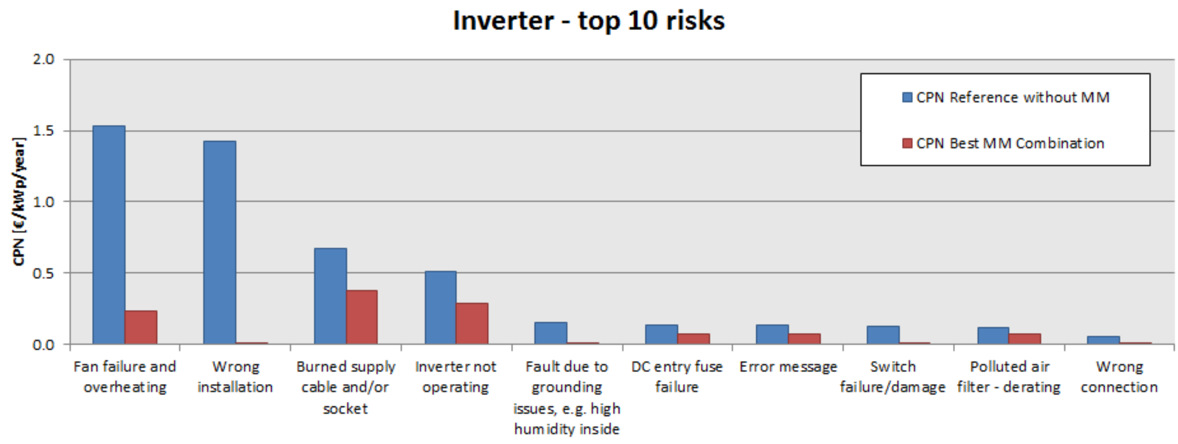


Figure 5.5. Top 10 risks of inverter with and without mitigation measures in CPN

Figures 5.4 and 5.5 show two examples of risk mitigation benefits in terms of CPN for the top 10 risks of PV modules and inverters. For these two examples the cost of the mitigation measure was spread over each specific failure. The CPN without any mitigation measures (blue bars) is compared to the CPN resulting from the best combination of mitigation measures (red bars) for each of the top 10 failures. When the CPN related to the mitigation measures is nearly zero, the benefit is the highest. This is the case for risks, which can easily be reduced by preventive measures e.g. bad installation, PID and defective back sheet for module risks (see Fig. 5.4) and wrong installation and grounding faults for inverter risks (see Fig. 5.5).

A right combination of mitigation measures can be very effective taking a failure specific CPN down to nearly zero.

5.2.1 Mitigation measures applied to the FIX scenario

The costs related to FIXING the failures result from the sum of the costs of repair/substitution, the costs of detection, the costs of transportation, and the cost of labour. Figure 5.6 shows the results of calculating the FIXING costs for selected failures when applying the eight mitigation measures listed in Table 5.3. The selection of failures was based on experts' panels and include the top 20 PV module failures, top 20 inverter failures, failures of mounting structure, combiner boxes, cabling as well as failures of transformer station as listed in Annex 2 of this report.

The total CPN without mitigation measures is 104.75 €/ kWp/year for the defined FIX scenarios, defined as FIX Reference. The CPN_{new} for all 256 combinations of mitigation measures are shown in Fig. 5.6 below. The total CPN without mitigation measures is given by the green area at 104.75 €/kWp/year. Applying specific mitigation measures (e.g. combinations 192 – 255 as given in Annex 3) it is possible to significantly reduce the risks and to obtain values of CPN_{new} in the order of 15 to 20 €/kWp/year (see Fig. 5.6). The index of combinations can be found in Annex 3.

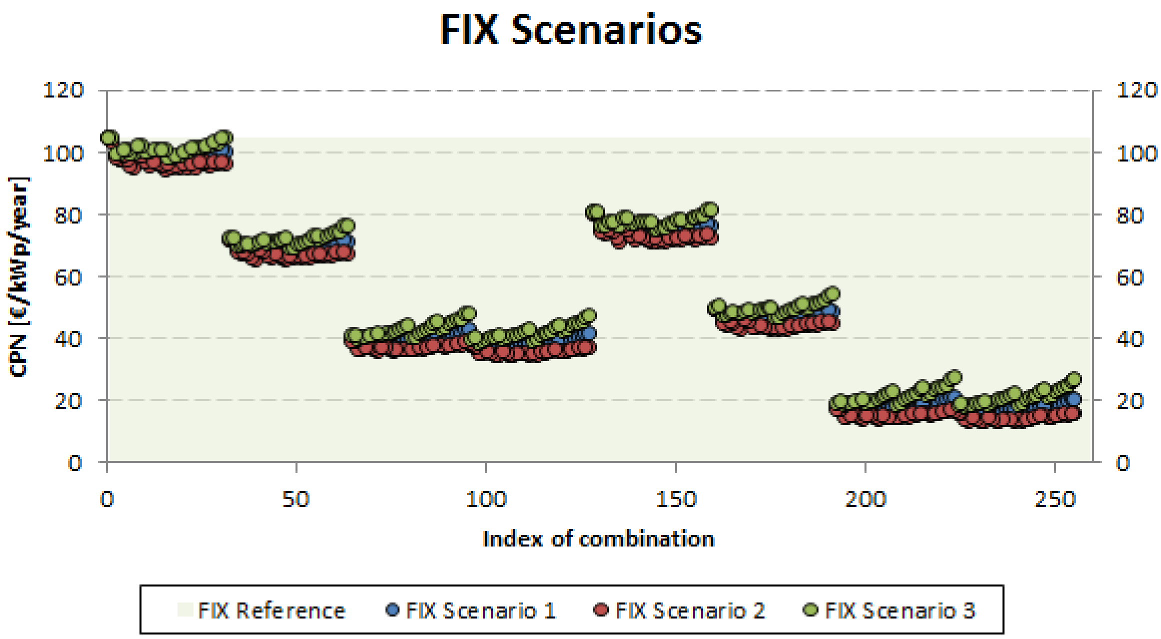


Figure 5.6: New CPN results of mitigation measure combinations for different FIX cost scenarios compared to CPN without MM – Index of mitigation measure combinations is given in Annex 3.

Table 5.6: Best combinations of mitigation measures for medium (1), low (2) and high (3) cost scenarios and their savings in CPN (last column)

		Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management	Saving [€/kWp]
FIX Scenario 1	RANK 1	1	1	1	0	0	0	1	0	89.3
	RANK 2	1	1	1	0	0	0	1	1	89.2
	RANK 3	1	1	1	1	0	0	0	0	88.9
	RANK 4	1	1	1	1	0	0	0	1	88.8
	RANK 5	1	1	1	0	0	1	1	0	88.7
	RANK 6	1	1	1	0	1	0	1	0	88.6
	RANK 7	1	1	1	0	0	1	1	1	88.5
	RANK 8	1	1	1	0	1	0	1	1	88.5
	RANK 9	1	1	0	0	0	0	1	0	88.4
	RANK 10	1	1	1	0	0	1	0	0	88.3
FIX Scenario 2	RANK 1	1	1	1	0	0	1	1	1	91.1
	RANK 2	1	1	1	0	1	0	1	1	91.1
	RANK 3	1	1	1	1	0	0	0	1	90.9
	RANK 4	1	1	1	0	0	1	1	0	90.9
	RANK 5	1	1	1	0	1	0	1	0	90.8
	RANK 6	1	1	1	0	0	0	1	1	90.8
	RANK 7	1	1	1	0	1	1	1	1	90.8
	RANK 8	1	1	1	1	0	0	0	0	90.6
	RANK 9	1	1	1	0	1	1	0	1	90.6
	RANK 10	1	1	1	0	0	0	1	0	90.5
FIX Scenario 3	RANK 1	1	1	1	0	0	0	1	0	86.6
	RANK 2	1	1	1	1	0	0	0	0	86.2
	RANK 3	1	1	0	0	0	0	1	0	86.0
	RANK 4	1	1	1	0	0	0	1	1	86.0
	RANK 5	1	1	1	0	0	0	0	0	85.9
	RANK 6	1	1	0	1	0	0	0	0	85.7
	RANK 7	1	1	1	0	0	1	0	0	85.6
	RANK 8	1	1	1	0	1	0	0	0	85.6
	RANK 9	1	1	1	1	0	0	0	1	85.6
	RANK 10	1	1	0	0	0	0	1	1	85.4

Table 5.6 shows the corresponding savings of those mitigation measures for the best combinations (Rank 1 to 10) and for the three cost scenarios. The savings ranging between 85 and 91 €/kWp/year are given by the difference between the total CPN (104.75 €/kWp/year) and the new CPN. The savings for low cost scenario (2) are slightly higher than for the medium (1) and high cost (3) scenario (see Tab. 5.6).

