SOLAR BANKABILITY

Best Practice Guidelines for PV Cost Calculation

Accounting for Technical Risks and Assumptions in PV LCOE

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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 approach 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 is a project funded by the European Commission under the Horizon 2020 Programme and runs for two years from 2015 to 2017.

The Solar Bankability consortium is pleased to present this report which as 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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Glossary & Abbreviations

AC	alternating current
CAPEX	capital expenditures
CE (marking)	(or CE compliance) signifies that the product has met the safety, health, and environmental protection requirements of the European Economic Area (EEA)
CM	corrective maintenance
COD	commercial operation date
CPN	cost priority number
DC	direct current
DLP	defect liability period
DSL	digital subscriber line
DSM	document management system
EL	electroluminescence (imaging analysis)
EPC	engineering, procurement and constructions
EU	European Union
FiT	feed-in tariff
GPRS	general packet radio service
GPS	global positioning system
H&S	health and safety
HVAC	heating, ventilation and air conditioning
IEC	International Electrotechnical Commission
I/O	input/output
IP	internet protocol
IR	infrared (thermal imaging analysis)
ISO	International Organization for Standardization
KPI	key performance indicator
LAN	local area network
LCOE	levelized cost of electricity
LD	liquidated damages

LTYA	long term yield assessment
MPP(T)	maximum power point (tracking)
HV/MV/LV	high voltage / medium voltage / high voltage
O&M	operation and maintenance
OPEX	operating expenditures
PLC	programmable logic controller
PM	preventive maintenance
POA	plane of array (irradiation, irradiance)
PPA	power purchase agreement
PPE	personal protective equipment
PR	performance ratio (of a PV plant)
PV	photovoltaic
RMSE	root mean square error
RV	residual value (used in LCOE formula)
SCADA	supervisory control and data acquisition
STC	standard test conditions
UK	United Kingdom
UPS	uninterruptable power supplies

Executive Summary

Establishing Best Practice Guidelines for Professional PV Risk Assessment

The Solar Bankability is a project funded by the European Commission under the Horizon 2020 Programme and runs from 2015 to 2017. The main goal of the Solar Bankability project is to establish a common practice for professional risk assessment which will serve to reduce the risks associated with investments in PV projects. To achieve this objective, best practice guidelines on how to manage technical risks in PV cost modeling and financial model have been developed in the works presented in this report.

The technical risks identified from previous works [1] were first categorized and ranked based on the impacts on the CAPEX, OPEX and yield element in the PV LCOE. A sets of LCOE technical risk flashcards (Annex A) have been created to serve as quick references for the 20 most common identified gaps in the technical assumptions used in PV financial models. A sensitivity analysis was then conducted to assess the relative impact of the technical risks on PV LCOE for different market segments under different scenarios. The impacts of implementing different combinations of risk mitigation measures on the LCOE were also evaluated. Using the outcomes of these works, best practice guidelines (Annex C) in the form of checklists are developed.

Conclusions and Takeaways

LCOE sensitivity analysis

A sensitivity analysis was performed by varying six input parameters to the PV LCOE (CAPEX, OPEX, yield, discount rate, yearly degradation and system lifetime) by ±20%. Each input was treated as if one is independent from the others. The analysis includes three different market segments: residential systems <5 kWp, commercial rooftop systems <1 MWp, and utility scale ground-mounted systems ≥1 MWp. Three scenarios have been selected for this analysis – one representing PV systems in mature markets such as Germany where high competition has driven the CAPEX and OPEX prices down and the market is less risky; the second representing systems in market such as Italy with a relatively high discount rate and where the irradiation level is high and the CAPEX and OPEX are in the mid-range among the values in EU region; and the last scenario representing PV systems in countries such as UK or Netherlands with high CAPEX and OPEX but with irradiation level rather low and a relatively moderate discount rate. The LCOE sensitivity analysis results rank the followings from having the most to least impact on LCOE.

Sensitivity of LCOE in 2015-2016 on CAPEX, OPEX, yield, discount rate, yearly degradation and system lifetime (ranking from most to least impact)				
1 *Yield*	*2* *CAPEX*	*3* *Lifetime or discount rate*	*4* *OPEX*	*5* *Degradation*

Technical risk mitigation measures and LCOE reduction

Eight mitigation measures have been proposed to address the LCOE technical risks identified in our previous works [2]. Three of these are component testing, design review and construction monitoring, and EPC qualification which can be implemented during the early phases of PV project lifecycle. The other five – basic monitoring, advanced monitoring, visual inspection, advanced inspection, and spare part management, are mitigation measures during the operational phase of the PV system.

A total of 255 different combinations of these eight mitigation measures were evaluated. The LCOE values resulted from the implementation of each mitigation measure combination were analyzed for the three market segments and three scenarios. Finally, case studies consisting of three PV systems with specific issues are considered: one case where poor yield estimation method has been used in the design phase; the second case involves low module power output in the procurement phase; and the last case where module cleaning is not included in the operational phase. The LCOE's before and after the application of mitigation measures for these three cases were calculated. The following conclusions could be drawn.

PV LCOE reduction up to 4 to 5% is observed in all cases.

The different combinations of mitigation measures have a larger impact in lowering the LCOE for scenarios where the higher CAPEX, OPEX, and/or discount rate results in a higher LCOE.

Mitigation measures which are most effective in lowering PV LCOE are similar across all three market segments and for all scenarios.

The most effective mitigation measures are those implemented at the *early stage of project lifecycle*. Those implemented in the operation phase still show some positive impact on LCOE but less gain is found.

Although the implementation of mitigation measures increase either CAPEX or OPEX or both, the overall LCOE decreases as the gain in yield surpasses the extra cost incurred.

Mitigation measures most effective in lowering PV LCOE are:

1. **Qualification of EPC;**
2. **Component testing prior to installation; and**
3. **Advanced monitoring system for early fault detection.**

Best practice guidelines

Our works have highlighted that technical risks exist across all PV project phases, from as early as the project is conceived to when the system is in its operational year. If not managed properly, these could affect the CAPEX, OPEX or yield of the PV system and thus impact the PV levelized cost of electricity. From our previous review and gap analysis exercise, it was highlighted that EPC, O&M and yield calculation/estimation methodology are important aspects affecting the CAPEX, OPEX or yield. It is therefore important to ensure that the system yield calculation/estimation and all technical aspects of EPC and O&M are based on best-practice quality. To this end, a set of six checklists have been established to serve as guidelines for best practices in EPC and O&M technical aspects and for yield estimation exercise. These checklists are presented in Annex C of this report. These checklists serve to guide different actors along the PV project value chain in the process of realizing and operating utility-scale (ground-mounted) and commercial rooftop PV installations. Since residential systems have very different business models, the best practice guidelines are treated separately due to the different nature of business models involved and presented in another report of this project ([3]).

1 Introduction

1.1 Background and Objectives

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 photovoltaic (PV) projects.

One of the principal objectives the Solar Bankability project is to develop guidelines on how the technical risks over the PV project life cycle should be taken into account in the different cost elements and when evaluating the PV investment cost. In this project we have reviewed the current industry practices to obtain a view on how technical risk assumptions in PV investment cost calculation are commonly accounted. With this information in hands, the consortium then performed gap analyses between the present practice and the state-of-the-art methodology. The results of the review of current practice and gap analyses in PV cost technical assumptions were presented in the report *Review and Gap Analyses of Technical Assumptions in PV Electricity Cost* [1].

The results highlight that technical gaps generally exist across all PV project phases. They occur in all elements of the PV levelized cost of electricity (LCOE), namely in the capital expenditures (CAPEX), operating expenditures (OPEX), and energy yield estimation. There are two types of technical risks: those which influence the PV system performance and energy yield but not necessarily create a partial or overall outage of the plant, and those which cause failures which affect both the plant availability and also the performance. The root causes of both types of risk could be introduced either during project development (procurement, planning and construction) or during PV operation (O&M).

In this report we establish a best practice guideline on how to address the technical assumptions in PV cost modeling and financial model evaluation based on the knowledge from the review and gap analysis work.

1.2 Guide to Readers

This report presents the best practice guidelines on how to account for the technical risks in the CAPEX, OPEX and energy yield estimation used for the PV cost modeling and financial models.

In Chapter 2, the technical risks are categorized and ranked. We describe here briefly the risk, where they can occur (i.e. project phase) and what LCOE variable are impacted (i.e. CAPEX, OPEX and Yield). In addition, we perform a sensitivity analysis to assess the relative impact on LCOE for different scenarios.

In Chapter 3, we present the best practice guidelines for different market segments i.e. the commercial rooftop and ground-mounted utility PV systems. The guidelines are presented in a form of various checklists which could be used in developing, operating and maintaining PV systems.

Finally, Chapter 4 presents the conclusions of the works described in this report with result highlights and recommendations for potential future works.

2 Categorization and Ranking of Technical Risks

Technical risks exist across all PV project phases, from as early as the project is conceived to when the system is in its operational years. The technical risks need to be timely and effectively managed or they will affect the PV plant performance, either by causing gradual degradation which leads to performance losses over time, or creating partial or overall system outage leading to abruption of the PV plant production. When considering risk mitigation measures, it is worth keeping in mind that PV technical risk management could be addressed not only from the technical but also from the financial, legal or insurance perspective. Moreover, the risks could be spread over the different stakeholders in the PV project development and investment value chain. This means the ownership of the measures does not have to lie in the hands of a single party (e.g. the project owner or investor) but spread over different stakeholders to optimize the mitigation costs and investment returns.

In this chapter, we categorize the important technical risks from the PV LCOE perspective, i.e. how each risk is associated to the different cost elements in the LCOE. The criticality of these risks and how strongly they influence the CAPEX, OPEX and yield are then analyzed by performing sensitivity analyses for different cases. In these case studies, we look at multiple scenarios of technical risk mitigation measures in different market segments. The results from these analyses are PV electricity costs for the different scenarios and the possible reductions in the LCOE from the implementation of the combinations of technical risk mitigations.

The outcomes of the risk categorization and sensitivity analyses are further used to recommend best practices on how technical risks should be accounted for in the PV investment cost in the next Chapter 3. These guidelines will serve to assist in the decision on where in the PV project lifecycle mitigation measures for PV technical risks need to be placed and who the owners are of the mitigation measures.

2.1 Risk Categorization in the Context of PV LCOE

In our previous work (*Review and Gap Analyses of Technical Assumptions in PV Electricity Cost* [1]), we have identified the 20 most common gaps in the technical assumptions used in PV financial models. Associated with these gaps are technical risks which could impact the PV LCOE; in this report these risks are referred to as the *LCOE technical risks.* Many of these LCOE technical risks have been identified in our earlier works presented in the report *Minimizing Technical Risks in Photovoltaic Project* [2]. In this section, the LCOE technical risks are categorized based on how they influence PV LCOE. The categorization is based on two aspects:

1. How the LCOE technical risk, if it occurs, impacts the CAPEX, OPEX or yield, and
2. How the LCOE technical risk mitigation, when implemented, impacts or influences the CAPEX, OPEX or yield.

The categorization results are presented in a form of LCOE technical risk “flashcard”. Each risk flashcard contains the following information:

- The description of the risk;
- The phase at which the risk occurs;
- The key takeaway of the risk;
- The impact of the risk on LCOE;
- The category and description of the mitigations;
- The impact of the risk mitigation on LCOE.

Figure 1 and Figure 2 below show examples of the flashcards for two LCOE technical risks in the PV project component procurement phase and in the plant operation and maintenance (O&M) phase. The complete set of these LCOE technical risk flashcards is give in Annex A of this report. In these flashcards, the procurement phase includes production and testing phases, and the construction phase includes the transportation and installation phases as described in [1] and [2]. The decommissioning phase has been excluded from the flashcards.

Figure 1: LCOE technical risk categorization flashcard – example of a risk from the procurement phase

<table>
<tr><td rowspan="3"><u>LCOE Technical Risk</u></td><td rowspan="3" colspan="2">1. Insufficient EPC technical specifications to ensure that selected components are suitable for use in the specific PV plant environment of application</td><td colspan="2">Phase of risk occurrence</td></tr>
<tr><td>Procurement ✓</td><td>Planning</td></tr>
<tr><td>O&M</td><td>Construction</td></tr>
<tr><td><u>Key takeaway</u></td><td colspan="4">PV plant component specification and requirement in the EPC contract should be as detailed as possible to ensure that the components procured are suited for the intended PV installation, specific application, site and environment</td></tr>
<tr><td><u>Impact of risk</u></td><td>LCOE variables impacted by this risk:</td><td>CAPEX</td><td>OPEX</td><td>Yield
↓</td></tr>
<tr><td><u>Mitigations</u></td><td>☐ Component testing
■ Design review + construction monitoring
☐ EPC qualification
☐ Advanced monitoring
☐ Basic monitoring
☐ Advanced inspection
☐ Visual inspection
☐ Spare part management
■ Others</td><td colspan="3">When specifying the technical requirements for PV plant components in the EPC contract, in addition to the component type and quantity, the specifications should also include:
• All applicable certifications and conformances (e.g. IEC61215, IEC61730, IEC61701, IEC62804, IEC61716 for modules; IEC62109, IEC61000 for inverters; CE mark of compliance for all electrical components)
• The environmental condition the components will be installed in (temperature, humidity, wind and snow load, any special chemical exposure, corrosion risk etc.)
• For PV modules, module component bill of materials and the proof of IEC certification documents for these materials</td></tr>
<tr><td><u>Impact of mitigation</u></td><td>LCOE variables impacted by the risk mitigations:</td><td>CAPEX</td><td>OPEX</td><td>Yield
↑</td></tr>
</table>

Figure 2: LCOE technical risk categorization flashcard – example of a risk from the O&M phase

LCOE Technical Risk	***17. Missing guaranteed key performance indicators (PR, availability or energy yield) in O&M***		***Phase of risk occurrence***	
			Procurement	*Planning*
			O&M ✓	*Construction*
Key takeaway	*Guaranteed performance indicator is important to ensure that the plant operation and maintenance is carried out properly*			
Impact of risk	**LCOE variables impacted by this risk:**	**CAPEX**	**OPEX** ↓	**Yield** ↓
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ■ Others	• Require the operator to guarantee plant performance or availability which will be assessed on a yearly basis • Include all details of the performance indicator, test procedure, calculation (incl. exclusions) and criteria in the O&M contract		
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	**CAPEX**	**OPEX** ↑	**Yield** ↑

As reflected in the LCOE technical risk flashcards, the mitigation measures could be grouped into nine types. The first eight were defined in [2]. The last type ("**Others**") has been added here to define the mitigation measures not associated to any of the other categories, e.g. those which are related to the guarantees in the engineering, procurement and constructions (EPC) or O&M contracting or O&M service scope.

1. **Component testing** of important plant components such as PV modules or inverters. The testing could be that which is done by the manufacturer in the factory, or independent testing at certified laboratory, or on-site at the PV plant;
2. **Design review and construction monitoring** serves to catch issues caused by bad PV plant conception and poor PV construction workmanship;
3. **EPC qualification** focuses on ensuring the competencies of the field workers, e.g., by requiring certain technical qualification prerequisites or regular training of the field workers;
4. Implementing **advanced monitoring** system for early detection and diagnosis of faults;
5. Use of **basic monitoring** system to monitor plant level alarms and notifications[1];

[1] Although basic monitoring is pretty standard in commercial and large PV installations, it is not widely included in residential systems and thus included here as a solution since our analysis will consider scenarios of basic monitoring for residential home PV installations.

6. **Advanced inspection** (e.g. using infrared or electroluminescence camera) to detect defects not usually visible by naked eyes;
7. **Visual inspection** to establish any visible changes in PV plant components;
8. **Spare part management** to minimize the downtime and repair/substitutions;
9. **Others** which are mitigation measures associated with EPC or O&M contracting, or O&M service scope.

