Fachhochschule Rosenheim
Rosenheim University of Applied Sciences
Department of Electrical Engineering and Information Technology

Master Thesis

Evaluation of PV system failures and their impact on the profitability of the plant

A thesis presented

by

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Matriculation no. 840768

FH Rosenheim Master of Engineering in Electrical Engineering and Information Technology

May 2016

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For the department of Electrical Engineering and Information Technology (EEIT) in

Fachhochschule Rosenheim

Date of thesis allocation:	01.12.2015
Submission deadline:	01.06.2016

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Keywords: PV failures, Inverters, Cost priority number, Mitigation measures, Solar Bankability, Risk Assessment,

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Acknowledgments

This thesis has been part of my studies in Fachschule Rosenheim for my master in Electrical Engineering and Information Technology and conducted at TÜV Rheinland Energy GmbH. I would like to thank my colleagues and professors that without their help in every aspect, this thesis would have been possible…

…Dr. Bogdanski for the trust and his help during all these months and the interesting thesis topic that he proposed me

…Prof. Mike Zehner and Prof.Martin Neumaier for the support and advices throughout the last six months

…Florian Reil because without him this thesis would not have been possible

…Magnus Herz for the amazing daily teamwork for my master thesis and solar bankability project

…Ulrike Jahn for letting me to participate in such a great project as solar bankability

…all my colleagues in TÜV Rheinland

…last but not least my family for the support and my girlfriend Eirini for her patience during this stressful period for me

Disclaimer

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Abstract

The risk of an investment in the PV industry is already high due to the characteristics of the materials, failures occurred during the planning and installation phase and the great uncertainty regarding legislation. This paper identifies the most detected failures, after the on-site inspection, in PV plants and develops a mathematical model in order to quantify the financial impact of the failures on the profitability of the PV plant.

A detailed description and a photographic demonstration of the failures recorded after inspection is given. The cause roots of the failures have been identified and commented. The mathematical model has been developed taking into consideration as many as possible parameters of the PV plants in order to calculate the Cost Priority Number of each risk. A comparison of the model stated in this report and the model of Solar Bankability project have been described.

Furthermore, mitigation measures for the distinguished failures/risks have been proposed as well as their positive impact in reducing the uncertainty concerning the profitability of the PV plants. The mitigations measures have been divided in two groups, preventive and corrective actions. Graphs representing the CPN value of each failure before and after the mitigation measures are shown. Finally, a proposal of a combination of measures is given and its impact on the overall CPN value of the plant is given.

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3 INTRODUCTION

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. PV project investments have been and still are 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. [1]

3.1 Photovoltaics today

In 2015, the PV market broke several records and continued its global expansion, with a 25% growth at 50 GW. After a limited development in 2014, the market restarted its growth, almost everywhere, with all regions of the world contributing to PV development for the first time. Africa, the Middle East, Latin America, South and Southeast Asia saw new markets popping up. [2]

In the Middle East, Turkey installed 208 MW for the very first time, while Israel remained the very first country in terms of cumulative installed capacity with 200 additional MW installed. In Europe, after years of market decline, the market grew thanks mainly to the growth of the UK market that established itself as the first one in Europe for the second year in a row with 3.5 GW in 2015. Germany experienced another market decline to 1.46 GW. France stabilized its market close to 0.9 GW. Some medium-size European markets continued to progress, such as the Netherlands or stabilized such as Switzerland or Austria, while others experienced a new growth at a lower level (Belgium, Denmark, Spain). New smaller markets emerged, such as Poland, Hungary and Sweden, but the level of installations remains below the 100 MW mark. Former GW markets continued to experience a complete shutdown, with between nothing and a few MW installed: Czech Republic, Greece, Romania and Bulgaria, for instance

In Africa, South Africa became the first African country to install close to 1 GW of PV in 2014 but the market declined significantly in 2015 to around 200 MW before a restart. Algeria installed close to 270 MW. Many countries have announced projects, with Egypt leading the pace (5 GW have been announced) but so far, most installations have been delayed or simply are still in the project evaluation phase. In North America, the US market continued to grow, and reached 7.3 GW in 2015. Canada (600 MW) and, to a lesser extent, Mexico (103 MW) are also progressing. Chile has installed close to 450 MW, together with Honduras (389 MW), but also Guatemala and Uruguay are below the 100 MW mark.