The following outcome can be derived from the results shown in Fig. 5.6 and Table 5.6:

- For all 256 combinations of mitigation measures the CPN_{new} for FIXING low cost scenario 2 shows better results than for FIX medium 1 and for FIX high cost scenarios 3 as expected.
- Preventive measures have the highest impact on CPN_{new} e.g. Qualification of EPC (index of mitigation measure combination 32 to 63) will bring down CPN_{new} to 75 €/kWp/year. E.g. Design review (index of combination 64 to 95) will further reduce CPN_{new} to 40 €/kWp/year (see Fig. 5.6).
- Corrective measures have less impact on CPN_{new} e.g. Basic and advanced monitoring and visual and advanced inspection (index of combination 1 to 31 – Fig. 5.6). However, corrective measures can be very important, when it comes to assigning liabilities at the end of the guarantee or warrantee period.
- Reducing the number of failures has the highest impact due to the high substitution costs.
- The highest savings for all three cost scenarios can be achieved by applying the three preventive measures (component testing plus design review plus qualification of EPC) as shown in the first three columns of Table 5.6. The savings may reach 90 €/kWp/year for the best combinations of selected mitigation measures.
- As shown in Fig. 5.6, for 99% of all mitigation measure combinations the scenarios will result in economic benefit by reducing the CPN_{new} to values lower than 104.75€/kWp/year.

5.2.2 Mitigation measures applied to the LOSS scenario

The LOSS scenario is focused on the economic losses due to downtime. Figure 5.7 and Figure 5.8 show the results of calculating the LOSS costs for the same failures as in Fig. 5.6 (Annex 2) when applying the eight mitigation measures listed in Table 5.3. For the calculation of the LOSS costs due to downtime, it is important to consider the missing income of feed-in tariffs or the missing income from Power Purchasing Agreement (PPA) or the missing savings in terms of Retail Cost of Electricity for PV plants on roofs. Here, we consider high PPA (0.25€/kWh) and low PPA (0.10€/kWh) for the three different cost LOSS scenarios of large-scale PV plants.

The total CPN without mitigation measures is 13.5 €/kWp/year for the defined LOSS scenarios, also known as “never detected”, defined as LOSS Reference based on high PPA value (0.25€/kWh). The CPN_{new} values for all 256 combinations of mitigation measures are shown in Fig. 5.7 below. The total CPN without mitigation measures is given by the green area at

13.5 €/kWp/year. Applying specific mitigation measures allows the significant reduction of the losses and obtain values of CPN_{new} in the order of 4 to 8 €/kWp/year for the low cost scenario (2) and between 4 and 10 €/kWp/year for the medium cost scenario (1) as shown in Fig. 5.7.

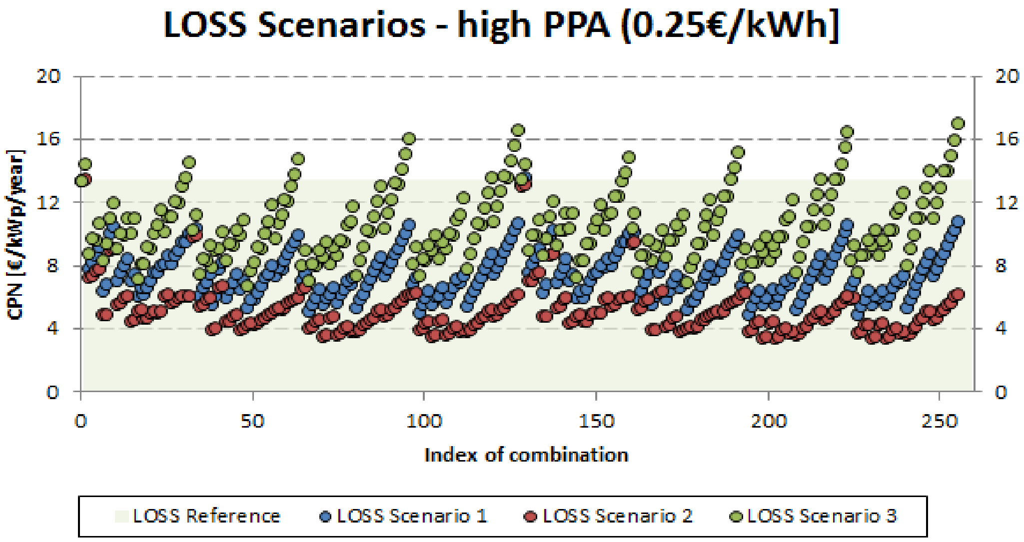


Figure 5.7: New CPN results of mitigation measure combinations of different LOSS scenarios based on high PPA compared to CPN without mitigation measures

Table 5.7: Combination of mitigation measures for the defined LOSS scenarios

		Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management	Saving [€/kWp]
LOSS Scenario 1	RANK 1	1	1	1	0	0	0	1	0	8.5
	RANK 2	1	1	0	0	0	0	1	0	8.5
	RANK 3	0	1	1	0	0	0	1	0	8.3
	RANK 4	0	1	0	0	0	0	1	0	8.3
	RANK 5	1	1	0	1	0	0	0	0	8.2
	RANK 6	1	0	1	1	0	0	0	0	8.2
	RANK 7	0	1	0	1	0	0	0	0	8.1
	RANK 8	1	1	1	1	0	0	0	0	8.1
	RANK 9	0	0	1	1	0	0	0	0	8.0
	RANK 10	1	1	1	0	0	0	1	1	8.0
LOSS Scenario 2	RANK 1	1	1	1	0	0	1	1	0	10.0
	RANK 2	1	1	1	0	1	0	1	0	10.0
	RANK 3	1	1	0	0	0	1	1	0	10.0
	RANK 4	1	1	0	0	1	0	1	0	10.0
	RANK 5	0	1	1	0	0	1	1	0	9.9
	RANK 6	1	1	1	0	0	1	1	1	9.9
	RANK 7	1	1	1	0	1	0	1	1	9.9
	RANK 8	0	1	0	0	0	1	1	0	9.9
	RANK 9	1	1	0	0	0	1	1	1	9.9
	RANK 10	1	1	0	0	1	0	1	1	9.9
LOSS Scenario 3	RANK 1	0	0	1	1	0	0	0	0	6.7
	RANK 2	1	0	1	1	0	0	0	0	6.5
	RANK 3	0	1	0	0	0	0	1	0	6.3
	RANK 4	0	0	0	1	0	0	0	0	6.3
	RANK 5	1	1	0	0	0	0	1	0	6.1
	RANK 6	1	0	0	1	0	0	0	0	6.1
	RANK 7	0	1	0	1	0	0	0	0	6.1
	RANK 8	0	1	1	0	0	0	1	0	6.0
	RANK 9	0	0	1	0	0	0	1	0	6.0
	RANK 10	1	1	0	1	0	0	0	0	5.8

Table 5.7 shows the corresponding savings of the mitigation measures for the best combinations (Rank 1 to 10) and for the three LOSS cost scenarios. The savings ranging between 6 and 10 €/kWp/year are given by the difference between the total CPN without mitigation measures (13.5 €/kWp/year) and the new CPN (Fig. 5.7). The savings for low cost scenario (2) are higher than for the medium (1) and high cost (3) scenario (see Tab. 5.7).

The following outcome can be derived from the results shown in Fig. 5.7 and Table 5.7:

- Most of the scenarios are economical beneficial (lower than 13.5 € / kWp/year) – Fig. 5.7.
- Low cost LOSS scenario 2 shows clear advantage, but the level of impact on the new CPN depends on the combination of selected mitigation measures (Fig. 5.7).
- The highest savings for LOSS cost scenarios 1 and 2 can be achieved by applying the three preventive measures (component testing plus design review plus qualification of EPC) as shown in the first three columns of Table 5.7. The savings may reach 10 €/kWp/year for the best combinations of selected mitigation measures.