These mitigation measures could have either positive or negative impact on the CAPEX, OPEX and yield. For example, implementing component testing before construction would increase the PV plant CAPEX (due to additional cost of testing) but decrease the OPEX (decreasing maintenance or repair of defects already pre-screened), resulting in an increase in the overall plant yield.

For mitigation measures which will impact the PV plant yield, it is worth keeping in mind that the impact may not be seen directly on the nominal value of the yield itself but on the uncertainties surrounding the yield variation (this is denoted by ↓↑ or ↑↓ in the table below). The economic impact in terms of uncertainty is discussed more in detail in [2].

The following table summarizes the impacts on LCOE of the mitigation measures for the 20 most common gaps in the technical assumptions used in PV financial models identified in [1]. This information is used for the sensitivity analysis in the next section of this chapter.

Table 1: LCOE technical risk categorization based on impact on CAPEX, OPEX and yield in PV financial models

Phase	LCOE technical risk	*Risk impact on LCOE*			*Mitigation impact on LCOE*		
		CAPEX	*OPEX*	*Yield*	*CAPEX*	*OPEX*	*Yield*
Procurement	1. Insufficient EPC technical specifications to ensure that selected components are suitable for use in the specific PV plant environment of application			↓			↑
Procurement	2. Inadequate component testing to check for product manufacturing deviations		↑	↓	↑		↑
Procurement	3. Absence of adequate third party product delivery acceptance test and criteria		↑	↓	↑		↑
Planning	4. Effect of long-term trends in the solar resource is not fully accounted for			↑↓	↑		↓↑
Planning /O&M	5. Exceedance probabilities (e.g. P90) are often calculated for risk assessment assuming a normal distribution for all elements contributing to the overall uncertainty			↑↓	↑		↓↑
Planning	6. Incorrect degradation rate and behavior over time assumed in the yield estimation			↓↑	↑		↑↓
Planning	7. Using plant (instead of overall) availability to calculate the initial yield for project investment financial model			↑	↑		↓

Phase	LCOE technical risk	Risk impact on LCOE			Mitigation impact on LCOE		
		CAPEX	OPEX	Yield	CAPEX	OPEX	Yield
Construction	8. Absence of standardized transportation and handling protocol		↑	↓	↑		↑
Construction	9. Inadequate quality procedures in component un-packaging and handling during construction by workers		↑	↓	↑		↑
Construction	10. Missing construction monitoring during construction		↑	↓	↑		↑
Construction	11. Inadequate protocol or equipment for plant acceptance visual inspection		↑	↓	↑		↑
Construction	12. Missing short-term performance (e.g. PR) check at provisional acceptance test, including proper correction for temperature and other losses		↑	↓	↑		↑
Construction	13. Missing final performance check and guaranteed performance		↑	↓	↑		↑
Construction	14. At provisional commissioning, incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, incorrect irradiance threshold to define time window of PV operation for PR/availability calculation			↓↑			↑↓
O&M	15. Standard monitoring system not capable of advanced fault detection and identification		↑	↓	↑	↑	↑
O&M	16. Visual inspection during preventive maintenance not capable to catch defects or faults not visible by naked eyes		↑	↓		↑	↑
O&M	17. Missing guaranteed key performance indicators (PR, availability or energy yield) in O&M		↓	↓		↑	↑
O&M	18. In operational phase, incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, incorrect irradiance threshold to define time window of PV operation for PR/availability calculation			↓↑			↑↓
O&M	19. Missing or inadequate maintenance of the monitoring system		↓	↓↑		↑	↑↓
O&M	20. Module cleaning missing or frequency too low		↑	↓		↑	↑

2.2 Sensitivity Analysis – Different Scenarios

The dependence of the PV LCOE on CAPEX, OPEX and yield is analyzed in this section through a sensitivity analysis for different scenarios. Different case studies combining diverse mitigation measures are explored. The first eight types of mitigation measures defined in §2.1 are considered. In addition, three different market segments are analyzed: residential systems up to 5 kWp, commercial rooftop systems <1 MWp, and utility ground-mounted systems ≥1 MWp.

2.2.1 LCOE calculation and input data

As introduced in [1], for the purpose of the works in the Solar Bankability project, the consortium together with the project advisory board have agreed to exclude the inflation rate and tax in our analyses as these values are not only country but also investors' specific risk return preferences dependent. Therefore, the PV LCOE in our sensitivity analysis is calculated as follows:

$$LCOE = \frac{CAPEX + \sum_{n=1}^{N} \frac{OPEX - RV}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Y_o \cdot (1-D)^n}{(1+r)^n}} \qquad (1)$$

where

N = PV system life [years]

$CAPEX$ = total initial investment (CAPEX) [€/kWp]

$OPEX$ = annual operation and maintenance expenditures (OPEX) [€/kWp]

RV = residual value [€/kWp]

r = discount rate [%]

Y_0 = initial yield [kWh]

D = system degradation rate [%]

For all LCOE calculations in this report, a linear system degradation rate is assumed. Discount rate values for different scenarios (countries) are extracted from [4]. Moreover, no residual value is accounted for in the calculations.

2.2.2 Sensitivity of LCOE to input parameters

In the LCOE sensitivity analysis, we analyzed three scenarios of CAPEX and OPEX values in 2015-2016 timeframe. We have based the CAPEX and OPEX prices in our analysis on information from multiple sources, i.e. the project partners and project advisory board as well as recent publications on PV system pricings. Table 2 below summarizes the values used in our analysis of the three scenarios.

Table 2: Input parameters used in the LCOE sensitivity analysis for different scenarios

Input parameter	Low scenario	Medium scenario	High scenario
CAPEX [€/kWp]			
Ground-mounted utility (≥ 1 MWp)	€ 900	€ 1000	€ 1200
Commercial rooftop (< 1 MWp)	€ 1000	€ 1200	€ 1400
Residential (up to 5 kWp) **(VAT excluded)**	€ 1300	€ 1400	€ 1600
OPEX [€/kWp/year]			
Ground-mounted utility (≥ 1 MWp)	€ 13	€ 15	€ 20
Commercial rooftop (< 1 MWp)	€ 10	€ 10	€ 18
Residential (up to 5 kWp) **(VAT excluded)**	€ 5	€ 5	€ 9
Performance Ratio 'PR' [%]			
Ground-mounted utility (≥ 1 MWp)	86%	84%	86%
Commercial rooftop (< 1 MWp)	84%	82%	84%
Residential (up to 5 kWp)	82%	80%	82%
Plane-of-array (POA) irradiation [kWh/m²]	1331	1821	1168
Discount rate [%]	4%	8%	6.5%
Degradation rate [%]		0.5% linear	
Lifetime [years]		25 years	

The low, medium and high level designation is associated with CAPEX and OPEX values among the scenarios analyzed. For the *low* scenario, the CAPEX range is set between 0.9 and 1.3 €/Wp and the OPEX ranges between 5 and 13 €/MWp/year, depending on the market segment. For this scenario, we have simulated the LCOE for a PV system in a location with an optimal plane-of-array irradiation comparatively in the mid-range among countries in EU (e.g. 1331 kWh/m² for Munich, Germany). For discount rate, 4% is assumed. Additional information on the components behind the calculation of this discount rate can be found in [4]. This scenario could be considered representing PV systems in mature markets such as Germany where high competition has driven the CAPEX and OPEX prices down and the market is less risky.

For the *medium* scenario, the CAPEX is set between 1 and 1.4 €/W. The OPEX is similar to the *low* scenario. The irradiation level is set quite high, 1821 kWh/m², to simulate PV systems in locations with lots of sunlight. The discount rate is assumed to be quite high (8%) thus the PV system in this scenario could be considered similar to those in countries such as Italy (in fact, the irradiation value is for the city of Rome).

In the last scenario (*high*) we have selected a PV system with the highest CAPEX and OPEX among the three cases. This scenario is selected to represent PV systems in countries such as UK or the Netherlands where the irradiation level is low and the discount rate is in between the other two cases. The irradiation value for Bristol has been used here.

In the sensitivity analysis, we varied the six parameters which have influences on the LCOE reflected in Table 2 above, namely the CAPEX, OPEX, yield (using PR or irradiation), discount rate, yearly degradation and system lifetime. Each of these inputs is varied by ±20%. For simplicity, we have treated each input as if one is independent from the others. The full results of the LCOE sensitivity analysis for the three different reference scenarios in three market segments are shown in Figure 4.

Figure 3 shows the results for the *high* scenario for a ground-mounted PV system (extracted from Figure 4). The horizontal axis on the chart indicates the percentage change of the six input variables when they are varied from -20% to +20%. The midpoint at 0% represents the nominal values given in Table 2 above; the resulting LCOE in this specific case is 12.4 eurocents/kWh. The charts show a strong dependency of the PV LCOE on the yield and investment expenditures. As the PV system yield increases, the LCOE goes down drastically. On the other hand, LCOE increases as the CAPEX becomes higher. OPEX appears to have much less impact than CAPEX on the LCOE value; this is in agreement with the findings in our previous work [1] that CAPEX makes up the majority portion of the PV lifecycle costs. By extending the lifetime of the PV system, the LCOE will decrease as the costs are amortized over a longer period of time.

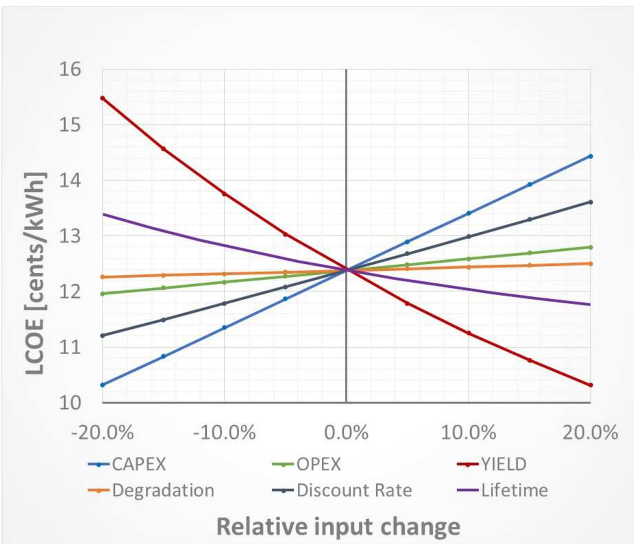


Figure 3: LCOE analysis for "high" scenario for ground-mounted utility system

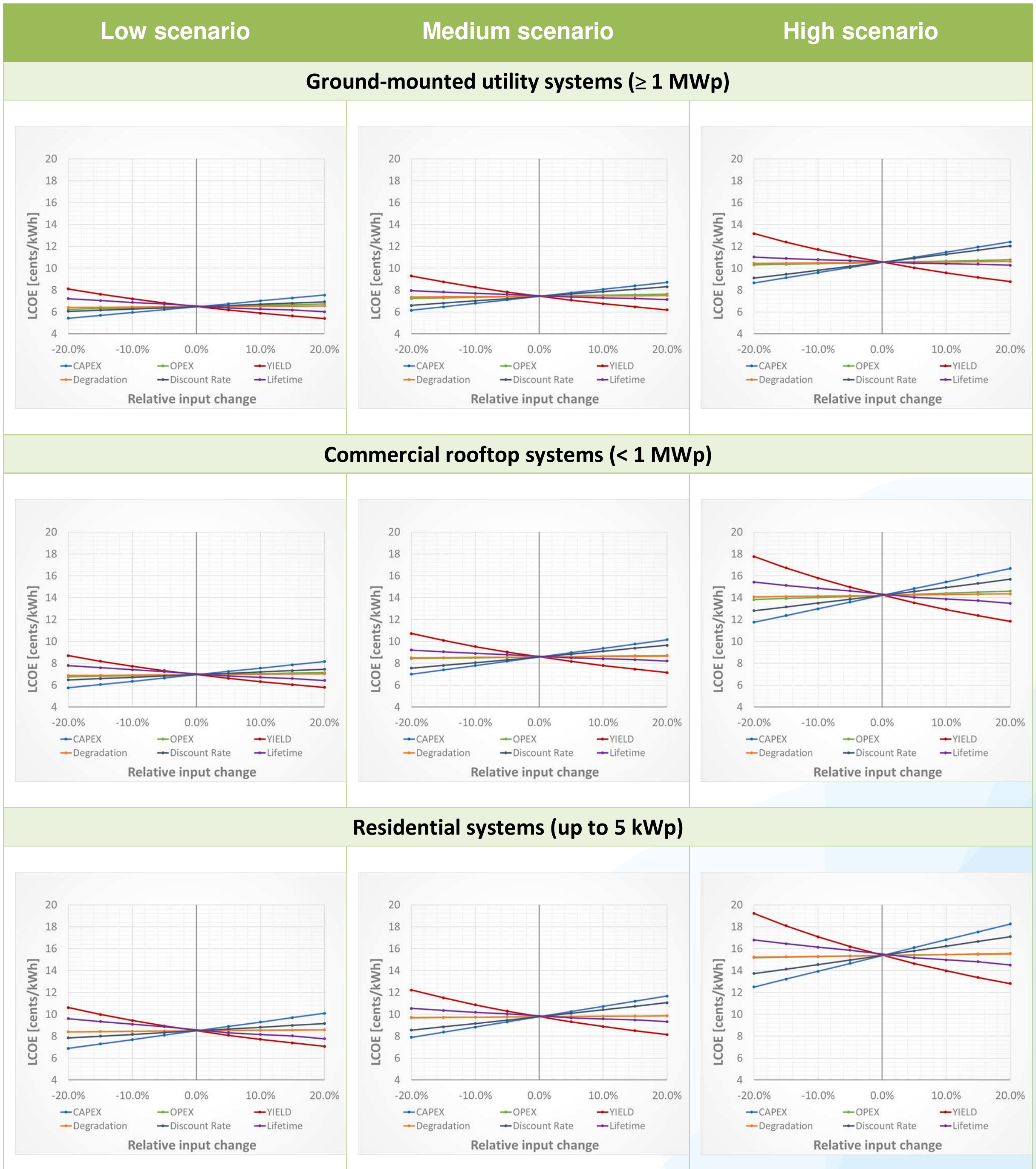


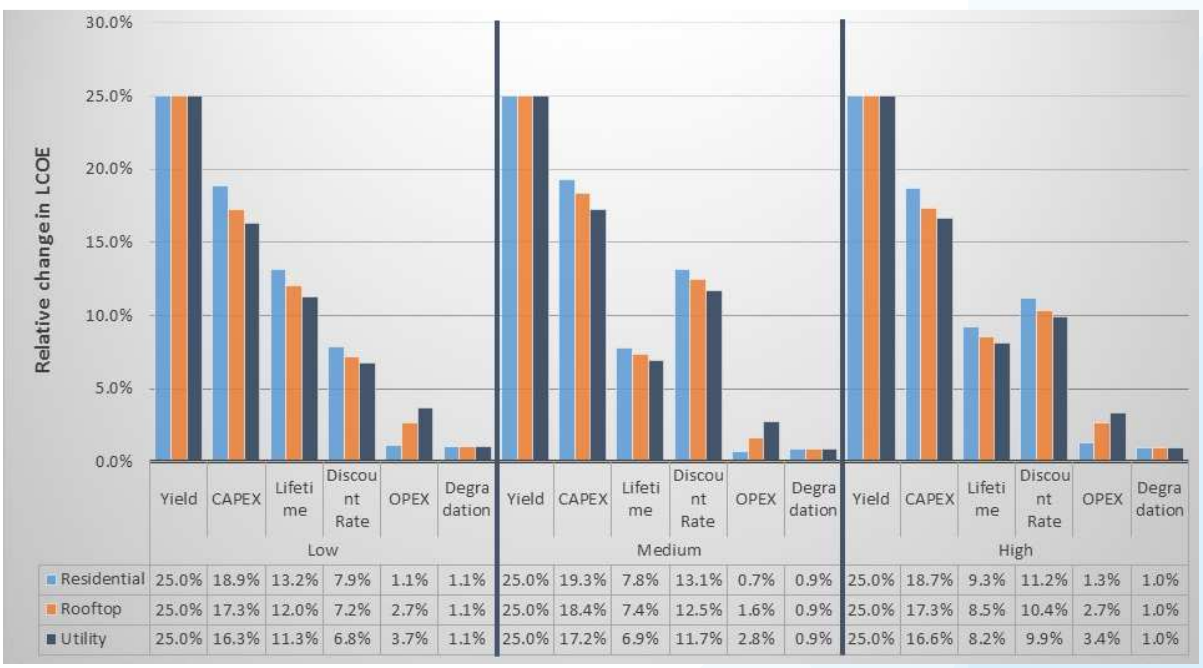
Figure 4: LCOE analysis - impact of ±20% independent variation of different input parameters for different scenarios

The resulting LCOE for the different scenarios and the three market segments from our analysis are summarized in Table 3 below. In the best case, the electricity could be produced at ca. 5.5 to 8 eurocents/kWh.