All of these developments raised the global PV market for the first time to 50 GW, a significant increase from 2014 numbers where around 40 GW were connected to the grid. With a positive outcome in all regions of the world, PV has now reached 1 GW of regional penetration on all continents, and much more on the leading ones. However the year 2015 was a year of records, and the global installed capacity that reached 50 GW is only one of them. 23 countries have passed the GW mark and the 200 GW mark has been crossed in 2015, with 227.1 GW producing electricity at the end of the year. Another record broken is the highest capacity installed in one single country: China has beaten the all-time record holder, Germany and, now leads the pace with as much as 43.6 GW compared to 39.7 GW in the European country.

While Europe represented a major part of all installations globally, Asia's share started to grow rapidly in 2012 and this growth was confirmed in recent years. Now Europe represents around 42% of the total installed capacity and this percentage shall continue decreasing in the coming years. Asia represents the same level as Europe with 42% and the Americas 13%, while the 3% remaining cover the MEA region. Figure 1 shows the relative share of cumulated PV installations in four regional market segments.

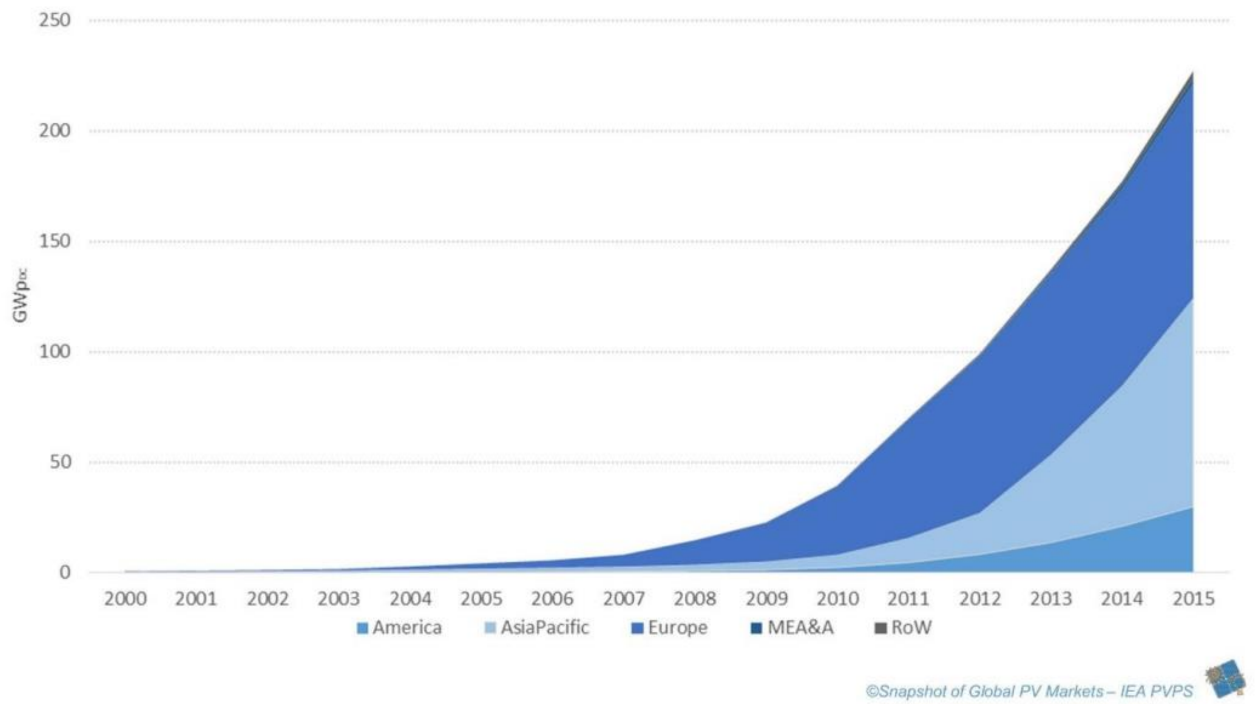


Figure 1 evolution of regional PV installations

3.2 Highlights of 2015

- The global PV market grew significantly, to at least 48.1 GW in 2015. With non-reporting countries, this number could grow up to 50 GW, compared to 40 GW in 2014. This represents a 25% growth year-on-year.