The total CPN without mitigation measures (LOSS Reference) for the defined LOSS scenarios with low PPA (0.10€/kWh) is 5.4 €/kWp/year. The CPN_{new} for all 256 combinations of mitigation measures are shown in Figure 5.8 below. The total CPN without mitigation measures is given by the green area at 5.4 €/kWp/year. Applying specific mitigation measures allows the reduction of the losses and obtain values of CPN_{new} in the order of 2 €/kWp/year for the low cost scenario (2) and CPN_{new} of 3 €/kWp/year for the medium cost scenario (1) as shown in Fig. 5.8.

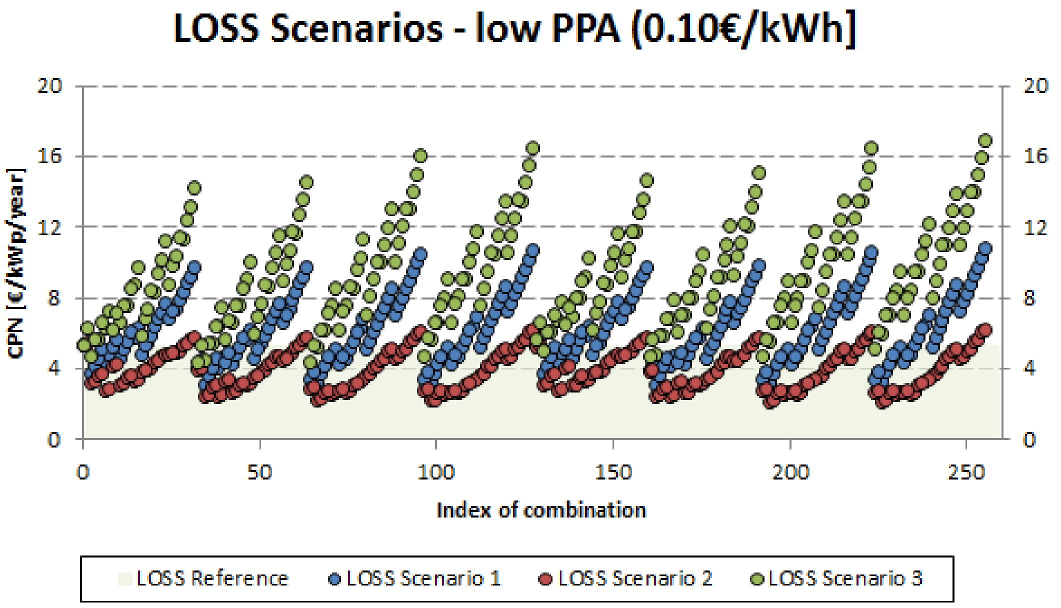


Figure 5.8: New CPN results of mitigation measure combinations of different LOSS scenarios based on Low PPA compared to CPN without mitigation measures

Table 5.8 shows the corresponding savings of the mitigation measures for the best combinations (Rank 1 to 10) and for the three LOSS cost scenarios. The savings ranging between 0.2 and 3.2 €/kWp/year are given by the difference between the total CPN without mitigation measures (5.4 €/kWp/year) and the new CPN (Fig. 5.8). The savings for low cost scenario (2) are higher than for the medium (1) and high cost (3) scenario (see Tab. 5.8).

Table 5.8: Combination of mitigation measures for the defined LOSS scenarios

		Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management	Saving [€/kWp]
LOSS Scenario 1	RANK 1	0	0	1	0	0	0	1	0	2.2
	RANK 2	1	0	1	0	0	0	1	0	2.2
	RANK 3	0	1	0	0	0	0	1	0	2.1
	RANK 4	1	1	0	0	0	0	1	0	2.1
	RANK 5	0	1	1	0	0	0	1	0	2.0
	RANK 6	1	1	1	0	0	0	1	0	2.0
	RANK 7	1	1	0	0	0	0	0	0	2.0
	RANK 8	0	1	0	0	0	0	0	0	2.0
	RANK 9	0	1	1	0	0	0	0	0	1.9
	RANK 10	1	1	1	0	0	0	0	0	1.9
LOSS Scenario 2	RANK 1	1	1	1	0	0	0	1	0	3.2
	RANK 2	1	1	0	0	0	0	1	0	3.2
	RANK 3	0	1	1	0	0	0	1	0	3.1
	RANK 4	0	1	0	0	0	0	1	0	3.1
	RANK 5	1	1	1	0	0	0	1	1	3.1
	RANK 6	1	1	0	0	0	0	1	1	3.1
	RANK 7	0	1	1	0	0	0	1	1	3.0
	RANK 8	0	1	0	0	0	0	1	1	3.0
	RANK 9	1	0	1	0	0	0	1	0	2.9
	RANK 10	1	0	1	0	0	1	1	0	2.8
LOSS Scenario 3	RANK 1	0	0	1	0	0	0	0	0	1.0
	RANK 2	0	1	0	0	0	0	0	0	1.0
	RANK 3	0	0	1	0	0	0	1	0	0.9
	RANK 4	0	0	0	0	0	0	1	0	0.7
	RANK 5	1	0	1	0	0	0	0	0	0.6
	RANK 6	1	1	0	0	0	0	0	0	0.6
	RANK 7	0	1	1	0	0	0	0	0	0.6
	RANK 8	1	0	1	0	0	0	1	0	0.5
	RANK 9	1	0	0	0	0	0	1	0	0.3
	RANK 10	1	1	1	0	0	0	0	0	0.2

The following outcome can be derived from the results shown in Fig. 5.8 and Table 5.8:

- Mostly low cost scenario 2 and only certain combinations of scenario 1 and scenario 3 are reducing the economic risks (lower than 5.4 €/kWp/year) – Fig. 5.8.
- A combination of **all** mitigation measures is not recommended and lead to higher costs. E.g. three times the reference LOSS for scenario 3 and combination 255 (Fig. 5.8).
- With low PPA it is more difficult to apply mitigation measures, which are economic beneficial. Best savings can only be obtained for low cost LOSS scenario 2 by applying the three preventive measures (component testing + design review + qualification of EPC) as shown in the first three columns of Table 5.8. The savings may reach 3.2 €/kWp/year for the best combinations of selected mitigation measures.

5.3 Risk Reduction Example (PID) before Detection

In the previous section, the impact of the mitigation measures was analysed for the sum of CPNs of the most important failures. In this section, we will focus on the effect of mitigation measures on a specific technical risk over a certain lifetime to fully assess the cost-benefits.

Potential induced degradation (PID) is used as an example of technical risk of a PV plant and the cost-benefit calculation is based on a period of five years of PV plant operation. As input parameters, given in Table 5.9, a failure rate of the PV plants of 10% and a failure rate of the PV modules of 20% are assumed. For the PID affected PV modules of the plant, an initial power loss of 20% and an annual power degradation rate of 5 % is used for the CPN LOSS calculation. Furthermore, an occurrence rate that the PID affected modules will fail of 5% is taken. For the loss due to performance losses, we consider a low PPA (0.10€/kWh).

Table 5.9: Input Data for Risk Reduction Example (PID)

Risk	Failure Rate plants	Failure Rate components	Initial Power Loss	Power Degradation rate	Occurrence degradation rate	PPA
PID	10%	20%	20%	5%	5%	0.10€/kWh

PID testing of PV modules prior to installation will result in a clear economic benefit when using the given input data (Table 5.9) and considering 5-year-operation as shown in Fig. 5.9. The annually increasing losses of the PV plant due to PID failure modules will result in an economic loss of CPN= 7.35 €/kWp after five years (light blue bars). This CPN loss is compared to the cost of the PID testing of the modules before installation (CPN= 0.64 €/kWp) and the cumulative reduced PID risks over 5 years (blue bars) which results in CPN= 1.35 €/kWp as shown in Fig. 5.9.