Table 3: LCOE for different scenarios and market segments without any mitigation

Market segment	Low scenario	Medium scenario	High scenario
LCOE without any mitigation	*[€cents/kWh]*	*[€cents/kWh]*	*[€cents/kWh]*
Ground-mounted utility (≥ 1 MWp)	5.4 – 8.1	6.2 – 9.3	10.3 – 15.5
Commercial rooftop (< 1 MWp)	5.8 – 8.7	7.0 – 10.7	11.8 – 17.8
Residential (up to 5 kWp)	6.9 – 10.6	7.9 – 12.2	12.5 – 19.2

Results of the sensitivity analysis show that for a variation range of ±20%, the variation in yield has the highest impact in LCOE, followed by the variation in CAPEX, lifetime, discount rate, OPEX and finally the degradation. These observations are true only for the *low* scenario (Figure 5). However, for the *medium* and the *high* scenarios, the discount rate impact surpasses that of the lifetime, taking the third place in the classification. This is clearly visible especially for the *medium* scenario mainly because in the *medium* scenario, the discount rate was set to be quite high (8%) compared to the other two scenarios. It is worth keeping in mind that a variation larger than ±20% may change the order of some elements. For example, a larger variation of the discount rate may result in a different sorting than the one presented in Figure 5.



	Low: Yield	Low: CAPEX	Low: Lifetime	Low: Discount Rate	Low: OPEX	Low: Degradation	Medium: Yield	Medium: CAPEX	Medium: Lifetime	Medium: Discount Rate	Medium: OPEX	Medium: Degradation	High: Yield	High: CAPEX	High: Lifetime	High: Discount Rate	High: OPEX	High: Degradation
Residential	25.0%	18.9%	13.2%	7.9%	1.1%	1.1%	25.0%	19.3%	7.8%	13.1%	0.7%	0.9%	25.0%	18.7%	9.3%	11.2%	1.3%	1.0%
Rooftop	25.0%	17.3%	12.0%	7.2%	2.7%	1.1%	25.0%	18.4%	7.4%	12.5%	1.6%	0.9%	25.0%	17.3%	8.5%	10.4%	2.7%	1.0%
Utility	25.0%	16.3%	11.3%	6.8%	3.7%	1.1%	25.0%	17.2%	6.9%	11.7%	2.8%	0.9%	25.0%	16.6%	8.2%	9.9%	3.4%	1.0%

Figure 5: Classification of input parameters according to their impact on LCOE for a variation of ±20% of each input parameter

In this analysis, the degradation is assumed to have a linear behavior over time and the effect of different degradation behavior over time is out of the scope of this analysis. This topic has been visited in a recent study [5] which has analyzed the effect on LCOE of four different degradation trends, i.e. linear degradation of 0.5%/year, 2-step degradation, exponential degradation, and 0.16%/year degradation starting at 90% of nameplate power. The authors reported that overall, the range of different degradation behaviors can be in the order of magnitude of 1.7 eurocents/kWh, which in the case of that study was even exceeding the impact of the initial costs.

Another recently published study ([6]) assessed the effect of the different CAPEX, OPEX and yield elements on the final LCOE. The results showed that within the CAPEX elements, the inverter costs and the construction/installation works have the greatest influence on the LCOE. In the past solar module cost used to be the dominant factor in PV capital investment but aggressive competitions among manufacturers have helped lowering the module pricing significantly in recent years. For the OPEX, the costs of preventive maintenance and the inverter warranty extension play the biggest role. From the yield perspective, temperature losses and inverter losses are the most influencing elements impacting the LCOE.

In the next section, we discuss the effect of mitigation measures on the different elements of the LCOE.

2.2.3 Effect of risk mitigation measures on LCOE

The considered costs for the first eight mitigation measures described in §2.1 are shown in Table 4 (medium cost scenario in [2]). As the last mitigation measure ("Others") does not have concrete and quantifiable cost, the sensitivity analysis will be addressed differently in one of the case studies in the next section §2.2.4. It is worth mentioning that although many of the mitigation measures are not practical from cost and usefulness perspectives for residential PV systems, we have nevertheless considered this market segment in our analysis for comparison purpose.

Table 4: Cost of mitigation measures for the medium cost scenario as defined in [2]

Mitigation measure	Cost of Mitigation Measure (MM)
Component testing – PV modules	3 €/kWp (0.15 €/kWp/year)
Design review + construction monitoring	20.00 €/kWp (1 €/kWp/year)
EPC qualification	€ 3.00 €/kWp (0.15 €/kWp/year)
Advanced monitoring	2.00 €/kWp/year
Basic monitoring	0.50 €/kWp/year
Advanced inspection	2.00 €/kWp/year
Visual inspection	1.00 €/kWp/year
Spare part management	0.50 €/kWp/year

Component testing, design review and construction monitoring, and EPC qualification are mitigation measures which can be implemented during the early phases of PV project lifecycle, i.e. before the PV system is commissioned into operation. The costs to implement these measures are therefore considered as investment capitals. The remaining five mitigation measures in Table 4 are more of operational costs.

To analyze the impact of the implementing risk mitigations on LCOE, different combinations of the mitigation measures are analyzed. In total of 255 combinations of the eight above measures are considered (cf. Annex 3 of [2]). How the application of each of these 255 combinations changes the LCOE value is analyzed. The impact on the criticality of PV technical risks (i.e. Cost Priority Number) was studied in another analysis and reported in [2].

For the purpose of this analysis we have assumed a hypothetical PV plant in all cases where there is a ~7% performance loss without any mitigation measure applied. This 7% loss and the impact of the different combinations of mitigation measures on this loss comes from the statistical analysis over a portfolio of 440 MWp presented in [2] (failures in the never detected scenario). Examples of specific cases where the losses can potentially be much higher are presented in §2.2.4.

How mitigation measures change the LCOE?

Figure 6 shows the resulting relative change in LCOE for the ground-mounted PV systems in the utility market segment under the *low* scenario defined in the previous section. Each point on the chart represents one possible mitigation measure combination. The analysis is done for the loss scenario[2] where plant performance loss is observed due to the occurrence of non-catastrophic faults and the faults are not fixed. We have also chosen the low PPA case of 10 eurocents/kWh [2].Thus, the relative change in LCOE is calculated using the reference cost priority number (CPN) value of 5.4 €/kWp/year.

Results presented in Figure 6 indicate that specific for ground-mounted PV systems under the *low* scenario, most of the mitigation combinations under this scenario yield in average a reduction of LCOE in the order of 1% to 2%. However, there are some few mitigation combinations that actually could lead to an undesirable increase of the LCOE. On the other hand, there are some mitigation combinations that may potentially decrease the LCOE by as much as 4%.

[2] The fix scenario defined in [2] is not used in this analysis as it represents an extreme case where the costs related to fixing all failures (i.e. reference CPN value of 104.75 €/kWp/year) would be by far much higher than the OPEX in any of the scenarios analyzed in this report.

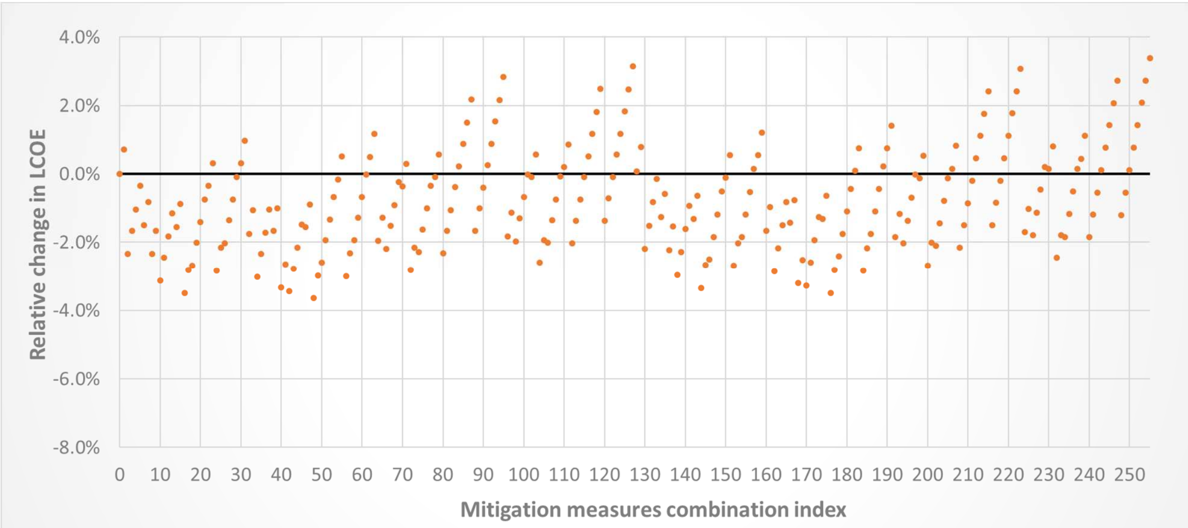


Figure 6: Relative change in LCOE for mitigation measure combinations under the "low" scenario for ground-mounted utility PV system

For an easier visualization of the potential reduction of LCOE through combination of different mitigation measures for the *low* scenario, Figure 7 presents the same results as Figure 6 but sorted according to the impact on the LCOE. This approach allows to rank the magnitude of the impact on LCOE of not only individual mitigation measures but also their combinations.

The orange line in Figure 7 (primary vertical axis) shows the relative change in the LCOE (%) resulting from the application of the different 255 combinations of mitigation measures. Each combination has a related CAPEX and/or OPEX cost, indicated by the blue and green areas on the chart (secondary vertical axis). Moreover, the application of the mitigation measures may have an impact in reducing the energy loss associated with the technical risks (red line in the figure – secondary vertical axis). We can draw the following observations from this analysis:

- For most of the analyzed combinations of mitigation measures, an average LCOE decrease of 1 to 2% is observed. The decline in LCOE is somehow correlated with a smaller increase of OPEX due to the application of mitigation measures.
- There are several combinations of mitigation measures that actually increase the LCOE. Mitigation measures with large combined increases in CAPEX and OPEX result in higher increase in LCOE.
- The best combinations of mitigation measures for this scenario could potentially decrease the LCOE by as much as 4%. The two best combinations in this scenario are:
    - Combination #48: qualification of EPC (+0.25% CAPEX) and advanced monitoring system (+13.3% OPEX), and
    - Combination #176: component testing and qualification of EPC (+0.5 % CAPEX) and advanced monitoring system (+13.3% OPEX).

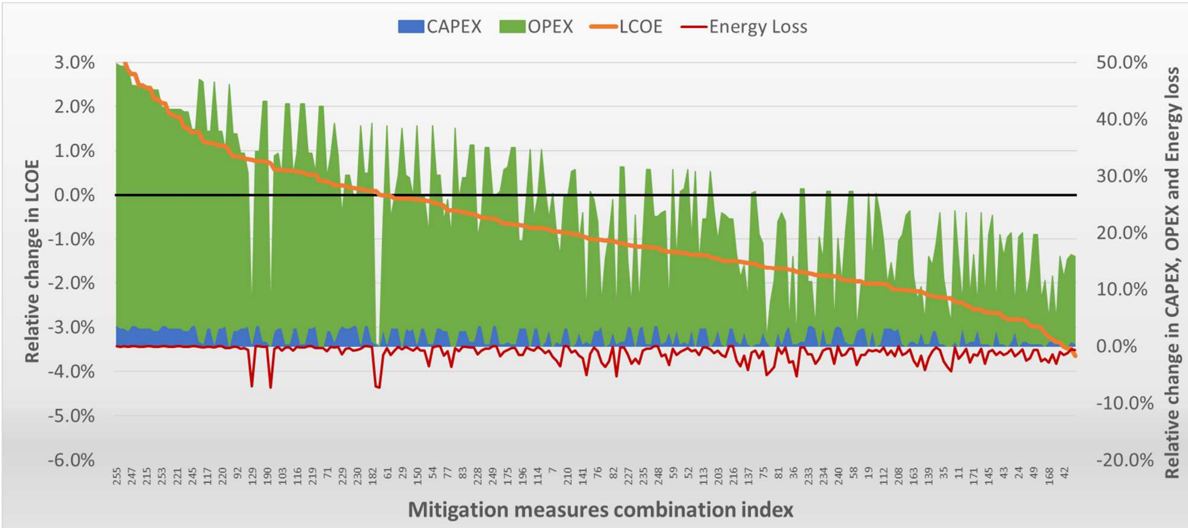


Figure 7: Sorted relative change in LCOE for 255 mitigation measure combinations for ground-mounted utility system for "low" scenario

Similar analysis was repeated for the *medium* and *high* scenario for the same market segments. The plots are presented in Figure 8 and Figure 9 below. As the figures show, the higher CAPEX, OPEX and/or discount rate in these two scenarios results in higher LCOE. Moreover, the different combinations of mitigation measures will have a larger impact in lowering the LCOE.