- Asia ranks in first place for the third year in a row with around 60% of the global PV mark.
- China reached 15,3 GW in 2015, and is now the leader in terms of cumulative capacity with 43,6 GW
- The US market increased again to 7.3 GW, with large-scale and third-party ownership dominating.
- India progressed significantly to around 2 GW and Pakistan installed an estimated 600 MW.
- The largest European market in 2015 was UK with 3.51 GW, followed by Germany (1.46 GW) and a stable French market (0.87 GW).
- Italy, Greece and Germany now have enough PV capacity to produce respectively 8%, 7.4% and 7.1% of their annual electricity demand with PV.
- PV represents at least 3.5% of the electricity demand in Europe and 7% of the peak electricity demand.
- PV represents around 1.3% of the global electricity demand. [2]

3.3 Necessity of reliable PV industry

Taking into consideration the growth of PV industry demonstrated in Figure 1 the need for reliable PV industry is more than important. The reliability of the PV industry it is not essential only to draw the attention of new investors but also to maintain the already installed power capacity of modules.

Additionally, another main fact that needs to be mentioned is that the rate of the new installed PV plants has fallen dramatically during the last years in Europe. For instance Germany, the biggest market in Europe, in 2012 installed more than 7 GW but in 2015 less than 1.5 GW as it is shown in the Figure 2. This tremendous drop is not due to the reliability of the PV Plants but mainly due to recent laws and policies applied for the PV market. However, in order to make PV industry attractive again to investors the focus should lie to what can be done or achieved from technical point of view as well. Thus, one significant parameter is the fineness of the PV installations and quality of PV components which is going to result to maximum energy production from the PV plants.

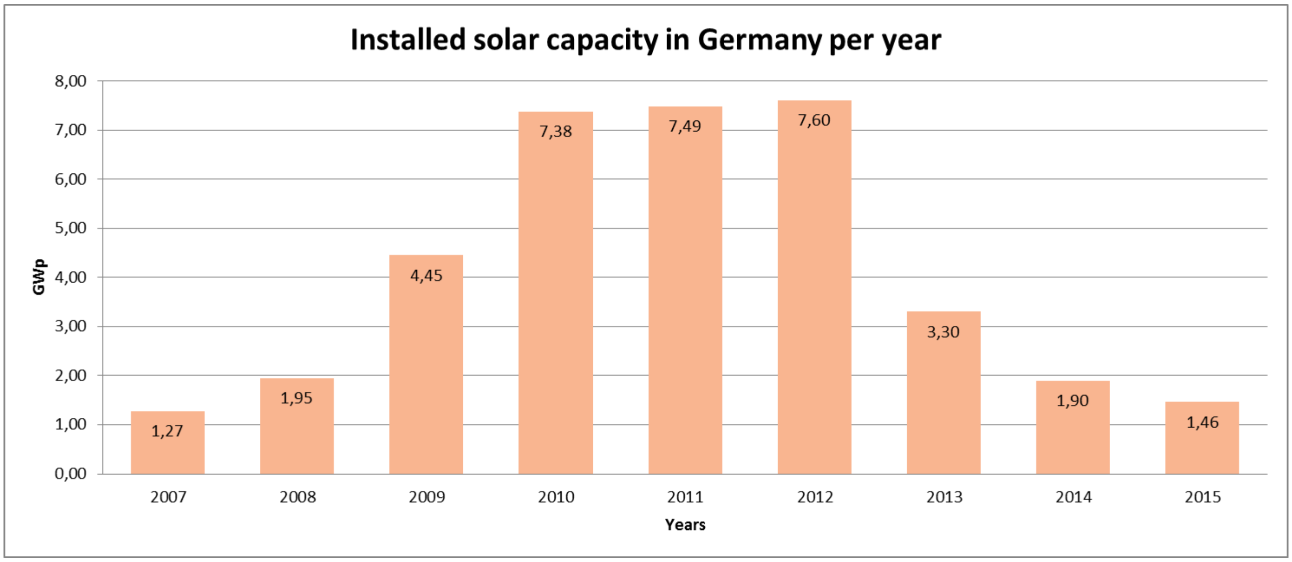


Figure 2 nominal installed PV power (GWp) per year during the last 12 years in Germany[1]