Table 5.10: Output Data for Risk Reduction Example (PID) after 0 to 5 Years

Risk	Mitigation	Mitigation cost (year 0)	Risk after 5 years	Reduced risk after 5 years	Savings after 5 years
PID	PID Test	0.6 €/kWp	7.35 €/kWp	1.35 €/kWp	6.00 €/kWp

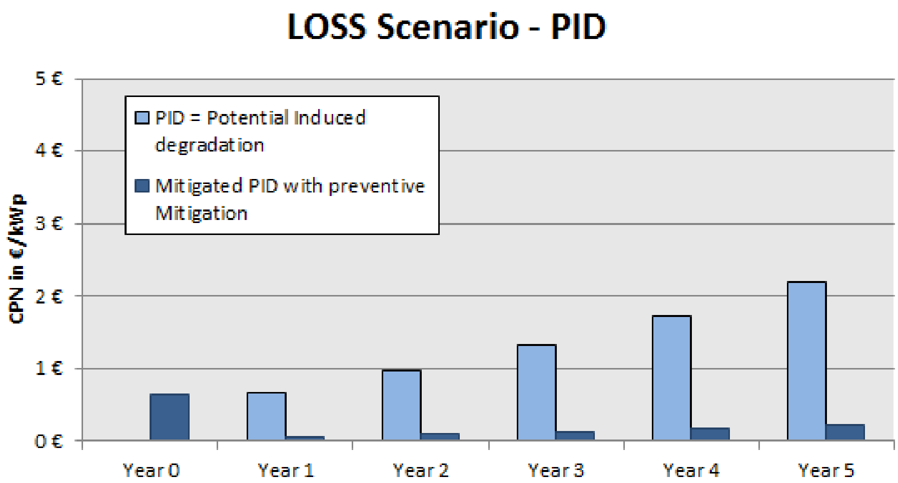


Figure 5.9: LOSS Scenario – PID Risk Reduction after 0 to 5 Years

The cost-benefit analysis of this mitigation measure (PID testing) yields in a cumulative saving of 6.00 €/kWp after 5-year-operation of the PV plant compared to the cumulative PID risk of CPN= 7.35 €/kWp as shown in Table 5.10.

6 Risk Reduction and Link to Gap Analysis

The overall CPN of the PV plants included in the database as a sum of the never detected and failure fix scenario was of the order of 120 Euros/kWp/year. This value includes the economic impacts of the identified technical risks for all components. Depending on when the failure occurs the ownership of the risk (and consequently, cost) will vary between the involved actors, i.e. PV plant owner, investor, EPC contractor, insurance company, O&M operator. It is thus important to be able to assign the risk to the relevant stakeholder along the lifetime of a PV project and to evaluate who will ultimately benefit in terms of cost reduction from mitigation measures which are put in place.

In the Solar Bankability project, one of the principal objectives is to develop guidelines on how technical risks over PV project life cycle should be taken into account in the different cost elements and when evaluating the PV investment cost. To-date the consortium has performed a review exercise to obtain a snapshot of the current industry practices in how technical risk assumptions in PV investment cost calculation are accounted. In addition, the consortium has compared these current practices to the state-of-the-art scientific data and the top 20 important technical risks identified using the CPN ranking method we developed in this Solar Bankability project. This gap analysis aims to identify gaps in the technical inputs that will introduce risks in the different cost elements of PV levelized cost of electricity (LCOE) value, namely the CAPEX, OPEX and energy yield[1]. This information will serve as the basis for Working Package 3 of this project to carry out the next task in the context of PV LCOE, i.e. to develop a best-practice guideline in how to account for the technical risks in PV investment cost.

From the review of the current industry practices, we found that in the LCOE, the EPC costs dominate the CAPEX while the O&M costs are the major contributor to the OPEX. The technical aspects in the EPC and O&M contracts are therefore important in managing the technical risks in PV project investment. Since the root-causes of the CPN-ranked technical risks and failures could be introduced either during project development (procurement and product testing, planning, transportation and construction) or during PV operation (O&M), the EPC and O&M contract terms should therefore account for these risks as much as possible. Whether to place the different mitigation measures in the hands of the EPC contractor or the O&M operator (or other parties) is a decision to be made with a goal to minimize the LCOE by optimizing the balance between the CAPEX and OPEX.

Our gap analysis exercise reveals that the technical aspects in the EPC and O&M contracts at present day are not sufficiently comprehensive to account for the CPN-ranked top technical risks

[1] The results of the review and gap analyses could be found in the report *Review and Gap Analyses of Technical Assumptions in PV Electricity Cost* (Tjengdrawira and Richter, 2016), available for public from August 2016 onwards.

and failures. We have identified the top 20 gaps found to be either missing from or inadequately defined in the EPC or O&M contracts (see (Tjengdrawira and Richter, 2016)). Using the results from this gap analysis, we have identified some recommendations to be included in the EPC or O&M contracts that could eventually address the important identified gaps (Table 6.1). A full discussion of best practice recommendations can be found in an upcoming report to be published in the last quarter of 2016. Here the cost associated with the mitigation measures will be simulated in several case studies where different scenarios of LCOE will be evaluated.

Table 6.1: Punch list of technical aspects to be considered in the EPC and O&M contracts

Area/phase	Recommendations
EPC/procurement and product testing phase	1. The EPC technical specifications should include requirements that the selected components are suitable for use in the specific PV plant environment of application. 2. The EPC should list tests to be performed by the component supplier while manufacturing the components. The test data should be submitted to the EPC contractor for verification. 3. The EPC should specify that the components must pass independent testing before acceptance. The tests and acceptance criteria should be included.
EPC/ system design phase - lifetime energy yield estimation	4. The effect of long-term trends in the solar resource should be taken into account. 5. When possible, exceedance probabilities (e.g. P90) must be calculated using empirical method based on available data instead of assuming normal distribution. 6. Correct degradation rate and behaviour (linear/stepwise) over time should be used in the yield estimation. 7. Overall availability assumption (not O&M guaranteed availability) must be used to calculate the initial yield for project investment financial model.
EPC/transportation	8. The EPC should specify requirement of transportation and handling protocol.
EPC/construction	9. The EPC should include comprehensive protocol and training to its field workers on how to un-package and handle components properly. 10. The EPC should include intermediate construction monitoring site visits.
EPC/plant commissioning and acceptance	11. The EPC should include IR imaging as part of plant acceptance visual inspection. 12. The EPC should include short-term performance (e.g. PR) check at provisional acceptance test, including proper correction for temperature and other losses. 13. The EPC should include correct final performance check and guaranteed performance. 14. The EPC should include correct measurement sensor calibrations and set a correct irradiation threshold to define time window of PV operation for PR/availability calculation.
O&M	15. The O&M should use smart monitoring system for plant fault detection and identification. 16. The maintenance should use IR or EL imaging analysis as regular plant inspection. 17. The O&M should include guaranteed PR, availability and/or energy yield. 18. The O&M should include correct measurement sensor calibrations and set a correct irradiation threshold to define time window of PV operation for PR/availability calculation. 19. The maintenance should specifically include the monitoring system. 20. Module cleaning should be at minimum once a year.

7 Conclusions

The overall methodology created within the Solar Bankability project allows the estimation of the economic impact of failures on the levelized cost of electricity (LCOE) and on business models of PV projects and has been developed to determine the economic impact of a failure, but also to be able to assess the effectiveness of mitigation measures.

There are two main reasons that highlight the importance of this mitigation measure. The first is the *Factor of 10* which means that in design phase, mistakes are costly, and the longer it takes to discover a problem, the more costly it becomes. According to Dr. David M. Anderson (Anderson, 2014), it costs 10 times more to find and repair a defect at the next stage of the plant, and then it costs 10 times more at each subsequent stage of the project. For this reason in the report we have identified and categorized mitigation measures in:

Category 1 (before) represents all the preventive measures, which are applied before the risk occurs in order to prevent it from happening. The costs are mostly related to the CAPEX as the implementation is included in the initial investment costs;

Category 2 (after) represents the corrective measures, which reduce higher losses and costs, if the risk has already occurred. The costs are mostly related to the OPEX due to the later implementation during the operation and maintenance phase.