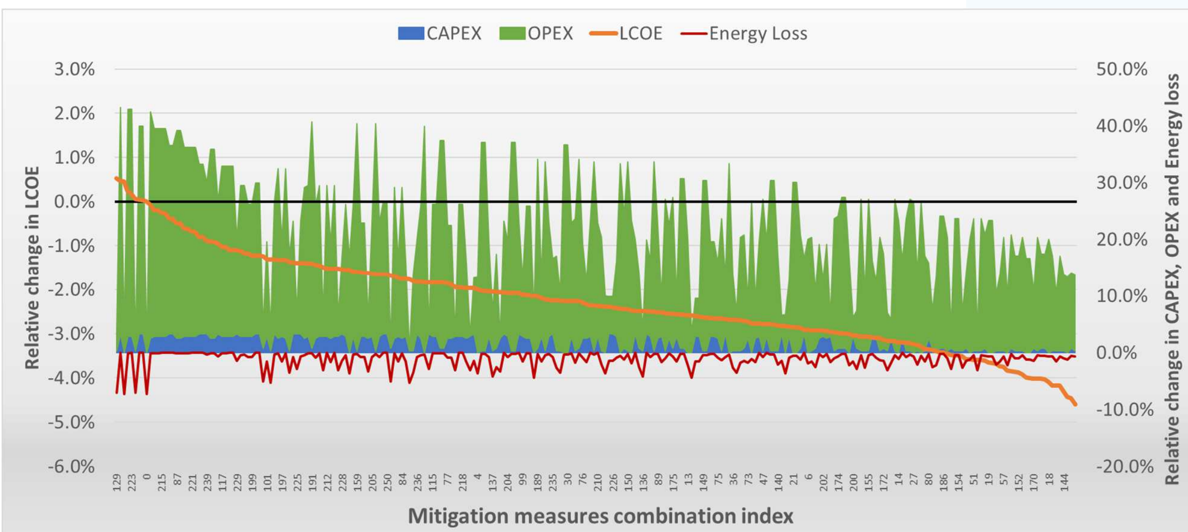


Figure 8: Sorted relative change in LCOE for 255 mitigation measure combinations for ground-mounted utility system for "medium" scenario

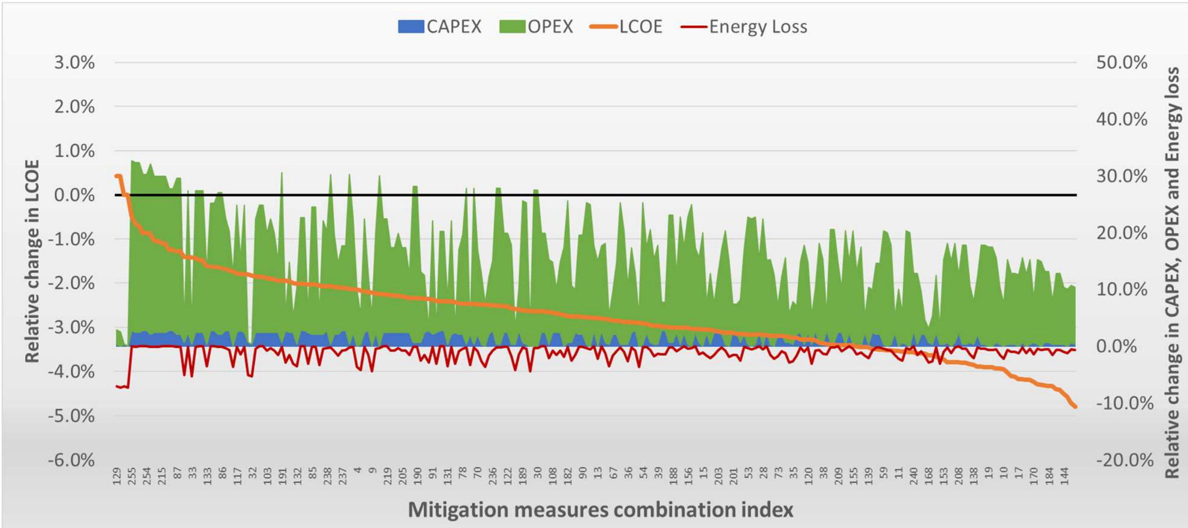


Figure 9: Sorted relative change in LCOE for 255 mitigation measure combinations for ground-mounted utility system for "high" scenario

The analysis on different combinations of mitigation measures on LCOE was replicated for the commercial rooftop and residential PV systems. As mentioned before, although many of the mitigation measures are not practical from cost and usefulness perspectives for residential PV systems, we have nevertheless considered this market segment in our analysis for comparison purpose. The resulting best case mitigation combinations for all three market segments are summarized in Table 5 below.

Table 5: Maximum LCOE reduction and LCOE after the application of the best combination of mitigation measures

Market segment	Low scenario	Medium scenario	High scenario
% maximum LCOE reduction			
Ground-mounted utility (≥ 1 MWp)	3.6%	3.8%	4.2%
Commercial rooftop (< 1 MWp)	4.6%	4.8%	5.0%
Residential (up to 5 kWp)	4.8%	5.0%	5.1%
LCOE after best mitigation combination	*[€cents/kWh]*	*[€cents/kWh]*	*[€cents/kWh]*
Ground-mounted utility (≥ 1 MWp)	5.2 – 7.8	5.9 – 8.9	9.9 – 14.8
Commercial rooftop (< 1 MWp)	5.5 – 8.4	6.7 – 10.3	11.2 – 17.0
Residential (up to 5 kWp)	6.6 – 10.1	7.5 – 11.6	11.9 – 18.2

In general, a reduction in the LCOE in the order of 4 to 5% was observed in all cases. The results continue to highlight that mitigation measures with most positive impacts in LCOE reduction are the ones implemented in early phase of project development (EPC qualification, component testing, and using advanced monitoring system).

The impact is less if the system size increase because the lifecycle costs are generally lower than those for the residential systems and thus, relative decrease in LCOE is less significant. More importantly, results show that the different combinations of mitigation measures have a larger impact in lowering the LCOE for scenarios where the higher CAPEX, OPEX, and/or discount rate results in a higher LCOE.

Which mitigation measures are most effective from LCOE perspective?

Our LCOE analysis includes three scenarios in three market segments and thus there are in total nine different cases considered. Here we analyze which combinations, among the 255 studied, of mitigation measure are most effective to reduce the LCOE. The top 10 most effective mitigation combinations from LCOE perspective for all nine cases are extracted and summarized in Figure 10 below. For detail lists of 10 most effective mitigation measure combinations for each of the nine different cases, refer to Annex B of this report.

In Figure 10, each individual plot represents one LCOE reduction ranking. On the x-axis of each plot is the number (index) representing each mitigation combination. On the y-axis on each plot is the number of cases (the *count*) a certain mitigation combination works. For example, for the most effective mitigation combination plot (“Rank = 1”), mitigation combination #48 has a count of 9 which means it is the most effective combination to lower the LCOE across three market segments under all three scenarios.

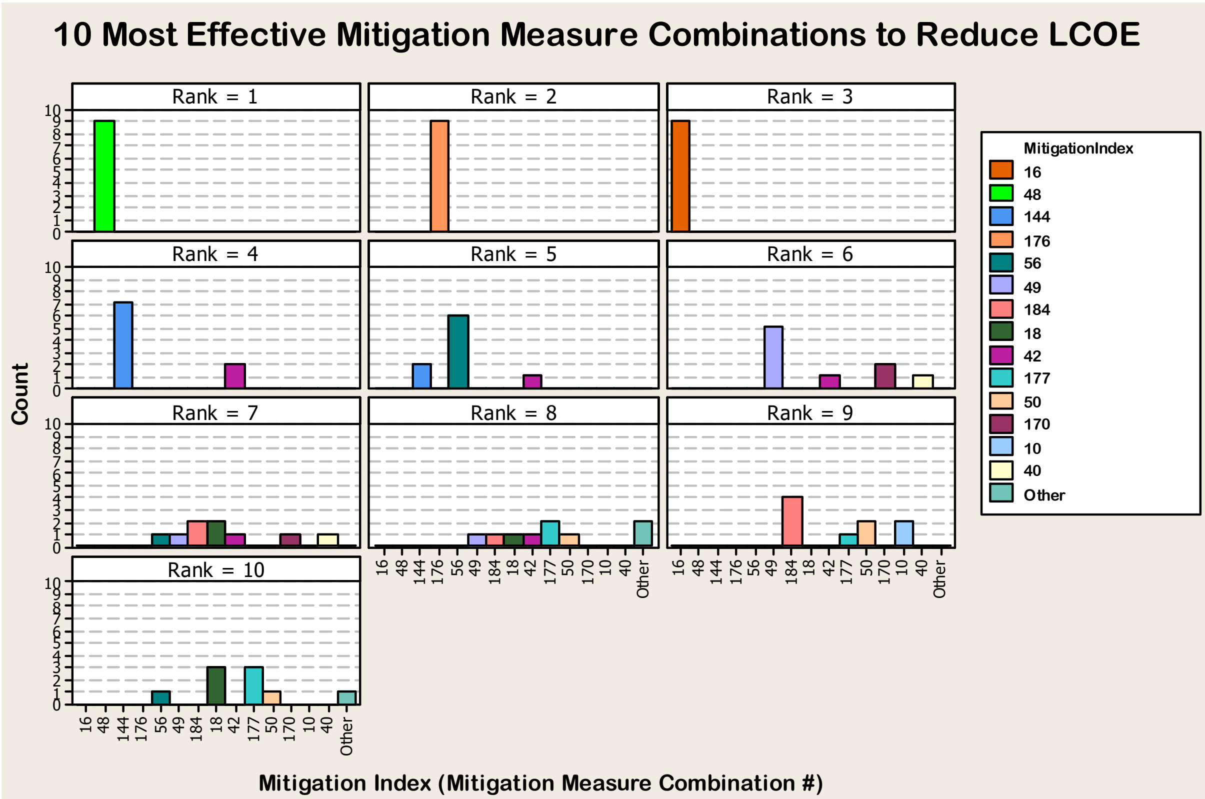


Figure 10: Top 10 most effective mitigation measure combinations for LCOE reduction

It is apparent from the figure above that there is only a dozen or so mitigation combinations which are most effective in reducing PV LCOE across all three market segments for all three scenarios. Moreover, the top three most effective combinations appear to involve mitigation measures which are to be implemented in the early phase of project lifecycle:

- #48: EPC qualification + advanced monitoring system;
- #176: component testing + EPC qualification + advanced monitoring system;
- #16: advanced monitoring.

2.2.4 Case studies

In the previous sections we have analyzed the impact of multiple risk and risk mitigation combinations on LCOE for different PV market segments on three scenarios. In this subsection we present three different more specific case studies where PV systems with specific issues are considered. The LCOE range is the result of the variation of ±20% of the input parameters as defined in §2.2.2. We have used the principal behind the risk flashcard introduced earlier in this report to illustrate how the risk flashcards can be used.

Case study 1: Cost benefit of design review during design phase

LCOE Technical Risks	***Under-estimation of the long-term yield of a PV plant during the design phase*** ***(Risk #4 and Risk #6 in** Table 1)*	*Phase of risk occurrence*	
		Procurement	*Planning* ✓
		O&M	*Construction*

Key takeaway	Even with an implementation of mitigation measure which increases the CAPEX, the overall LCOE decreases as the gain in yield surpasses the extra CAPEX cost.
Plant info	Ground-mounted utility PV system with crystalline silicon PV modules
Risk info	• 5% under-estimation of the solar resource due to unaccounted long-term solar resource trends. • 0.7% degradation rate was assumed while the manufacturer guarantees annual degradation of 0.5%.

Impact of risk	**Overall LCOE**	**CAPEX**	**OPEX**	**Yield**
	Over-estimated			↓

Mitigations

- ☐ Component testing
- ■ Design review + construction monitoring
- ☐ EPC qualification
- ☐ Advanced monitoring
- ☐ Basic monitoring
- ☐ Advanced inspection
- ☐ Visual inspection
- ☐ Spare part management
- ☐ Others

The cost of design review in project due diligence is assumed to be ca. 0.5 €/kWp (CAPEX).

A reduction in the order of 6.5%, 6.2% and 6.4% in LCOE can be achieved for the *low*, *medium* and *high* scenarios respectively by implementing best practices during design review as a mitigation measure.

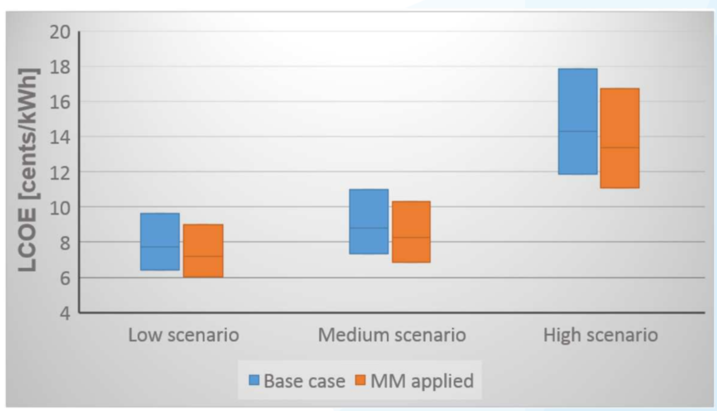


Figure 11: Impact of design review on LCOE – case study 1

Impact of mitigation	**Overall LCOE**	**CAPEX**	**OPEX**	**Yield**
	Decreases	↑		↑

Case study 2: Cost benefit of implementing PV module power rating verification pre-installation

		Phase of risk occurrence	
LCOE Technical Risks	***Module power below contracted value*** **(*Risk #2 in*** *Table 1)*	*Procurement* ✓	*Planning*
		O&M	*Construction*

Key takeaway: Even with an implementation of mitigation measure which increases the CAPEX, the overall LCOE decreases as the gain in yield surpasses the extra CAPEX cost.

Plant info: Ground-mounted utility PV system with crystalline silicon PV modules

Risk info:

- 1.2% of the delivered modules are below contracted power which translates into an overall decrease in initial plant performance ratio of roughly 1%.
- Under-performing modules are replaced at 120 €/unit (OPEX).

Impact of risk	Overall LCOE	CAPEX	OPEX	Yield
	Over-estimated		↑	↓

Mitigations

- ■ Component testing
- ☐ Design review + construction monitoring
- ☐ EPC qualification
- ☐ Advanced monitoring
- ☐ Basic monitoring
- ☐ Advanced inspection
- ☐ Visual inspection
- ☐ Spare part management
- ☐ Others

The cost of PV module testing prior to installation is assumed to be ca. 0.5 €/kWp (CAPEX).

A reduction in the order of 6.8%, 5.2% and 4.8% in LCOE can be achieved for the *low*, *medium* and *high* scenarios respectively by implementing PV module STC testing prior to installation as a mitigation measure.

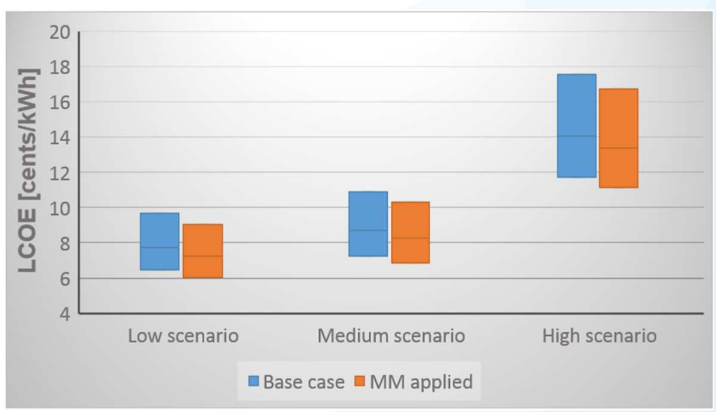


Figure 12: Impact of module testing prior to installation on LCOE – case study 2

Impact of mitigation	Overall LCOE	CAPEX	OPEX	Yield
	Decreases	↑		↑

Case study 3: Cost benefit of PV module cleaning to reduce soiling loss

LCOE Technical Risks	***Missing module cleaning* *(Risk #20 in* *Table 1)***	*Phase of risk occurrence*	
		Procurement	*Planning*
		O&M ✓	*Construction*

Key takeaway	Even with an implementation of mitigation measure which increases the OPEX, the overall LCOE decreases as the gain in yield surpasses the extra OPEX cost.
Plant info	Ground-mounted utility PV system with crystalline silicon PV modules
Risk info	• No module cleaning is planned in the maintenance schedule. • 7% of soiling losses due to high pollution region and low yearly rainfall.

Impact of risk	**Overall LCOE**	**CAPEX**	**OPEX**	**Yield**
	Over-estimated			↓

Mitigations

- ☐ Component testing
- ☐ Design review + construction monitoring
- ☐ EPC qualification
- ☐ Advanced monitoring
- ☐ Basic monitoring
- ☐ Advanced inspection
- ☐ Visual inspection
- ☐ Spare part management
- ■ Others

The cost of PV module cleaning is assumed to be ca. 1 €/kWp/year (OPEX).

A reduction in the order of 7%, 7.2% and 7.4% in LCOE can be achieved for the *low*, *medium* and *high* scenarios respectively by implementing PV module cleaning as a mitigation measure.

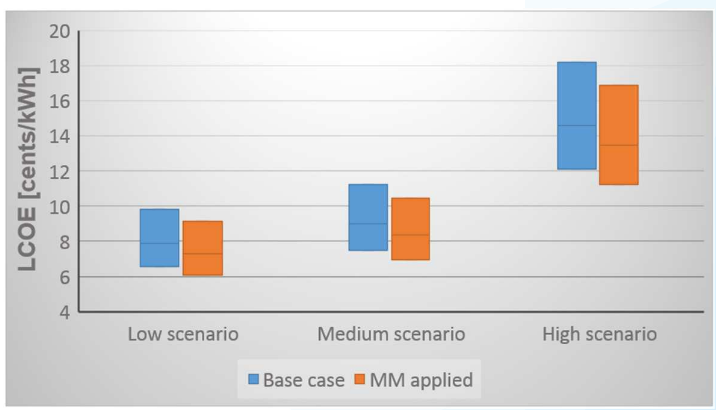


Figure 13: Impact of module cleaning on LCOE – case study 3

Impact of mitigation	**Overall LCOE**	**CAPEX**	**OPEX**	**Yield**
	Decreases		↑	↑

2.3 Chapter Summary

In this chapter we analyzed how PV LCOE is influenced by the technical risks associated with the 20 most common gaps in the technical assumptions in PV financial models. A sensitivity analysis was performed by varying 6 input parameters of the LCOE (CAPEX, OPEX, yield, discount rate, yearly degradation and system lifetime) by ±20%. The CAPEX and OPEX prices used in the analysis are inputs from our project partners, project advisory board and recent publications on PV system pricings. In the sensitivity analysis, each input was treated as if one is independent from the others. The analysis includes three different market segments: residential systems <5 kWp, commercial rooftop systems <1 MWp, and utility scale ground-mounted systems ≥1 MWp. For each market segment, three scenarios representing PV systems in three countries in EU where LCOE is low, medium and high were evaluated.

➔ ***The LCOE sensitivity analysis results highlight that the variation in yield has the highest impact in LCOE, followed by the variation in CAPEX, lifetime or discount rate, OPEX, and finally the degradation.***

The impact of the technical risk mitigations on LCOE was then evaluated. Eight mitigation measures have been proposed to address the LCOE technical risks identified in the works. Three of these are component testing, design review and construction monitoring, and EPC qualification which can be implemented during the early phases of PV project lifecycle. The other five – basic monitoring, advanced monitoring, visual inspection, advanced inspection, and spare part management, are mitigation measures during the operational phase of the PV system. We simulated 255 different combinations of these eight mitigation measures and calculated the corresponding LCOE values. The analysis was performed for the three market segments and three scenarios used in the above LCOE sensitivity analysis. The results show the followings:

➔ ***In general, an LCOE reduction up to 4 to 5% is observed in all cases.***

➔ ***The different combinations of mitigation measures have a larger impact in lowering the LCOE for scenarios where the higher CAPEX, OPEX, and/or discount rate results in a higher LCOE.***

➔ ***Mitigation measures which are most effective in lowering PV LCOE are similar across all three market segments and all scenarios.***

➔ ***The three mitigation measures most effective in lowering LCOE are those implemented at the early stage of project lifecycle: qualification of EPC, component testing prior to installation, and advanced monitoring system for early fault detection.***

Finally, we presented 3 case studies where PV systems with specific issues are considered: one case where poor yield estimation method was used in the design phase; the second case involves low module power output in the procurement phase, and the last case where module cleaning was not included in the operational phase. The LCOE's before and after the application of mitigation measures were calculated.

➔ ***In all three cases the results highlight that even though the implementation of mitigation measures increases either CAPEX or OPEX or both, the overall LCOE after mitigation decreases as the gain in yield surpasses the extra incurred cost.***

3 Best Practice Guidelines

The analyses done in the preceding chapter on the impacts of the LCOE technical risks and their associated mitigations on the PV investment cost have highlighted that PV LCOE cost is sensitive to the changes in the CAPEX, lifetime or discount rate, OPEX, and finally the degradation. Moreover, from our previous works on gaps analysis in the technical assumptions used in PV cost calculations, we have identified gaps in the EPC and O&M activities which ultimately could have negative influences on the project CAPEX, OPEX and yield. It is therefore essential to ensure that the activities revolving around the EPC and O&M phases of the PV system are executed in manners which will minimize the occurrence or impact of the LCOE technical risks. In this regards, a set of best practice guidelines for the technical aspects in the EPC and O&M contracts have been developed to serve different actors along the PV project value chain in the process of realizing and operating PV plants.

In total six checklists have been developed based on inputs from the project partners and published references [7]–[11]. Each checklist could be used as a stand-alone document. The three main checklists are:

1. Best Practice Checklist for EPC Technical Aspects
2. Best Practice Checklist for O&M Technical Aspects
3. Best Practice Checklist for Long-Term Yield Assessment

The three supplementary checklists are:

4. Checklist for As-Build Documents – Type and Details
5. Checklist for Record Control
6. Checklist for Reporting Indicators

The above checklists have been developed for use for utility-scale (ground-mounted) and commercial rooftop PV installations. The checklists for residential systems are treated separately since they are based on very different business models; these checklists are presented in another report of the Solar Bankability project (*Technical Bankability Guidelines - Recommendations to Enhance Technical Quality of PV Investments* [3]).

4 Closing Remarks

In this report, we have presented the results of various analyses on how PV technical risks and the associated risk mitigation measures could impact the PV levelized cost of electricity. This is important as PV LCOE is an important factor influencing the investment-attractiveness of a PV project. The results from the works provide a valuable insight on how to link more concretely the PV investment financial side and the PV technical side. One straightforward way is to manage the technical risks in PV investment via best practices in EPC and O&M technical aspects, and in the methodology to estimate and calculate PV system yield.

In this regard, we have therefore developed a set of best practice guidelines in the form of checklists for different actors in the PV value chain. The main three checklists are for best practices to set up EPC contracting, O&M contracting, and yield calculation/estimation. The three other checklists compliment the EPC and O&M contracting best practices. Each checklist could be used as a stand-alone document.

In addition, a set of flash cards for the 20 most common technical risks associated with the gaps in technical assumptions to calculate PV LCOE have been created to serve as quick references for the users.

We would like to note that the best practice checklists presented in this report are best suited for use for utility-scale (ground-mounted) and commercial rooftop PV installations. The residential systems are based on different business models and thus the best practice guidelines are addressed in another work of this project [3].

Last but not least, in the LCOE sensitivity analysis and case studies, we have used inputs (for CAPEX, OPEX, yield, discount rate, yearly degradation, and system lifetime) provided by project partners and advisory board as well as recent publications on PV system pricings. These values are from recent years (2015-2016) and will change over time as the PV market continues to evolve. Consequently, we recommend repeating the analysis once new input numbers become available.

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Annex A – Top 20 LCOE Technical Risks and Mitigation Measure

This annex details the categorization of the most common PV technical risks we have identified with respect to their impacts and their mitigations on PV LCOE. We have included the recommended mitigations as well as the key takeaway for each of these risks. The categorization method is explained in §2.1 of this report.

<table>
<tr><td rowspan="3"><u>LCOE Technical Risk</u></td><td rowspan="3" colspan="2">1. Insufficient EPC technical specifications to ensure that selected components are suitable for use in the specific PV plant environment of application</td><td colspan="2">Phase of risk occurrence</td></tr>
<tr><td>Procurement ✓</td><td>Planning</td></tr>
<tr><td>O&M</td><td>Construction</td></tr>
<tr><td><u>Key takeaway</u></td><td colspan="4">PV plant component specification and requirement in the EPC contract should be as detailed as possible to ensure that the components procured are suited for the intended PV installation, specific application, site and environment</td></tr>
<tr><td><u>Impact of risk</u></td><td>LCOE variables impacted by this risk:</td><td>CAPEX</td><td>OPEX</td><td>Yield ↓</td></tr>
<tr><td><u>Mitigations</u></td><td>☐ Component testing
■ Design review + construction monitoring
☐ EPC qualification
☐ Advanced monitoring
☐ Basic monitoring
☐ Advanced inspection
☐ Visual inspection
☐ Spare part management
■ Others</td><td colspan="3">When specifying the technical requirements for PV plant components in the EPC contract, in addition to the component type and quantity, the specifications should also include:
• All applicable certifications and conformances (e.g. IEC61215, IEC61730, IEC61701, IEC62804, IEC61716 for modules; IEC62109, IEC61000 for inverters; CE mark of compliance for all electrical components)
• The environmental condition the components will be installed in (temperature, humidity, wind and snow load, any special chemical exposure, corrosion risk etc.)
• For PV modules, module component bill of materials and the proof of IEC certification documents for these materials</td></tr>
<tr><td><u>Impact of mitigation</u></td><td>LCOE variables impacted by the risk mitigations:</td><td>CAPEX</td><td>OPEX</td><td>Yield ↑</td></tr>
</table>

LCOE Technical Risk	2. ***Inadequate component testing to check for product manufacturing deviations***			*Phase of risk occurrence*	
				Procurement ✓	*Planning*
				O&M	*Construction*
Key takeaway	*Comprehensive relevant product testing in the manufacturer's factory should be included as an EPC requirement to minimize issues due to product defects caused by manufacturing deviations*				
Impact of risk	**LCOE variables impacted by this risk:**		**CAPEX**	**OPEX** ↑	**Yield** ↓
Mitigations	■ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	For critical PV plant components such as modules or inverters, the following product quality control must be included as part of procurement process required from the EPC contractor: • Reviewing how the products are tested by the manufacturer in the factory (including checking the pass/fail criteria for the tests) • Requesting specific tests to be included in the product test plan in the factory • Reviewing the factory test results at the latest upon delivery			
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**		**CAPEX** ↑	**OPEX**	**Yield** ↑

LCOE Technical Risk	3. ***Absence of adequate third party product delivery acceptance test and criteria***			*Phase of risk occurrence*	
				Procurement ✓	*Planning*
				O&M	*Construction*
Key takeaway	*Plant components such as PV modules should only be accepted for PV project installation when independent testing shows that they have met the contracted technical specifications*				
Impact of risk	**LCOE variables impacted by this risk:**		**CAPEX**	**OPEX** ↑	**Yield** ↓
Mitigations	■ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	For critical PV plant components such as modules or inverters, the following product quality control must be included as part of procurement process required from the EPC contractor: • Have a sample group of product shipment tested by an independent trustworthy party if they perform according to the contracted requirements • Clearly define the tests and acceptance criteria prior to testing • Accept only the product shipment if the test results indicate the product meets the contracted requirements			
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**		**CAPEX** ↑	**OPEX**	**Yield** ↑

<table>
<tr><td rowspan="2"><u>LCOE Technical Risk</u></td><td rowspan="2" colspan="2">4. Effect of long-term trends in the solar resource is not fully accounted for</td><td colspan="2">Phase of risk occurrence</td></tr>
<tr><td>Procurement

O&M</td><td>Planning ✓

Construction</td></tr>
<tr><td><u>Key takeaway</u></td><td colspan="4">Not counting the long-term trend in solar irradiation could result in under-estimation of PV plant yield and over-estimation of the annual variability in risk assessment</td></tr>
<tr><td><u>Impact of risk</u></td><td>LCOE variables impacted by this risk:</td><td>CAPEX</td><td>OPEX</td><td>Yield
↑↓</td></tr>
<tr><td><u>Mitigations</u></td><td>☐ Component testing
■ Design review + construction monitoring
☐ EPC qualification
☐ Advanced monitoring
☐ Basic monitoring
☐ Advanced inspection
☐ Visual inspection
☐ Spare part management
☐ Others</td><td colspan="3">In a long-term yield estimation:
• Analyze long-term solar resource databases (ideally more than 20 years) for the presence of long-term trends
• In the presence of long-term trends, use methods described in best practices to account for the effect of these trends in the solar resource</td></tr>
<tr><td><u>Impact of mitigation</u></td><td>LCOE variables impacted by the risk mitigations:</td><td>CAPEX
↑</td><td>OPEX</td><td>Yield
↓↑</td></tr>
</table>

<table>
<tr><td rowspan="2"><u>LCOE Technical Risk</u></td><td rowspan="2" colspan="2">5. Exceedance probabilities (e.g. P90) are often calculated for risk assessment assuming a normal distribution for all elements contributing to the overall uncertainty</td><td colspan="2">Phase of risk occurrence</td></tr>
<tr><td>Procurement

O&M</td><td>Planning ✓

Construction</td></tr>
<tr><td><u>Key takeaway</u></td><td colspan="4">Assuming a normal distribution for all elements in the calculation of exceedance probabilities may result in misleading risk assessment studies</td></tr>
<tr><td><u>Impact of risk</u></td><td>LCOE variables impacted by this risk:</td><td>CAPEX</td><td>OPEX</td><td>Yield
↑↓</td></tr>
<tr><td><u>Mitigations</u></td><td>☐ Component testing
■ Design review + construction monitoring
☐ EPC qualification
☐ Advanced monitoring
☐ Basic monitoring
☐ Advanced inspection
☐ Visual inspection
☐ Spare part management
☐ Others</td><td colspan="3">• In a long-term yield estimation, calculate exceedance probabilities (e.g. P90) using empirical method based on available data instead of simply assuming normal distribution</td></tr>
<tr><td><u>Impact of mitigation</u></td><td>LCOE variables impacted by the risk mitigations:</td><td>CAPEX
↑</td><td>OPEX</td><td>Yield
↓↑</td></tr>
</table>

LCOE Technical Risk	**6. *Incorrect degradation rate and behavior over time assumed in the yield estimation***	***Phase of risk occurrence***	
		Procurement	*Planning* ✓
		O&M ✓	*Construction*
Key takeaway	*Incorrect assumption of degradation rate and behavior over time could have significant impact on the cash flow and exceedance probabilities in risk assessment*		

		CAPEX	OPEX	Yield
Impact of risk	**LCOE variables impacted by this risk:**			↓↑

Mitigations	☐ Component testing ■ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Take into account the degradation rate and behavior when estimating the long-term yield; these assumptions should be backed up by guaranteed values offered by the module manufacturers or validated independently • O&M operator should use guaranteed degradation values to derive the yearly performance ratio

		CAPEX	OPEX	Yield
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	↑		↑↓

LCOE Technical Risk	**7. *Using plant (instead of overall) availability to calculate the initial yield for project investment financial model***	***Phase of risk occurrence***	
		Procurement	*Planning* ✓
		O&M	*Construction*
Key takeaway	*Incorrect optimistic assumption of PV plant availability in long-term yield estimation could have a significant impact on the cash flow of the project*		

		CAPEX	OPEX	Yield
Impact of risk	**LCOE variables impacted by this risk:**			↑

Mitigations	☐ Component testing ■ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Use overall availability (which includes downtime beyond the O&M), and not the plant availability guaranteed by the O&M operator) to calculate the initial yield for project investment financial model and PV LCOE

		CAPEX	OPEX	Yield
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	↑		↓

LCOE Technical Risk	8. ***Absence of standardized transportation and handling protocol***			*Phase of risk occurrence*	
				Procurement	*Planning*
				O&M	*Construction ✓*
Key takeaway	*Transportation method should ensure that the PV plant components arrive undamaged to the project site*				
Impact of risk	**LCOE variables impacted by this risk:**		**CAPEX**	**OPEX** ↑	**Yield** ↓
Mitigations	☐ Component testing ☐ Design review + construction monitoring ■ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Require the description of the transportation method to be included in the EPC contract • Audit the loading and unloading important PV plant components • Implementing visual inspection on components upon deliver; for PV modules, the inspection should include electroluminescence scan to check for micro-cracks in solar cell due to module mishandlings • Taking a transportation insurance			
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**		**CAPEX** ↑	**OPEX**	**Yield** ↑

LCOE Technical Risk	9. ***Inadequate quality procedures in component un-packaging and handling during construction by workers***			*Phase of risk occurrence*	
				Procurement	*Planning*
				O&M	*Construction ✓*
Key takeaway	*The EPC field workers should be aware of and execute special care and handling of PV plant components*				
Impact of risk	**LCOE variables impacted by this risk:**		**CAPEX**	**OPEX** ↑	**Yield** ↓
Mitigations	☐ Component testing ☐ Design review + construction monitoring ■ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Inspect construction work quality by carrying out construction monitoring site visits. This can be done through the assistance of a technical advisor. Ideally construction monitoring should be included in the EPC contract • Training of field workers on how to correctly store PV plant component before installation • Training of field workers on any special unpacking protocol and how to carry e.g., PV modules from the unpacking point to the installation place			
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**		**CAPEX** ↑	**OPEX**	**Yield** ↑