All mitigation measures that affect the uncertainty related to the initial yield assessment (e.g. PV plant planning, reducing uncertainty (irradiance), reducing uncertainty (temperature), reducing uncertainty (degradation)) fall under Category 1. A reduction in uncertainty can in fact lead to a higher exceedance probability for P75, P90 and P99 and thus a more robust business model and bankable PV project. The analysis presented in the report show that typical values for the uncertainty of the initial yield are in the range of 5-10%. The analysis was carried out with the investigation of several scenarios by varying the source of uncertainty. There is a group of cases assuring a low level of uncertainty (4.55% to 8.70%). This includes the base case and the alternative cases with lower uncertainties than the base case. They all refer to the use of long time-series of either ground measurements or satellite-derived estimates of insolation. The temporal range of the available insolation data was found to be the most important factor affecting the uncertainty of the yield estimation. There is for example a 5% improvement when using 20 years instead of 5 years of GTI data, which increases up to 7.6% when GHI and DiffHI data are used.

The best case corresponds to the use of 20 years of measured values of GTI, showing also that a lower uncertainty is assured when a) ground measurements are used in place of satellite-derived estimates and b) time series of plane-of-array irradiance is available without the need to apply transposition models. In the first case there is, for example, a 1.9% improvement when using long series of measured GTI data, which increases up to 2.9% when using long series of measured GHI and DiffHI data. Results show also that using a combination of long time series of satellite data with a short series of measured data is recommended than just using satellite data. In terms of

P90, when the highest uncertainty is considered (16.6% for the specific case presented in the report) together with a wrong assumption on the average yield (i.e. use of short-term insolation database), the reduction could be as high as 22%.

Compared to many other power generating technologies, PV plants have reduced maintenance and service requirements. However, a continuous O&M programme is essential to optimise energy yield and maximise the lifetime and viability of the entire plant and its individual components. Many aspects of O&M practices are interrelated and significantly affect the performance of all the components in the generation chain and project lifecycle. Mitigation measures under Category 1 and Category 2 can have an effect on the overall CPN as defined in the Project Report “Technical Risks in PV Projects” (Moser et al., 2016) in terms of downtime, production performance, operational costs and time to complete the required activities. It is important that risk ownership is also considered to better understand which key actor is responsible for the action of mitigating the risk. These risks can then be turned in opportunities to meet or even exceed the expectations of the developers and owners in terms of return on the investment. In particular, suitable planning, supervision and quality assurance actions are critical at all stages of a PV project in order to minimise the risk of damages and outages, optimise the use of warranties, avoid non optimal use of resources and ultimately optimise the overall performance of the PV plant.

The cost of mitigation measures was included in a cost benefit analysis, which has to consider the expectations of the stakeholders that are involved in a PV project (Bächler, 2016). Investors are seeking for long defect warranty periods, performance guarantees, reasonable low CAPEX and OPEX, high long-term plant performance and lifetime (ideally above the initial prediction). Banks have requirements similar to those of the investors which are looking for projects with a 10-15-year financing period and PV plant performance which can also be slightly below prediction. Insurers try to limit their liability to failures with an external root cause based on PV plants, which meet technical market standards and are maintained on a regular basis. On the contrary, EPC contractors will look for short defect warranty periods, minimum of additional guarantees and warranties, high sale price with low OPEX showing a very different time horizon compared to the investors.

Mitigation measures with an impact on the overall CPN were identified as: component testing, design review + construction monitoring, qualification of EPC, basic and advanced monitoring system, visual and advanced inspection, and spare part management. The total CPN without mitigation measures was found to be 104.75 €/kWp/year for the defined FIX scenario, defined as FIX Reference. The impact of mitigation measures massively reduces this figure and in the report we have shown that it is possible to significantly reduce the risks and to obtain values of CPN in the order of 15 to 20 €/kWp/year. The value includes the economic impacts of the mitigation measures, their cost and the economic impact of the identified technical risks for all components after mitigation. Depending on when the failure occurs the ownership of the risk (and consequently, cost) will vary between the involved actors, i.e. PV plant owner, investor, EPC contractor, insurance company, O&M operator. It is thus important as a next step to be able to assign the risk to the relevant stakeholder along the lifetime of a PV project and to evaluate who will ultimately benefit in terms of cost reduction from mitigation measures, which are implemented.

As consequence of the different needs between the key actors, O&M operators are in a difficult position to manage all these conflicting requirements for a long period of time. The best condition for O&M operators is in fact in the presence of long defect warranty period and low sale price to allow for higher OPEX. Recent trends in the PV market have put a lot of pressure on the O&M price which is reported to be as low as 8 Euros/kWp/year in Germany in 2016 (Bächler, 2016). A large share of these costs is labour intensive (i.e. site keeping and inspection, preventive maintenance, monitoring and reporting). It is therefore of extreme importance to identify which O&M scope is obligatory vs what is optional. Furthermore, it is highly important to know the required reaction time depending on the severity of the failure by assessing the cost of various mitigation options during the operational phase which can be part of an effective O&M strategy.

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Appendices

Annex 1: List of All Mitigation Measures with Description

Mitigation measure	Description
PV plant planning	The planning of a PV plant requires taking assumptions of a set of input parameters in order to predict its final yearly energy production and its lifetime performance. This is usually done using specific software. Each input has a given uncertainty, depending on the availability and quality of the information that the planner has. PV projects, whose simulations are run in a context of little information on the input parameters, have the highest uncertainties of the output values, and therefore are more risky and is less attractive for PV investments.
Reducing uncertainty (irradiance)	Some of the main technical risks in lifetime energy yield calculations arise from the uncertainties related with the solar resource quantification and its long-term behaviour. These uncertainties affect directly the business plan and the investment decision can be compromised. Therefore, reducing these uncertainties can help to make the investment of the PV system more attractive.
Reducing uncertainty (temperature)	Use temperature coefficients or Ross coefficients from laboratory measurements or extrapolated from existing plants in similar conditions. When applying models to translate the available series of ambient temperature, use models that take also the influence of wind on module performance into consideration.
Reducing uncertainty (degradation)	Consider available research results on typical values of degradation rates according to technology and climate. Include spectral effects in modelling if possible to further reduce uncertainty (Belluardo et al., 2015).
Component testing	High-quality photovoltaic modules are subject to a number of requirements. First, they the manufacturer have to deliver the guaranteed rated power reliably. At the same time, the modules must be able to withstand, while withstanding an extremely wide range of environmental conditions. They The modules must also be safe and durable, ensuring the system's high yield over the long- term period. But, withWith testing actions, the quality of the modules can be fully certified.
Design review + construction monitoring	The total number of detected failures due to wrong design or installation in our database highlights the importance of this measure. In order for the PV project to meet the expectations of the investors regarding the profitability and life expectancy a number of actions have to be taken. Risks such as underperformance, warranty coverage, delay, cost overrun etc. are minimised

	after the application of this measure.
Qualification of EPC	The qualification of EPC is a preventive mitigation measure that will reduce the risk at an early stage of the PV project phase. EPC personell shall have a high educational level as well as appropriate technical knowledge. Regular training schemes should be designed and available to EPC personell for maintaining the high quality of staff and service provision.
Advanced monitoring system	An advanced monitoring system allows the early detection and diagnosis of faults. Early detection and diagnosis of faults during PV plant operation are essential in order to obtain and maintain the energy yield high. Early remediation of faults not only restores generation promptly but also avoids the occurrence of additional component failures and leads to reduction of O&M costs. The benefit of advanced monitoring is built up through reduced operational costs on one hand and additional revenues resulting from a higher performance ratio and higher availability on the other hand.
Basic monitoring system	A basic monitoring system typically allows the monitoring on plant level including device alarm collection and notifications. Furthermore, aggregation functionality on plant level for energy, irradiation and performance ratio are typically provided.
Advanced inspection	Advanced inspection relies on the use of techniques which go beyond visual inspection such as infrared imaging (IR) and electroluminescence imaging (EL), IV string analyser, etc.
Visual inspection	Visual inspection can establish whether any visual changes are occurring that may affect the performance of the principal components or reduce the effective life of the system or components providing data needed for planning maintenance and operation requirements. Through visual inspection technical risks with high occurrence can be typically detected (inverter polluted air filter, PV module glass breakage, broken connectors, etc).
Spare parts management	Spare parts management is a mitigation measure which has an impact in the initial investment and can be applied to several components of a PV plant. An effective spare parts management ensures the availability of the right amount and type of components, equipment, parts, etc. either on site or in warehouses or in manufacturers' consignment stocks, for prompt replacement in case of failure and/or to meet guarantees under O&M contracts.