LCOE Technical Risk	**10. *Missing construction monitoring during construction***	***Phase of risk occurrence***	
		Procurement	*Planning*
		O&M	*Construction* ✓

Key takeaway	*Good workmanship of the EPC field workers is key to constructing a good quality PV plant*			
Impact of risk	**LCOE variables impacted by this risk:**	**CAPEX**	**OPEX** ↑	**Yield** ↓

Mitigations		
	☐ Component testing ■ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Perform construction monitoring / site visits to monitor and audit construction progress and work quality. This can be done through the assistance of a technical advisor. Ideally construction monitoring should be included in the EPC contract • Training of field workers on the correct procedures to construct different parts of PV plant

Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	**CAPEX** ↑	**OPEX**	**Yield** ↑

LCOE Technical Risk	**11. *Inadequate protocol or equipment for visual inspection during plant acceptance***	***Phase of risk occurrence***	
		Procurement	*Planning*
		O&M	*Construction* ✓

Key takeaway	*Visual inspection during plant acceptance should include advanced tools such as IR thermography to detect defects not visible by naked eyes*			
Impact of risk	**LCOE variables impacted by this risk:**	**CAPEX**	**OPEX** ↑	**Yield** ↓

Mitigations		
	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ■ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Require advanced visual inspection tool such as IR thermal camera or EL camera as part of the plant completion/acceptance test • Include the requirement for such inspection, the protocol and acceptance criteria in the EPC contract

Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	**CAPEX** ↑	**OPEX**	**Yield** ↑

LCOE Technical Risk	**12. *Missing short-term performance (e.g. PR) check at provisional acceptance test, including proper correction for temperature and other losses***	***Phase of risk occurrence***	
		Procurement	*Planning*
		O&M	*Construction* ✓
Key takeaway	*Short-term performance test should be part of provisional plant acceptance and at least one form of key performance indicator must be used to determine if the EPC contractor has delivered PV plant which can operate without major issues*		

		CAPEX	OPEX	Yield
Impact of risk	**LCOE variables impacted by this risk:**		↑	↓

Mitigations

- ☐ Component testing
- ☐ Design review + construction monitoring
- ☐ EPC qualification
- ☐ Advanced monitoring
- ☐ Basic monitoring
- ☐ Advanced inspection
- ☐ Visual inspection
- ☐ Spare part management
- ■ Others

- Require the EPC contractor to include guarantee of plant performance to be achieved as condition for provisional acceptance. This can be either guaranteed PR or guaranteed output measured over a short provisional test period following construction completion and grid connection
- Include all details of the performance test procedure, calculation (incl. exclusions) and criteria in the EPC contract

		CAPEX	OPEX	Yield
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	↑		↑

LCOE Technical Risk	**13. *Missing final performance check and guaranteed performance***	***Phase of risk occurrence***	
		Procurement	*Planning*
		O&M	*Construction* ✓
Key takeaway	*PV plant acceptance should include not only provisional but also final performance test after the plant has been operational for representative period of time*		

		CAPEX	OPEX	Yield
Impact of risk	**LCOE variables impacted by this risk:**		↑	↓

Mitigations

- ☐ Component testing
- ☐ Design review + construction monitoring
- ☐ EPC qualification
- ☐ Advanced monitoring
- ☐ Basic monitoring
- ☐ Advanced inspection
- ☐ Visual inspection
- ☐ Spare part management
- ■ Others

- Require in the EPC contract that a guaranteed final plant performance ought to be achieved before the plant is completely accepted
- Include all details of the performance indicator, test procedure, calculation (incl. exclusions) and criteria in the EPC contract

		CAPEX	OPEX	Yield
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	↑		↑

LCOE Technical Risk	**14. *At provisional commissioning, incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, incorrect irradiance threshold to define time window of PV operation for PR/availability calculation***			***Phase of risk occurrence***	
				Procurement	*Planning*
				O&M	*Construction* ✓
Key takeaway	*Unreliable or incorrect plant operational data could lead to incorrect assessment PV plant performance during plant acceptance phase*				
Impact of risk	**LCOE variables impacted by this risk:**		**CAPEX**	**OPEX**	**Yield** ↓↑
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ■ Others	• Specify in detail in the EPC contract, the plant parameters to be measured and the equipment or sensor required to measure them, and the data acquisition time format • Consider the seasonal effects of temperature and irradiance when evaluating plant performance and availability evaluation • Ensure that the cut-off windows to the irradiance and time for data to be used in the performance calculation are correctly set in order to not discount valid data or include invalid data			
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**		**CAPEX**	**OPEX**	**Yield** ↑↓

LCOE Technical Risk	**15. *Standard monitoring system not capable of advanced fault detection and identification***			***Phase of risk occurrence***	
				Procurement	*Planning*
				O&M ✓	*Construction*
Key takeaway	*Early fault detection could prevent defect propagation which could lead to PV plant outage*				
Impact of risk	**LCOE variables impacted by this risk:**		**CAPEX**	**OPEX** ↑	**Yield** ↓
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ■ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Use smart monitoring system for PV plant operation supervision and control			
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**		**CAPEX** ↑	**OPEX** ↑	**Yield** ↑

LCOE Technical Risk	16. ***Visual inspection during preventive maintenance not capable to catch defects or faults not visible by naked eyes***		***Phase of risk occurrence***	
			Procurement	*Planning*
			O&M ✓	*Construction*
Key takeaway	*Defects not visible by naked eyes should be detected and rectified to prevent their impacts on PV plant performance*			
Impact of risk	**LCOE variables impacted by this risk:**	**CAPEX**	**OPEX** ↑	**Yield** ↓
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ■ Advanced inspection ☐ Visual inspection ☐ Spare part management ☐ Others	• Require advanced visual inspection tool such as IR thermal camera or EL camera as part of the plant regular maintenance inspection • Include the requirement for such inspection, the protocol and acceptance criteria in the O&M contract		
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	**CAPEX**	**OPEX** ↑	**Yield** ↑

LCOE Technical Risk	17. ***Missing guaranteed key performance indicators (PR, availability or energy yield) in O&M contract***		***Phase of risk occurrence***	
			Procurement	*Planning*
			O&M ✓	*Construction*
Key takeaway	*Guaranteed performance indicator is important to ensure that the plant operation and maintenance is carried out properly*			
Impact of risk	**LCOE variables impacted by this risk:**	**CAPEX**	**OPEX** ↓	**Yield** ↓
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ■ Others	• Require the operator to guarantee plant performance or availability which will be assessed on a yearly basis • Include all details of the performance indicator, test procedure, calculation (incl. exclusions) and criteria in the O&M contract		
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	**CAPEX**	**OPEX** ↑	**Yield** ↑

LCOE Technical Risk	18. *In operational phase, incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, incorrect irradiance threshold to define time window of PV operation for PR/availability calculation*	*Phase of risk occurrence*	
		Procurement	*Planning*
		O&M ✓	*Construction*
Key takeaway	*Unreliable or incorrect plant operational data could lead to incorrect assessment PV plant performance*		
Impact of risk	**LCOE variables impacted by this risk:** **CAPEX**	**OPEX**	**Yield** ↓↑
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ■ Others	• Specify in detail in the O&M contract, the plant parameters to be measured and the equipment or sensor required to measure them, and the data acquisition time format • Consider the seasonal effects of temperature and irradiance when evaluating plant performance and availability evaluation • Ensure that the cut-off windows to the irradiance and time for data to be used in the performance calculation are correctly set in order to not discount valid data or include invalid data	
Impact of mitigation	**LCOE variables impacted by the risk mitigations:** **CAPEX**	**OPEX**	**Yield** ↑↓

LCOE Technical Risk	19. *Missing or inadequate maintenance of the monitoring system*	*Phase of risk occurrence*	
		Procurement	*Planning*
		O&M ✓	*Construction*
Key takeaway	*Monitoring system functionality will affect the quality of the plant operational data. Maintenance should specifically include the monitoring system*		
Impact of risk	**LCOE variables impacted by this risk:** **CAPEX**	**OPEX** ↓	**Yield** ↓↑
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ☐ Basic monitoring ☐ Advanced inspection ☐ Visual inspection ☐ Spare part management ■ Others	• Include in the PV plant preventive maintenance activities a regular maintenance of plant monitoring system (functionality check, sensor calibration)	
Impact of mitigation	**LCOE variables impacted by the risk mitigations:** **CAPEX**	**OPEX** ↑	**Yield** ↑↓

LCOE Technical Risk	20. *Module cleaning missing or frequency too low*		*Phase of risk occurrence*	
			Procurement	*Planning*
			O&M ✓	*Construction*
Key takeaway	*PV module surface must be kept clean and free of obstacles to maintain maximum absorbed sun light for electricity generation*			
Impact of risk	**LCOE variables impacted by this risk:**	**CAPEX**	**OPEX** ↑	**Yield** ↓
Mitigations	☐ Component testing ☐ Design review + construction monitoring ☐ EPC qualification ☐ Advanced monitoring ■ Basic monitoring ☐ Advanced inspection ■ Visual inspection ☐ Spare part management ■ Others	• The PV plant preventive maintenance activities should include module cleaning as standard and the cleaning frequency should be optimized to match the soiling rate		
Impact of mitigation	**LCOE variables impacted by the risk mitigations:**	**CAPEX**	**OPEX** ↑	**Yield** ↑

Annex B – Top 10 Mitigation Measures Combinations for Different Market Segments and Scenarios

Ground-mounted utility scale PV system

Scenario	Rank	Mitigation Measure Index	CAPEX change	OPEX change	LCOE change
Low	1	48	0.3%	15.4%	-3.6%
	2	176	0.7%	15.4%	-3.5%
	3	16	0.0%	15.4%	-3.5%
	4	42	0.3%	11.5%	-3.4%
	5	144	0.3%	15.4%	-3.3%
	6	40	0.3%	3.8%	-3.3%
	7	170	0.7%	11.5%	-3.3%
	8	168	0.7%	3.8%	-3.2%
	9	10	0.0%	11.5%	-3.1%
	10	34	0.3%	7.7%	-3.0%
Medium	1	48	0.3%	13.3%	-3.8%
	2	176	0.6%	13.3%	-3.6%
	3	16	0.0%	13.3%	-3.6%
	4	42	0.3%	10.0%	-3.5%
	5	144	0.3%	13.3%	-3.5%
	6	170	0.6%	10.0%	-3.4%
	7	40	0.3%	3.3%	-3.4%
	8	168	0.6%	3.3%	-3.3%
	9	10	0.0%	10.0%	-3.2%
	10	56	0.3%	16.7%	-3.2%
High	1	48	0.3%	10.0%	-4.2%
	2	176	0.5%	10.0%	-4.1%
	3	16	0.0%	10.0%	-4.0%
	4	144	0.3%	10.0%	-3.9%
	5	42	0.3%	7.5%	-3.9%
	6	170	0.5%	7.5%	-3.8%
	7	56	0.3%	12.5%	-3.7%
	8	49	0.3%	12.5%	-3.7%
	9	184	0.5%	12.5%	-3.6%
	10	177	0.5%	12.5%	-3.6%

Commercial rooftop-mounted PV system

Scenario	Rank	Mitigation Measure Index	CAPEX change	OPEX change	LCOE change
Low	1	48	0.3%	20.0%	-4.6%
	2	176	0.6%	20.0%	-4.5%
	3	16	0.0%	20.0%	-4.4%
	4	144	0.3%	20.0%	-4.3%
	5	56	0.3%	25.0%	-4.2%
	6	42	0.3%	15.0%	-4.2%
	7	49	0.3%	25.0%	-4.2%
	8	18	0.0%	30.0%	-4.1%
	9	184	0.6%	25.0%	-4.0%
	10	177	0.6%	25.0%	-4.0%
Medium	1	48	0.3%	20.0%	-4.8%
	2	176	0.5%	20.0%	-4.7%
	3	16	0.0%	20.0%	-4.6%
	4	144	0.3%	20.0%	-4.5%
	5	56	0.3%	25.0%	-4.5%
	6	49	0.3%	25.0%	-4.4%
	7	18	0.0%	30.0%	-4.4%
	8	42	0.3%	15.0%	-4.3%
	9	184	0.5%	25.0%	-4.3%
	10	50	0.3%	30.0%	-4.3%
High	1	48	0.2%	11.1%	-5.0%
	2	176	0.4%	11.1%	-4.9%
	3	16	0.0%	11.1%	-4.8%
	4	144	0.2%	11.1%	-4.7%
	5	56	0.2%	13.9%	-4.7%
	6	49	0.2%	13.9%	-4.7%
	7	18	0.0%	16.7%	-4.6%
	8	50	0.2%	16.7%	-4.6%
	9	184	0.4%	13.9%	-4.6%
	10	177	0.4%	13.9%	-4.6%

Residential PV system

Scenario	Rank	Mitigation Measure Index	CAPEX change	OPEX change	LCOE change
Low	1	48	0.2%	40.0%	-4.8%
	2	176	0.5%	40.0%	-4.7%
	3	16	0.0%	40.0%	-4.6%
	4	144	0.2%	40.0%	-4.5%
	5	56	0.2%	50.0%	-4.4%
	6	49	0.2%	50.0%	-4.4%
	7	42	0.2%	30.0%	-4.3%
	8	184	0.5%	50.0%	-4.3%
	9	177	0.5%	50.0%	-4.3%
	10	18	0.0%	60.0%	-4.3%
Medium	1	48	0.2%	40.0%	-5.0%
	2	176	0.4%	40.0%	-4.9%
	3	16	0.0%	40.0%	-4.7%
	4	144	0.2%	40.0%	-4.7%
	5	56	0.2%	50.0%	-4.7%
	6	49	0.2%	50.0%	-4.6%
	7	184	0.4%	50.0%	-4.6%
	8	177	0.4%	50.0%	-4.6%
	9	50	0.2%	60.0%	-4.6%
	10	18	0.0%	60.0%	-4.6%
High	1	48	0.2%	22.2%	-5.1%
	2	176	0.4%	22.2%	-5.0%
	3	16	0.0%	22.2%	-4.8%
	4	144	0.2%	22.2%	-4.8%
	5	56	0.2%	27.8%	-4.8%
	6	49	0.2%	27.8%	-4.7%
	7	184	0.4%	27.8%	-4.7%
	8	177	0.4%	27.8%	-4.7%
	9	50	0.2%	33.3%	-4.7%
	10	18	0.0%	33.3%	-4.7%

Annex C – Best Practice Checklists

This annex presents 6 checklists which are aimed for use for utility-scale (ground-mounted) and commercial rooftop PV installations. The checklists for residential systems are presented in the report *Technical Bankability Guidelines - Recommendations to Enhance Technical Quality of PV Investments* [3].

C.1. Best Practice Checklist for EPC Technical Aspects

☑/☒	Technical aspect & what to look for in the EPC contract
A	**Definitions, interpretation**
☐	1. Is there a set of definitions of important terms provided and are those clear and understood by all stakeholders?
B	**Contractual commitments**
☐	2. EPC contractor qualification
☐	3. Responsibility and accountability
☐	4. Date of ownership and risk transfer are defined and acceptable
☐	5. Construction start date and end date are defined and acceptable
☐	6. Plant Commercial Operation Date (COD) is defined and in line with FiT or PPA commencement dates
☐	7. The EPC works should be carried in compliance with (non-exhaustive list) • Grid code compliance: plant controls (e.g. ability for emergency shut-downs or curtailment according to grid regulations) • PPA compliance • Building permits (if applicable) • Environmental permits • Specific regulation for the site (e.g. vegetation management, disposal of green waste)
C	**Scope of works – engineering**
☐	8. Overall the scope of works for the EPC should be clearly defined. Which activities are included in the EPC services (is it a turnkey EPC)? Are they clearly defined?
☐	9. The EPC should include Technical Specifications consisting of • [Best practice] The operating environment is defined for: o Minimum and maximum ambient temperature o Maximum relative humidity o Maximum altitude o Local climate

- Local conditions (e.g., snowy, sandy, near sea/chemical source/corrosive/agricultural activity/purpose of building usage/etc.)