Annex 2: List of Impact of Applied Mitigation Measures on Risks

Component	Risk	Component Testing	Design Review + constructio	Qualification of EPC	Advanced Monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare Part Management
Modules	Snail track	High	No	No	No	No	Medium	Medium	High
Modules	Improperly installed	No	High	Medium	Low	No	Medium	Medium	High
Modules	Glass breakage	Medium	Medium	Low	No	No	Medium	Medium	High
Modules	Broken module	No	High	Medium	Medium	No	Medium	Medium	High
Modules	Theft of modules	No	No	No	High	High	Medium	Medium	High
Modules	Module damaged due to fire	No	No	No	High	High	Medium	Medium	High
Modules	Failure bypass diode and junction box	High	No	No	High	Medium	Medium	Medium	High
Modules	Shading	No	Low	No	High	Medium	Medium	Medium	No
Modules	Soiling	No	No	No	High	Medium	Medium	Medium	No
Modules	Cell cracks	High	Low	No	No	No	Medium	No	High
Modules	Delamination	Low	No	No	No	No	Medium	No	High
Modules	Defective backsheet	High	No	No	No	No	Medium	Medium	High
Modules	Hotspot	High	No	No	No	No	Medium	No	High
Modules	Missing modules	No	High	Medium	High	No	Medium	Medium	High
Modules	EVA discoloration	High	No	No	No	No	Medium	Medium	High
Modules	Corrosion in the junction box	High	No	No	No	No	Medium	Medium	High
Modules	Corrosion of cell connectors	High	No	No	No	No	Medium	Medium	High
Modules	Overheating junction box	High	No	No	No	No	Medium	No	High
Modules	PID = Potential Induced degradation	High	No	No	No	No	Medium	No	High
Inverter	Wrong installation	No	High	Medium	Medium	No	Medium	Medium	High
Inverter	Inverter not operating (inverter failure or don't worki	No	No	No	High	Medium	Medium	Medium	High
Inverter	Wrong connection (positioning and numbering)	No	High	Medium	No	No	Medium	Medium	High
Inverter	Inverter theft or vandalism	No	No	No	High	Medium	Medium	Medium	High
Inverter	Inverter pollution	No	No	No	No	No	Medium	Medium	High
Inverter	Burned supply cable and/or socket	No	No	No	High	Medium	Medium	Medium	High
Inverter	Display off (broken or moisture inside of it)	No	No	No	No	No	Medium	Medium	High
Inverter	Fault due to grounding issues, e.g. high humidity insid	No	High	Medium	High	Medium	Medium	Medium	High
Inverter	Inverter firmware issue	No	No	No	No	No	Medium	Medium	High
Inverter	Data entry broken	No	No	No	No	No	Medium	Medium	High
Inverter	Slow reaction time for warranty claims, Vague or inap	No	No	No	No	No	Medium	No	High
Inverter	Fan failure and overheating	No	Medium	Medium	High	Medium	Medium	Medium	High
Inverter	Switch failure/damage	No	High	Medium	High	Medium	Medium	Medium	High
Inverter	DC entry fuse failure causing or caused by array disco	No	No	No	High	Medium	Medium	Medium	High
Inverter	Inverter damage due to lightning strike	No	High	Medium	High	Medium	Medium	Medium	High
Inverter	Inverter wrongly sized	No	High	Medium	Medium	No	Medium	Medium	High
Inverter	Error message	No	No	No	High	Medium	Medium	Medium	High
Inverter	Polluted air filter - derating	No	No	No	High	Medium	Medium	Medium	High
Mounting structure	Not proper installation	No	High	Medium	Medium	No	Medium	Medium	High
Mounting structure	Wind damage	No	No	No	No	No	Medium	Medium	High
Mounting structure	Tracker failure	No	Low	No	High	Medium	Medium	Medium	High
Mounting structure	Corrosion	No	Low	No	No	No	Medium	Medium	High
Mounting structure	Disallignment caused by ground instability	No	Medium	Low	No	No	Medium	Medium	High
Mounting structure	Tracker maintenance	No	No	No	No	No	Medium	Medium	High
Mounting structure	Oil leakage	No	Low	No	No	No	Medium	Medium	High
Mounting structure	Corrosion of module clamps	No	Medium	Low	No	No	Medium	Medium	High
Connection & Distribution boxes	Incorrect installation	No	High	Medium	No	No	Medium	Medium	High
Connection & Distribution boxes	Main switch open and does not reclose again automa	No	No	No	High	Medium	Medium	Medium	High
Connection & Distribution boxes	IP failure	No	High	Medium	No	No	Medium	Medium	High
Connection & Distribution boxes	Broken/Wrong general switch	No	High	Medium	High	Medium	Medium	Medium	High
Connection & Distribution boxes	General switch off	No	No	No	High	Medium	Medium	Medium	High
Connection & Distribution boxes	Wrong wiring	No	High	Medium	No	No	Medium	Medium	High
Connection & Distribution boxes	Cable gland missing or not installed correctly	No	High	Medium	No	No	Medium	Medium	High
Connection & Distribution boxes	Missing protection	No	High	Medium	No	No	Medium	Medium	High
Connection & Distribution boxes	Broken, missing or corroded cover	No	High	Medium	No	No	Medium	Medium	High
Connection & Distribution boxes	Overcurrent protection not correctly sized	No	High	Medium	No	No	Medium	Medium	High
Connection & Distribution boxes	UPS off/broken	No	No	No	No	No	Medium	Medium	High
Connection & Distribution boxes	Wrong/Missing labeling	No	High	Medium	No	No	Medium	Medium	High
Cabling	improper installation	No	High	Medium	No	No	Medium	Medium	High
Cabling	Wrong/Absent cables connection	No	High	Medium	High	Medium	Medium	Medium	High
Cabling	Broken/Burned connectors	No	Low	No	High	Medium	Medium	Medium	High
Cabling	Wrong/absent cables	No	High	Medium	High	Medium	Medium	Medium	High
Cabling	Damaged cable	No	No	No	High	Medium	Medium	Medium	High
Cabling	Broken cable ties	No	High	Medium	No	No	Medium	Medium	High
Cabling	Conduit failure	No	Medium	Low	No	No	Medium	Medium	High
Cabling	Wrong connection, isolation and/or setting of strings	No	High	Medium	High	Medium	Medium	Medium	High
Cabling	UV Aging	No	High	Medium	No	No	Medium	Medium	High
Cabling	Cables undersized	No	High	Medium	No	No	Medium	Medium	No
Cabling	Wrong wiring	No	High	Medium	No	No	Medium	Medium	High
Cabling	Theft cables	No	No	Low	High	Medium	Medium	Medium	High
Transformer station & MV/HV	Improper / Inadequate installation	No	High	Medium	No	No	Medium	Medium	High
Transformer station & MV/HV	Broken transformer	No	No	Low	High	High	Medium	Medium	No
Transformer station & MV/HV	Wrong transformer configuration	No	No	Low	High	Medium	Medium	Medium	No

Annex 3: Index of All Combinations

Combination Index	Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	1
2	0	0	0	0	0	0	1	0
3	0	0	0	0	0	0	1	1
4	0	0	0	0	0	1	0	0
5	0	0	0	0	0	1	0	1
6	0	0	0	0	0	1	1	0
7	0	0	0	0	0	1	1	1
8	0	0	0	0	1	0	0	0
9	0	0	0	0	1	0	0	1
10	0	0	0	0	1	0	1	0
11	0	0	0	0	1	0	1	1
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14	0	0	0	0	1	1	1	0
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27	0	0	0	1	1	0	1	1
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38	0	0	1	0	0	1	1	0
39	0	0	1	0	0	1	1	1
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64	0	1	0	0	0	0	0	0
65	0	1	0	0	0	0	0	1

Combination Index	Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management
66	0	1	0	0	0	0	1	0
67	0	1	0	0	0	0	1	1
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73	0	1	0	0	1	0	0	1
74	0	1	0	0	1	0	1	0
75	0	1	0	0	1	0	1	1
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128	1	0	0	0	0	0	0	0
129	1	0	0	0	0	0	0	1
130	1	0	0	0	0	0	1	0

Combination Index	Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management
131	1	0	0	0	0	0	1	1
132	1	0	0	0	0	1	0	0
133	1	0	0	0	0	1	0	1
134	1	0	0	0	0	1	1	0
135	1	0	0	0	0	1	1	1
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185	1	0	1	1	1	0	0	1
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188	1	0	1	1	1	1	0	0
189	1	0	1	1	1	1	0	1
190	1	0	1	1	1	1	1	0
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192	1	1	0	0	0	0	0	0
193	1	1	0	0	0	0	0	1
194	1	1	0	0	0	0	1	0
195	1	1	0	0	0	0	1	1

Combination Index	Component testing	Design review + construction monitoring	Qualification of EPC	Advanced monitoring system	Basic Monitoring system	Advanced Inspection	Visual Inspection	Spare part management
196	1	1	0	0	0	1	0	0
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255	1	1	1	1	1	1	1	1

Annex 4: Uncertainty Values of Input and Output Parameters in the Different Uncertainty Scenarios

			INPUTS												OUTPUTS					
rel.unc(k=1)	note	parameter affected	GHI var.	DiffHI var.	Solar resource	Tamb var.	Soiling	Nominal power	Thermal fact.	Degradation	Transp. model	Shading	Spectral mism.	Inverter effic.	GHI	GTI	Ya	Yf	Yr	PR
case 1	22 years satellite GHI and DiffHI in BZ	BASE CASE	3.31%	2.24%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	5.99%	8.36%	8.70%	8.70%	8.36%	12.07%
case 2	5 years measured GHI and DiffHI in BZ	insolation variability	9.00%	9.00%	2.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	9.22%	13.19%	13.40%	13.41%	13.19%	18.81%
case 3	22 years of measured GHI and DiffHi in BZ	solar resource quantification	3.31%	2.24%	2.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	3.86%	5.29%	5.80%	5.80%	5.29%	7.85%
case 4	long-term satellite + short-term measured GHI and DiffHI	solar resource quantification	3.31%	2.24%	3.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	4.46%	6.16%	6.61%	6.61%	6.16%	9.04%
case 5	5 years satellite GHI and DiffHI in BZ	insolation variability	9.00%	9.00%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	10.30%	14.70%	14.89%	14.89%	14.70%	20.92%
case 6	22 years of measured GHI and DiffHi, location with high variability (e.g. London)	insolation variability	7.10%	7.10%	2.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	7.38%	10.62%	10.89%	10.89%	10.62%	15.21%
case 7	22 years satellite GTI in BZ	transposition model	0.00%	0.00%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	0.00%	5.99%	6.45%	6.45%	5.99%	8.81%
case 8	5 years measured GTI in BZ	insolation variability, solar resource quantification, transposition model	0.00%	0.00%	2.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	0.00%	9.22%	9.52%	9.53%	9.22%	13.26%
case 9	22 years of measured GTI in BZ	solar resource quantification, transposition model	0.00%	0.00%	2.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	0.00%	3.86%	4.54%	4.55%	3.86%	5.97%
case 10	long-term satellite + short-term measured GTI	solar resource quantification, transposition model	0.00%	0.00%	3.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	0.00%	4.46%	5.06%	5.07%	4.46%	6.75%
case 11	5 years satellite GTI in BZ	insolation variability, transposition model	0.00%	0.00%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	0.00%	10.30%	10.57%	10.57%	10.30%	14.76%
case 12	22 years of measured GTI, location with high variability (e.g. London)	insolation variability, transposition model	0.00%	0.00%	2.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	0.00%	7.38%	7.75%	7.76%	7.38%	10.70%
case 13	worst transposition model for Bolzano	transposition model	3.31%	2.24%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	5.40%	2.00%	0.20%	0.20%	5.99%	9.75%	10.04%	10.04%	9.75%	14.00%
case 14	high uncertainty of temperature effects (e.g. choice of temperature model not accounting for wind effect)	temperature effect	3.31%	2.24%	5.00%	0.43%	0.49%	0.98%	1.15%	0.50%	2.00%	2.00%	0.20%	0.20%	5.99%	8.36%	8.77%	8.77%	8.36%	12.12%
case 15	high variability of ambient temperature	ambient temperature variability	3.31%	2.24%	5.00%	2.00%	0.49%	0.98%	0.00%	0.50%	2.00%	2.00%	0.20%	0.20%	5.99%	8.36%	8.91%	8.92%	8.36%	12.22%
case 16	high uncertainty of performance loss rate	performance loss rate	3.31%	2.24%	5.00%	0.43%	0.49%	0.98%	0.14%	2.00%	2.00%	2.00%	0.20%	0.20%	5.99%	8.36%	8.91%	8.91%	8.36%	12.22%
case 17	high uncertainty of shading effect (e.g. mountainous region, no measurement of the horizon)	shading effect	3.31%	2.24%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	5.00%	0.20%	0.20%	5.99%	8.36%	9.83%	9.83%	8.36%	12.91%
case 18	high uncertainty of soiling effect (e.g. desert area, no estimation of soiling in the region)	soiling effect	3.31%	2.24%	5.00%	0.43%	4.00%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	5.99%	8.36%	9.56%	9.56%	8.36%	12.70%
case 19	high uncertainty of spectral mismatch effect (e.g. use of technology with narrow spectral responsivity such as	spectral mismatch effect	3.31%	2.24%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	2.00%	0.20%	5.99%	8.36%	8.92%	8.92%	8.36%	12.23%
case 20	high uncertainty of nominal power	nominal power	3.31%	2.24%	5.00%	0.43%	0.49%	2.00%	0.14%	0.50%	2.00%	2.00%	0.20%	0.20%	5.99%	8.36%	8.87%	8.87%	8.36%	12.19%
case 21	high uncertainty of inverter efficiency	inverter efficiency	3.31%	2.24%	5.00%	0.43%	0.49%	0.98%	0.14%	0.50%	2.00%	2.00%	0.20%	0.50%	5.99%	8.36%	8.70%	8.71%	8.36%	12.08%
case 22	simultaneous combination of highest uncertainty used for each input parameter	WORST CASE	9.00%	9.00%	5.00%	2.00%	4.00%	2.00%	1.15%	2.00%	5.40%	5.00%	2.00%	0.50%	9.00%	14.70%	16.57%	16.58%	14.70%	22.16%

Annex 5: Examples of uncertainty reduction in the yield assessment

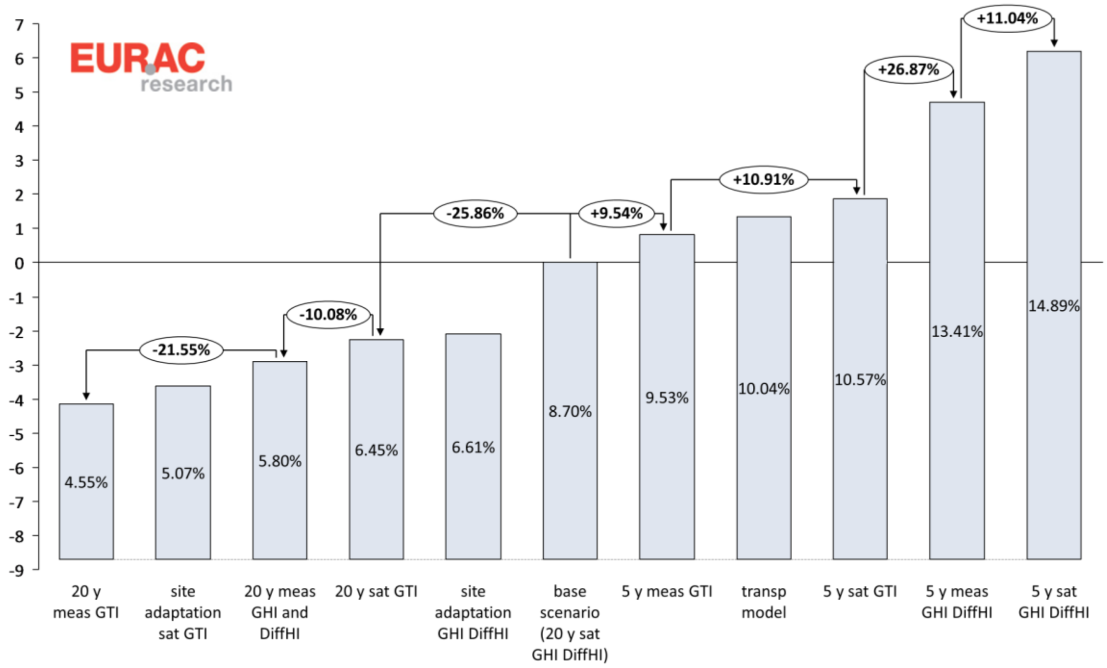

Figure A5.1: Impact of mitigation measures compared to the base scenario (fixed at 0)