- Detail plant description on all major components including MV/HV equipment, monitoring, meteo stations, security and surveillance
- Plant implantation schematic including not only the major components but also auxiliaries (electrical cabinet, substations etc.) and facilities (storage, office, guard house, fences, road access etc.)
- Single wire diagram
- Bill of materials of the major components
- Recommended minimum spare part lists (draft version of this information during EPC negotiation should be updated to the final version when the plant is completed and handed over)
- [Best practice] List of all applicable technical standards for major components (panels, inverters, electrical equipment) (non-exhaustive list)
    - CE Compliance
    - Panel: IEC61215, IEC61730, IEC61701, IEC62716, IEC62804, IEC62108 (CPV)
    - IR/EL: IEC60904-12 & 13
    - Inverter: IEC62109
    - Electrical equipment: IEC61000
    - Tracker: IEC62817, IEC62727
    - Design and installation: IEC TS 62548
    - Commissioning: IEC62446
    - Performance monitoring: IEC61724

☐ 10. Who is responsible for grid connection and the infrastructure to connect the PV plant to the grid (transformer, export lines, substation) is clearly defined

☐ 11. Site suitability (ground installation)

- Geotechnical and soil study
- Any flood risk
- Other constraints (chemical in the air, corrosive air, etc.)

Site suitability (rooftop installation)

- Roof stability study
- Structural requirements of roof and mounting structure (both static/snow load and dynamic/wind load
- Lightning protection requirement
- Fire protection (PV system should not be built across fire protection walls); design should be in compliance with the building fire protection codes
- Requirement for weathering protection (lifetime of roofing film)

☐	12.	If the site study has been done and the results have been shared with the owner and the EPC, the EPC contract should clearly acknowledge that the contractor has reviewed the results of the study and has designed the PV system taking into account the site conditions and constraints
☐	13.	For rooftop system, the roof should be weatherproof throughout operations of PV plant without major overhaul of roof laminate layer
☐	14.	Estimation of plant yield/production should follow best practice guidelines (see Annex C.3)
☐	15.	The plant design and estimated yield/production should be validated by third party
D	**Scope of works – procurement**	
☐	16.	All major components should be visually inspected at delivery
	17.	All modules should be tested for STC performance according to the IEC60904 standards at the factory and the test data should be submitted to the EPC contractor for verification [Best practice] All modules should be inspected with electroluminescence imaging camera at the factory and the test data should be submitted to the EPC contractor for verification
☐	18.	PV modules should be sampled and tested after delivery and before acceptance • List of test (and criteria) should be included in the EPC contract • Tests are to be done by an accredited independent test laboratory
☐	19.	[Best practice] Transportation and handling requirements on components should be specified
☐	20.	[Best practice] EPC contractor is required to perform factory inspection on the module factory
☐	21.	[Best practice] Negotiation of technical requirement in supply agreement (i.e. module) and warranty terms and conditions should involve inputs from technical advisors
E	**Scope of works – construction**	
☐	22.	The EPC should include comprehensive protocol and training to its field workers on how to un-package and handle components properly
☐	23.	The installation of components should adhere the manufacturer's guidelines when applicable
☐	24.	Regular construction monitoring by the owner (assisted by technical advisor) should be performed to check construction progress and quality (and for milestone payments)
☐	25.	Reporting of construction progress should be included in the contract
☐	26.	Health and safety, housekeeping and site security are defined as the responsibilities of the contractor during construction
F	**Scope of works – administrative and others**	
☐	27.	Responsible party for securing the site use is clearly defined: • For ground-mounted utility systems: land lease, land purchase, and land access • For commercial rooftop systems: roof lease, roof access
☐	28.	Responsible party to obtain permits and authorizations to develop PV plant is clearly defined
	29.	Any support required from the EPC contractors in permitting, grid connection etc. should be clearly defined
☐	30.	Is the contractor responsible to carry out or only support warranty and insurance claims management during the EPC period?

G	**Manufacturer warranties**
☐	31. The terms and conditions of major components' manufacturer warranties are clearly defined • Effective start and end date • Definition of defects • Claim procedure • The compensations proposed are reasonable and logical • Exclusions • Provision to allow for the involvement of third party expert during technical dispute • Transferability
☐	32. The warranty timelines should be in line with the EPC warranty timelines
☐	33. Check if the jurisdiction of the warranty allows it to be legally enforceable
☐	34. [Best practice] Are there additional insurances (transportation damages, e.g.) from either the EPC contractor or component manufacturer?
H	**EPC warranty and Defect Liability Period (DLP)**
☐	35. Provide warranty of Good Execution of Works
☐	36. The EPC contract shall provide at minimum 2-year EPC warranty from the date of plant take-over
☐	37. The DLP duration coincides with the EPC and component manufacturer warranty duration
☐	38. During this DLP, the EPC contractor is responsible to repair faults or defect at its own cost, or an arrangement has been made with the O&M contractor to execute this. For the latter, clear scope of work ownerships must be aligned to prevent avoidance of responsibilities
☐	39. The party responsible to maintain the PV plant after take-over and before the end of DLP is clearly defined
I	**Key performance indicators (KPIs) and guarantees**
☐	40. The EPC contract should have key performance indicators for two aspects • Completion timeline: guaranteed completion date • System performance and quality: guaranteed performance ratio (PR) or guaranteed output
☐	41. The guaranteed PR or output should be calculated in a long-term yield estimation exercise using correct technical assumptions, i.e. all relevant losses and uncertainties
☐	42. Liquidated damages (LD) or penalties should be assigned in the contract in case the guaranteed KPIs are not met
☐	43. Completion delay LDs should be in line with the project revenue loss due to lateness in project entering operation. The LD is commonly a % of EPC price for each day of delay
☐	44. Performance LDs should be in line with the project revenue loss when the system is not meeting the guaranteed performance level. The LD is commonly a % of EPC price for each point of PR or output below the guaranteed value
☐	45. Maximum amount of LD (LD cap) to limit contractor's liability is usually included in the EPC contract. E.g., delay LD and performance LD could each be capped at 20% of the EPC contract price and the combined cap is 30% of the EPC contract price

J	Commissioning and acceptance
☐	46. The EPC contract should include plant provisional and final commissioning
☐	47. Short term performance test should be carried out after the PV system completes the construction phase
☐	48. Provisional test set-up should include appropriate: • Duration of the test • Irradiance threshold • Monitoring system, including measurement sampling rate and averaging method
☐	49. The calculation method for the key performance indicator for provisional acceptance should account for short-term effect on temperature and irradiance
☐	50. Final acceptance plant performance should be carried out after the plant has been in operation for a representative period of time (2 years after provisional acceptance)
☐	51. Final performance test set-up should include appropriate • Irradiance threshold • Monitoring system, including measurement sampling rate and averaging method
☐	52. The calculation method for the key performance indicator for final acceptance should account for: • Annual degradation • Plant availability
☐	53. Measurement of irradiance to assess plant performance • Irradiance measurements • Measurement in the POA according to the Secondary Standard or First Class quality classification (ISO9060:1990) • Minimum requirement: one measurement device (pyranometer of high quality) • [Best practice] At least 2 pyranometers • If different array orientations, one pyranometer per orientation – careful assignment for proper calculation of PR and yield • Sensors placed at the least shaded location • Sensors installed according to manufacturer's guidelines • Preventative maintenance and calibration according to manufacturer's guidelines • Set irradiance to be recorded with averages of 15 min (minimum requirement) or 1 min and less (best practice) • High quality satellite-based data to complement terrestrial measurements [best practice] – mainly for monthly and annual values and not daily since the RMSE is high (8-14%) • Minimum requirements for satellite data: hourly granularity or 15 min. Set data to be retrieved once per day at least
☐	54. Measurement of irradiance to assess plant performance • Temperature sensor properly installed according to manufacturer's guidelines

	• Use of stable thermally conductive glue to the middle of the backside of the module in the middle of the array, in the center of the cell away from junction box • Accuracy should be <±1 C including signal conditioning • For large systems, different representative positions for installing the sensor should be considered: module at the center of the array and at the edge of this module where temperature variations are expected
☐	55. Inverter measurement to assess plant performance • AC level: energy and power data should be collected • Energy data should be cumulative values over the lifetime of the inverter • Collect all inverter alarms – important to plan your maintenance activities (corrective and preventative) • Monitor and manage control settings at the inverter level and the grid injection level • DC input measurements <1s sampling and <1min averaging • DC voltage to be measured and stored separately for allowing MPP-tracking and array performance problems • [Best practice] measure all parameter from the inverters including internal temperature, isolation level etc.
☐	56. Energy meter • Collection of energy meter data by the monitoring system in daily basis and with 15 min granularity • High accuracy energy meter is required – uncertainty of ±0.5% for plants >100 kWp • The above point can be considered as best practice for plants smaller than 100 kWp
☐	57. Plant visual inspection should be carried out during acceptance test [Best practice] The visual inspection uses advanced tools such as IR camera
☐	58. As part of the plant hand-over process, the EPC contractor must provide (non-exhaustive list) • A complete set of as-build documentation (IEC62446, see Annex C.4 for complete set) • Recommended minimum spare parts list

C.2. Best Practice Checklist for O&M Technical Aspects

☑/☒	Technical aspect & what to look for in the O&M contract
A	**Definitions, interpretation**
☐	1. Is there a set of definitions of important terms provided and are those clear and understood by all stakeholders?
B	**Purpose and responsibilities**
☐	2. Is the fundamental purpose (goals) of the contract clearly defined?
☐	3. Are the roles and responsibilities (and boundary conditions) of the multiple stakeholders within the contract clear and understood?
C	**Scope of works – environmental, health and safety** Note: The Asset Owner has the ultimate legal and moral responsibility to ensure the health and safety of people in and around the solar plant and for the protection of the environment around it. The practical implementation is normally subcontracted to the O&M contractor.
☐	4. Environment • Regular inspection of transformers and bunds for leaks (according to the annual maintenance plan) • Recycling of broken panels and electric waste • Sensible water usage for module cleaning • Proper environmental management plan in place
☐	5. Health and safety (H&S) • Properly controlled access and supervision in the solar plant – necessary boundaries and site restrictions • Proper induction to ensure awareness of risks and hazards • Proper training and certification on the specifics of a PV plant and voltage level • Hazard identification/marking • Wiring sequence marking • H&S legislation available • Established personal protective equipment (PPE) (not exhaustive list): safety shoes, high visibility clothing, helmet, gloves (and/or insulated gloves), slash masks and glasses (depending on the site), fire retardant and/or arc flash rated PPE where necessary • Calibrated and certified equipment (full documentation available)
D	**Scope of works – operations**

☐	6. Documentation Management System (DSM)
	• As-built documentation / IEC62446 (see Annex C.4)
	    ○ Site information
	    ○ Project drawings
	    ○ Project studies

- Studies according to national regulation requirements
    - PV modules
    - Inverters
    - Medium voltage / inverter cabin
    - MV/LV transformer
    - HV switchgear
    - UPS and batteries
    - Mounting
- Management and control
    - Define type of storage (physical or/and electronical)
    - Ensure electronic copy of all documents
    - Ensure controlled access to documents
    - Ensure authorization for modifications – keep a logbook on name of person who modified the document, date of modification, reason for modification and further information e.g. link to the work orders and service activities
    - Ensure history of the documents (versioning)
- Record control (see Annex C.5)

☐ 7. [Best practice] Predictive maintenance

- Define scope of this cluster, the type of performance analysis, the level (portfolio level, plant level, inverter level, string level)
- Define the monitoring requirements needed to perform predictive maintenance, provide basic trending and comparison functionality

☐ 8. Power generation forecasting

- Ensure a service level agreement with the forecast provider
- Define the purpose and consequently the requirements for power forecasting (e.g. time horizon, time resolution, update frequency)

☐ 9. Reporting (see Annex C.6)

☐ 10. Regulatory compliance

- Grid code compliance: plant controls (e.g. ability for emergency shut-downs or curtailment according to grid regulations)
- PPA compliance
- Building permits (if applicable)
- Environmental permits
- Specific regulation for the site (e.g. vegetation management, disposal of green waste)

☐ 11. Management of change: define responsibilities and involvement when PV plant needs to be adjusted after the Commercial Operation Date: e.g. spare parts, site operation plan, annual maintenance plan etc.

☐ 12. Warranty management

	• Warranty of Good Execution of Works • Warranty of Equipment • Performance Warranty: agree on reporting period • Classification of anomalies and malfunctions: Pending Works, Insufficiencies, Defects, Failure or malfunction of equipment
☐	13. Insurance claims management
E	**Scope of works – maintenance**
☐	14. Inclusion of an adequate Preventive Maintenance Plan
☐	15. The minimum requirements for preventative tasks and their frequency follow the manufacturer's guidelines when applicable
☐	16. The minimum requirements for preventative tasks and their frequency should respect relevant national standards
☐	17. Corrective maintenance (CM) • Fault diagnosis (troubleshooting) • Repair and temporary repairs • Agreed response times and/or minimum repair times • Clear definition of "boarders" and "limitations" of CM tasks, especially with preventative maintenance and extraordinary maintenance. Definition of yearly cap of CM works (when applicable)

☐	18. Extraordinary maintenance
	• Define what is included in this cluster
	  ○ Damages that are a consequence of a Force Majeure event
	  ○ Damages as a consequence of a theft or a fire
	  ○ Serial defects on equipment, occurring suddenly and after months or years from plant start-up
	  ○ Modifications required by regulatory changes
	  ○ Agreed interventions for reconditioning, renewal and technological updating
	• Define the rules on how to execute tasks and prepare quotations – ways of payment

☐	19. Additional services: define what is included in this cluster and how this service is paid (non-exhaustive list) • Module cleaning • Vegetation management • Road maintenance • Snow removal • Pest control • Waste disposal • Maintenance of buildings • Perimeter fencing and repairs

- Maintenance of security equipment
- String measurements – to the extent exceeding the agreed level of preventative maintenance
- Thermal inspections – to the extent exceeding the agreed level of preventative maintenance
- Meter weekly/monthly readings and data entry on fiscal registers or in authority web portals for FiT tariff assessment (where applicable)

F Scope of works – data and monitoring

☐ 20. Irradiance measurements

- Measurement in the POA according to the Secondary Standard or First Class quality classification (ISO9060:1990)
- Minimum requirement: one measurement device (pyranometer of high quality)
- [Best practice] At least 2 pyranometers
- If different array orientations, one pyranometer per orientation – careful assignment for proper calculation of PR and yield
- Sensors placed at the least shaded location
- Sensors installed according to manufacturer's guidelines
- Preventative maintenance and calibration according to manufacturer's guidelines
- Set irradiance to be recorded with averages of 15 min (minimum requirement) or 1 min and less (best practice)
- High quality satellite-based data to complement terrestrial measurements [best practice] – mainly for monthly and annual values and not daily since the RMSE is high (8-14%)
- Minimum requirements for satellite data: hourly granularity or 15 min. Set data to be retrieved once per day at least

☐ 21. Module temperature measurements

- Temperature sensor properly installed according to manufacturer's guidelines
- Use of stable thermally conductive glue to the middle of the backside of the module in the middle of the array, in the center of the cell away from junction box
- Accuracy should be <±1 C including signal conditioning
- For large systems, different representative positions for installing the sensor should be considered: module at the center of the array and at the edge of this module where temperature variations are expected

☐ 22. Local meteorological data

- [Best practice] Ambient temperature and wind speed with sensors installed according to manufacturer's guidelines
- Ambient temp with shielded thermometer e.g. PT100
- Wind speed with anemometer at 10 m height above ground level
- For large plants >10 MW automated data from an independent nearby meteo source to smooth local phenomena and installation specific results

☐ 23. String measurements

	• If not DC input current monitoring at inverter level, then current monitoring at string level is recommended – depending on module technology, combined strings (harnesses) can help reducing operating costs • [Best practice] Increase up-time for timely detection of faults: 1 sec sampling and 1 min averaging at data logger, maximum two strings current measurement in parallel
☐	24. Inverter measurement • AC level: energy and power data should be collected • Energy data should be cumulative values over the lifetime of the inverter • Collect all inverter alarms – important to plan your maintenance activities (corrective and preventative) • Monitor and manage control settings at the inverter level and the grid injection level • DC input measurements <1s sampling and <1min averaging • DC voltage to be measured and stored separately for allowing MPP-tracking and array performance problems • [Best practice] measure all parameter from the inverters including internal temperature, isolation level etc.
☐	25. Configuration • In cases of change of O&M contractor (or recommissioning of the monitoring system), the configuration of the monitoring system and the data loggers should be checked • [Best practice] if technically available, auto-configuration is recommended – e.g. automatic collection of inverter and sensor IDs and labels • Back up of the configuration should be in place
☐	26. Energy meter • Collection of energy meter data by the monitoring system in daily basis and with 15 min granularity • High accuracy energy meter is required – uncertainty of ±0.5% for plants >100 kWp • The above point can be considered as best practice for plants smaller than 100 kWp
☐	27. AC circuit / protection relay • [Best practice] Monitor the AC switch position for (sub) plants. Read the alarms from the protection relay via communication bus if possible
☐	28. Data loggers • Sufficient memory to store at least one month of data • Historical data should be backed up • After communication failure, the data logger should resend all pending information • The entire installation (monitoring system, signal converters, data loggers, measurement devices) should be protected by a UPS • [Best practices] Memory to store at least six months of data and full data backup in the cloud. Separate remote server to monitor the status of the data loggers and inform the operations.

	The system should be an open protocol to allow transition between monitoring platforms. If possible, reboot itself once per day (during night time) to increase reliability

☐	29. Alarms
	• Minimum requirement: alarms sent by email (non-exhaustive list)
	  ○ Loss of communication
	  ○ Plant stop
	  ○ Inverter stop
	  ○ Plant with low performance
	  ○ Inverter with low performance (e.g. due to overheating)
	• [Best practice] (non-exhaustive list)
	  ○ String without current
	  ○ Plant under UPS operation
	  ○ Intrusion detection
	  ○ Fire alarm detection
	  ○ Discretion alarm (or alarm aggregation)

☐	30. Dashboard / web portal
	• Minimum requirements for features of the monitoring system (non-exhaustive list)
	  ○ Web portal accessible 24h/365d
	  ○ Graphs of irradiation, energy production, performance and yield
	  ○ Downloadable tables with all the registered figures
	  ○ Alarms register
	• [Best practices] (non-exhaustive list)
	  ○ User configurable dashboard
	  ○ User configurable alarms
	  ○ User configurable reports
	  ○ Ticket management

☐	31. Data format • Data format of recorded files according to IEC61724 – clearly documented • Data loggers should collect alarms according to manufacturer's format
☐	32. Communication from the site to the monitoring servers • Best network connectivity with sufficient bandwidth according to the available monitoring system • DSL connection preferred if available at the PV site – industrial routers recommended • [Best practice] GPRS-connection as back up • For sites >1 MW it is advised to have a LAN connection and as an alternative an industrial router that allows for GPRS or satellite communication back-up in case the LAN connection fails. A router with an auto-reset capability in case of loss of internet connection is recommended

	• Data security should be ensured: as minimum requirements loggers should not be accessible directly from the internet or at least be protected via a firewall. Secure and restrictive connection to the data server is also important • Communication cables must be shielded and protected by direct sunlight • Physical distance between DC or AC power cables and communication cables should be ensured • Cables with different polarities must be clearly distinguishable (label or color) for avoiding polarity connection errors
G	**Scope of works – spare parts management**
☐	33. Definition of ownership and responsibility of insurance
☐	34. Define separate list of consumables if applicable (e.g. tools and fuses)
☐	35. Stocking level: consider initial EPC list and the following parameters • Frequency of failure • Impact of failure • Cost of spare part • Degradation over time • Possibility of consignment stock with the manufacturer
☐	36. Location of storage/warehouse • Proximity to the plant • Security • Environmental conditions
☐	37. List of minimum spare parts (non-exhaustive list) • Fuses for all equipment (e.g. inverter, combiner boxes etc.) and fuse kits • Modules • Inverter spares (e.g. power stacks, circuit breakers, contactor, switches, controller board) • UPS • Voltage terminations • Power plant control spares • Transformer and switchgear spares • Weather station sensors • Motors and gearboxes for trackers • Harnesses and cables • Screws and other supply tools • Security equipment (e.g. cameras)
H	**Scope of works – plant security**
☐	38. Define protective measures for the plant • Security protocol in place

	• Video monitoring • Alerting system • Fencing or barriers • Warning signs and notices • Security pad codes and passwords • Back up communication in case of vandalism
I	**Key performance indicators (KPIs)**
☐	39. Plant KPIs • Availability • Energy-based availability • Performance Ratio • Energy Performance Index
☐	40. O&M contractor KPIs • Reaction time • Reporting • O&M contractor experience • Maintenance effectiveness and maintenance support efficiency
☐	41. Security and surveillance of PV plant • On-site or remote • Around the clock coverage (24h/365d) • On-site patrol, security camera • On-site intervention time upon alarm etc.
J	**Contractual commitments**
☐	42. Qualification of parties involved: Owner's Engineer, O&M contractor, monitoring, security firm
☐	43. Responsibility and accountability
☐	44. Bonus schemes and liquidated damages

C.3. Best Practice Checklist for Long-Term Yield Assessment

☑/☒		Technical aspect & what to look for in the LTYA
A		**Solar resource assessment**
☐	1.	Only reliable solar irradiation data sources should be used and the name(s) and version(s) must be clearly stated. Data source(s) used must be able to provide uncertainty estimations and ideally have been extensively validated
☐	2.	The period covered by the solar irradiation data source(s) used must be reported. Only data sources with more than 10-year recent data should be used for LTYA calculations
	3.	The effect of long-term trends in the solar resource should be analyzed. In the presence of such trends, the long-term solar resource estimation should be adjusted to account for this effect
☐	4.	The use of site adaptation techniques is recommended to reduce the uncertainty. A measurement campaign of at least 8 months and ideally one full year is recommended
B		**PV yield modeling**
☐	5.	The PV modeling software and the specific version used must be clearly stated in the report
☐	6.	If in-house software is used, the name(s) and version(s) must also be stated
☐	7.	All assumptions (e.g. soiling losses, availability, etc.) and sub-models used (e.g. transposition model) must be clearly stated
C		**Degradation rate and behavior**
☐	8.	The degradation rate(s) used for the calculations must be clearly stated in the report. It is recommended to differentiate between first year effects and yearly behavior over project lifetime
☐	9.	Degradation behavior assumption (e.g. linear, stepwise, etc.) over time should be clearly stated and ideally backed up with manufacturer warranties
☐	10.	If specific manufacturer warranties are available (e.g. module warranty document or sales agreement), these can be used to fine tune the lifetime degradation calculation
D		**Uncertainty calculation**
☐	11.	All steps in the long-term yield calculation are subject to uncertainties. All uncertainties should be clearly stated and references must be provided in the report
☐	12.	Special attention must be paid to the solar resource related uncertainties as these are among the most important elements in the contribution to the overall uncertainty
☐	13.	If special methods are used to reduce some uncertainties e.g. site adaptation techniques, these should be clearly documented and ideally backed up with scientific validation
☐	14.	Special care must be taken when classifying each uncertainty as either systematic or variable (stochastic) since these are treated differently in overall lifetime uncertainty calculations
☐	15.	When possible, exceedance probabilities (e.g. P90) for each uncertainty must be calculated using empirical methods based on available data instead of assuming normal distribution for all elements

C.4. Checklist for As-Build Documents – Type and Details

Information type and depth of detail / as-built documents		
No.	**Minimum Requirements**	**Description**
1	Site information	• Location / map / GPS Coordinates • Plant access / keys • Access roads • O&M building • Spare parts storage / warehouse • Site security information • Rooftop condition and load requirements / restrictions (rooftop system only) • Stakeholder list and contact information (for example, owner of the site, administration contacts, firefighters, sub-contractors / service providers, ...)
2	Project drawings	• Plant layout and general arrangement • Cable routing drawings • Cable list • Cable schedule/ cable interconnection document • Single line diagram • Configuration of strings (string numbers, in order to identify where the strings are in relation to each connection box and inverter) • Earthing / grounding system layout drawing • Lightning protection system layout drawing (optional) • Lighting system layout drawing (optional) • Topographic drawing • Grid access point schematic
3	Project studies	• Shading study / simulation • Energy yield study / simulation • Inverter sizing study
4	Studies according to national regulation requirements	• Voltage drop calculations • Protection coordination study • Short circuit study • Grounding study • Cable sizing calculations • Lightning protection study
5	PV modules	• Datasheets • Flash list with PV modules positioning on the field (reference to string numbers and positioning in the string) • Warranties and certificates
6	Inverters	• O&M manual • Commissioning report • Warranties and certificates • Factory Acceptance Test • Inverter settings

		• Dimensional drawings
7	Medium Voltage / Inverter Cabin	• Medium Voltage / inverter cabin layout and general arrangement drawing • Medium Voltage / inverter cabin foundation drawing • Erection procedure • Internal normal / emergency lighting layout drawing • Fire detection and firefighting system layout drawing (if required) • HVAC system layout drawing • HVAC system installation and O&M manual • HVAC study (according to national regulations) • Earthing system layout drawing • Cable list
8	MV/LV transformer	• O&M manual • Commissioning report • Factory Acceptance Test report • Type Test reports • Routine Test reports • Warranties and certificates • Dimensional drawing with parts list
9	Cables	• Datasheets • Type and Routine test reports
10	LV & MV switchgear	• Single line diagram • Switchgear wiring diagrams • Equipment datasheets and manuals • Factory Acceptance Test report • Type Test reports • Routine Test reports • Dimensional drawings • Warranties and certificates • Protection relays settings (only for MV switchgear) • Switching procedure (according to national regulations) (only for MV switchgear)
11	HV switchgear	• Single line diagram • Steel structures assembly drawings • HV switchyard general arrangement drawing • HV equipment datasheets and manuals (CTs, VTs, circuit breakers, disconnectors, surge arresters, post insulators) • Protection and metering single line diagram • HV equipment type and routine test reports • Interlock study • Switching procedure (according to national regulations) • Warranties and certificates
12	UPS and batteries	• Installation and O&M manual • Commissioning report • Warranties and certificates

		• Datasheets • Dimensional drawings
13	Mounting structure	• Mechanical assembly drawings • Warranties and certificates • Structural design calculation (rooftop systems only)
14	Trackers	• Mechanical assembly drawings • Electrical schematic diagrams • Block diagram • Equipment certificates, manuals and datasheets (motors, encoders) • PLC list of inputs and outputs (I/O) by type (digital, analog or bus) • Commissioning reports • Warranties and certificates
15	Security, anti-intrusion and alarm system	• Security system layout / general arrangement drawing • Security system block diagram • Alarm system schematic diagram • Equipment manuals and datasheets • Access to security credentials (e.g. passwords, instructions, keys etc.) • Warranties and certificates • Service level agreement with security company (if applicable)
16	Monitoring / SCADA system	• Installation and O&M manual • List of inputs by type (digital, analog or bus); I/O list includes e.g. sensor readings that are collected by data loggers • Electrical schematic diagram • Block diagram (including network addresses) • Equipment datasheets
17	Plant controls	• Power plant control system description • Control room (if applicable) • Plant controls instructions • Breaker control functionality (remote / on-site) and instructions • List of inputs and outputs
18	Communication system	• Installation and O&M manual • System internal communication • External communication to monitoring system or operations center • IP network plan • Bus network plans

C.5. Checklist for Record Control

Record control			
No.	**Activity Type**	**Information Type**	**Input Record**
1	Alarms / operation incidents	Alarms description	Date and time, affected power, equipment code / name, error messages / codes, severity classification, curtailment period, external visits / inspections from third parties
2	Contract management	Contract general description	Project name / code, client name, peak power (kWp)
3	Contract management	Asset description	Structure type, installation type
4	Contract management	Contract period	Contract start and end date
5	Contract management	Contractual clauses	Contract value, availability (%), PR (%), materials / spare parts, corrective work labor
6	Corrective maintenance	Activity description	Detailed failure typification, failure, fault status, problem resolution description, problem cause (*)
7	Corrective maintenance	Corrective maintenance event	Associated alarms (with date), event status (*)
8	Corrective maintenance	Corrective maintenance event log	Date and time of corrective maintenance creation (or work order), date and time status change (pending, open, recovered, close), end date and time of the intervention, start date and time of the intervention, technicians and responsible names and function (*)
9	Corrective maintenance	Intervention equipment / element name	Affected power and affected production, equipment code / name
10	Inventory management	Warehouse management	Inventory stock count and movement, equipment code / name
11	Monitoring and supervision	Equipment status	Date, status log (protection devices, inverters, monitoring systems, surveillance systems)
12	Monitoring and supervision	Meteo data	Irradiation, module temperature, other meteo variables (ambient temperature, air humidity, wind velocity and direction, …) (**)
13	Monitoring and supervision	Production / consumption data	AC active and reactive power at PV plant injection point and other subsystems or equipment, consumption from auxiliary systems, other variables (DC/AC voltages and currents, frequency), power from DC field (**)
14	Monitoring and supervision	Performance data	PV plant energy production; PR; expected vs real
15	Preventative maintenance	Intervention equipment / element name	Affected power and affected production, equipment code / name, intervention start and end date
16	Preventative maintenance	Maintenance description	Measurements, preventative maintenance tasks performed, problems not solved during activity and its

			classification and typification, technicians and responsible names and function
17	PV plant documentation	Commissioning	Commissioning documentation and tests results (***)
18	PV plant documentation	Operation and maintenance	Equipment manuals, PV plant O&M manual (***)
19	PV plant documentation	System documentation	As built documentation (datasheets, wiring diagrams, system data) (***)
20	Warranty management	Claims registration	Affected equipment, claim description, occurrence date, communications between O&M, client and manufacturer/supplier
21	Security management	Alarm intervention	Alarms log, type of alarm, time of occurrence, counter measures

(*) EN 13306 - Maintenance. Maintenance terminology

(**) IEC 61724 - Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis

(***) IEC 62446 - Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection

C.6. Checklist for Reporting Indicators

Reporting Indicators				
No.	**Proposed Indicator**	**Predicted**	**Measured**	**Estimated**
1	Insolation	●	●	
2	Active energy produced	●	●	✓
3	Active energy consumed		✓	
4	Reactive energy produced		✓	
5	Reactive energy consumed		✓	
6	Peak power achieved		✓	
7	Performance Ratio	●	●	✓
8	Energy Performance Index			✓
9	Balance of system efficiency			✓
10	Plant external energy losses			✓
11	Plant internal energy losses			✓
12	Energy-based availability			✓
13	Time-based availability			✓
14	Inverter specific energy losses			✓
15	Inverter specific efficiency			✓
16	Module soiling losses		✓	
17	Module degradation			✓

Note: ● Minimum Requirement, ✓ Best Practice www.solarbankability.eu

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