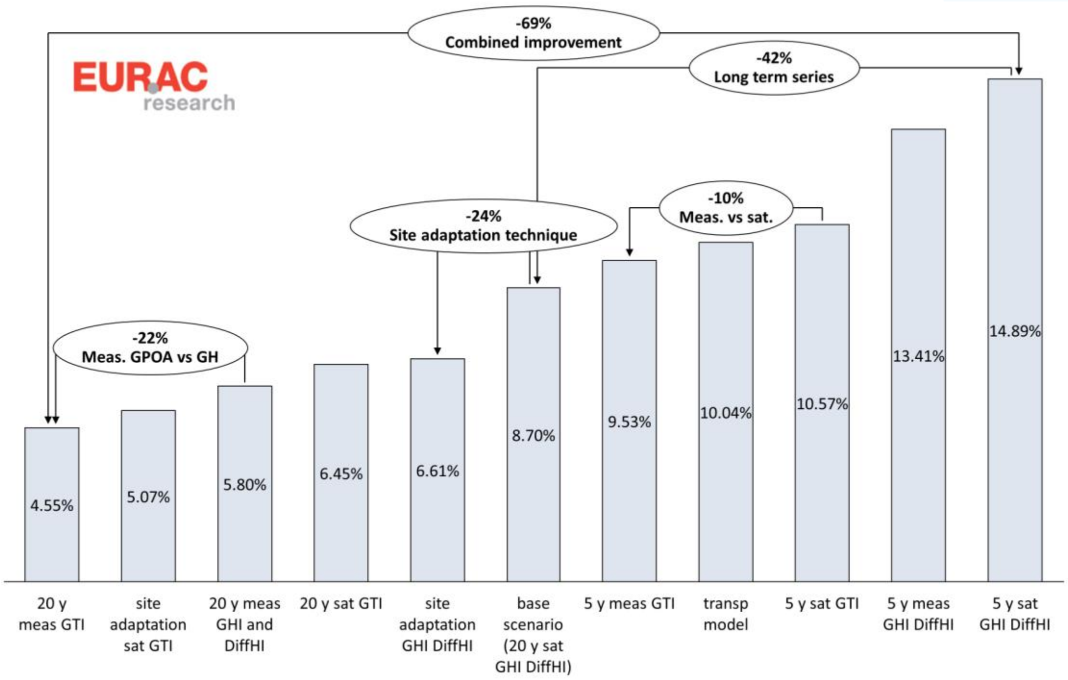

Figure A5.2: Typical values of uncertainty reduction in relative terms for a few selected mitigation measures

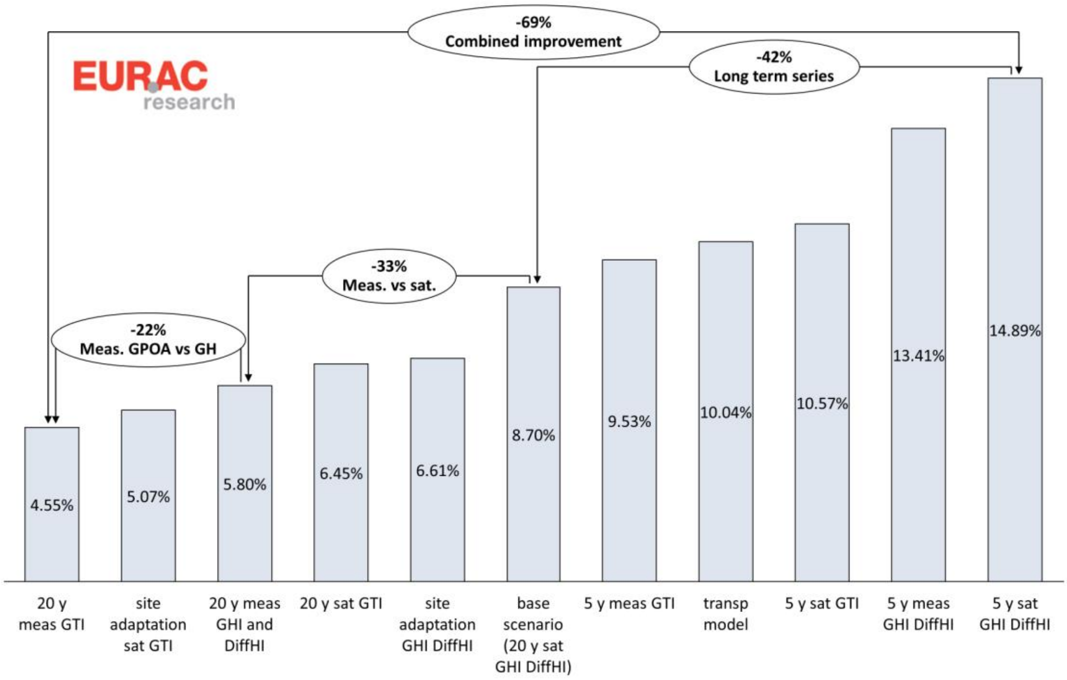

Figure A5.3: Example of uncertainty reduction (in relative terms) for a scenario where long term series of measured data on the plane of array are available (low-end scenario)

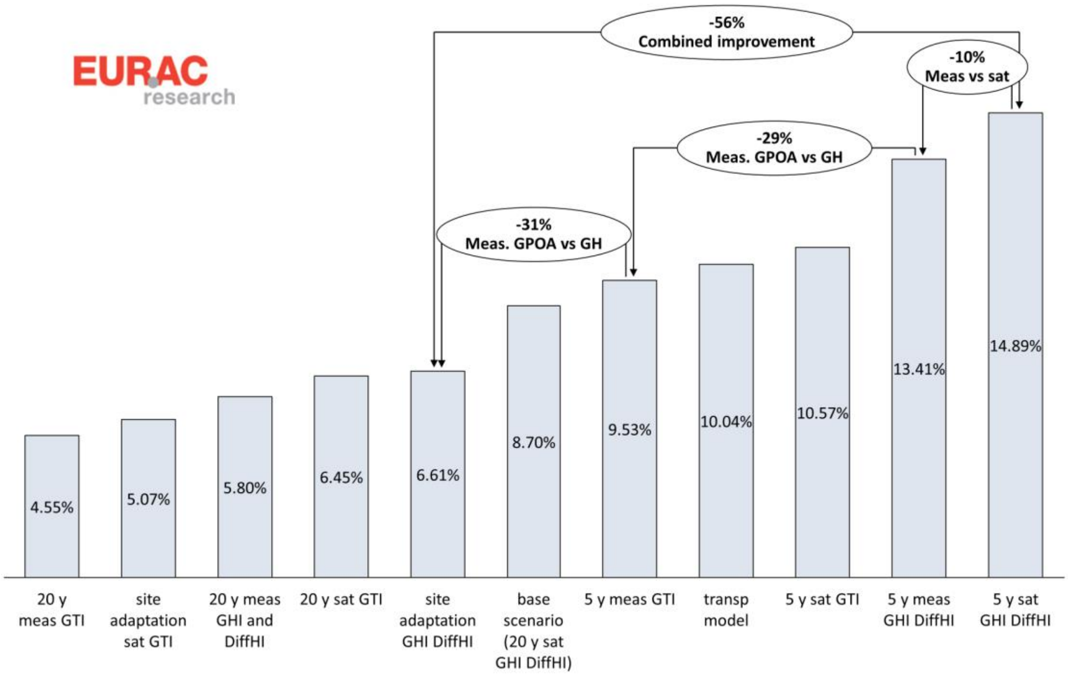

Figure A5.4: Example of uncertainty reduction (in relative terms) where long term series of satellite data are combined with short term series of measured data

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