3.4 Aim of the thesis

Historical performance data for PV systems on which to base technical risks assessments and investment decisions are difficult to be accessed by all market players, such as investors, PV plant owners, EPC contractors, etc. Reasons for this difficulty are that most PV systems have been operational for only a few years and a tendency among system operators and component manufacturers to keep available performance data as confidential. In addition, performance data are in most cases not available for PV plants with low nominal power (e.g. residential-commercial market segments up to 250 kWp) as the cost of monitoring is still perceived as an added cost. Finally, although description of failure and corrective measures is common practice in the field of operation and maintenance, this is not often carried out with the sufficient level of details to derive meaningful statistical analysis due to missing cost information and lack of a common approach in the assignment of failures to a specific category. For the PV industry to reach mature market level, a better understanding of technical risks, risk management practices and the related economic impact is thus essential to ensure investors' confidence.

The thesis aims to establish a common practice for professional risk assessment, which will serve to reduce the risks associated with investments in PV projects. One objective is to improve the current understanding of several key aspects of risk management during the project lifecycle. From the identification of technical risks and their economic impact, to the process of mitigating those risks. To achieve this, a statistical data of failures has been built upon existing studies with the aim to

- suggest a guideline for the categorization of failures

[1] https://www.energy-charts.de/power_inst.htm

- ➢ develop a methodology for the assessment of the economic impact of failures occurring during operation but which might have originated in previous phases

The methodology is based on statistical analysis and can be applied to a single PV plant or to a large portfolio of PV plants. The quality of the analysis depends on the amount of failure data available and on the assumptions taken for the calculation of a Cost Priority Number (CPN), which is an indicator that will be explained later on this thesis. The methodology described in this thesis can only be applied to the failures with a direct economic impact to the business plan either in terms of the reduced income due to downtime or the costs for repair or substitution.

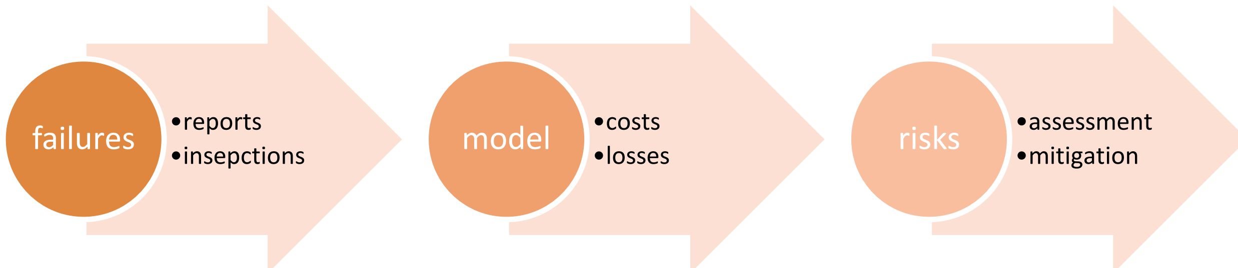


Figure 3 aim of the thesis

4 DESCRIPTION OF RISKS IN PV PLANTS

In this chapter an introduction to risks that have been studied are presented. Specifically the most essential failures, for each component, according to the detected frequency are considered. An analysis of the cause roots and a photographic demonstration for different examples for each type of failure are given. The impact of the failures and their mitigation measures are discussed in Chapter 6 and Chapter 7 respectively.

4.1 Definition of risk and uncertainty

According to ISO 31000, risk is the "effect of uncertainty on objectives" and an effect is a positive or negative deviation from what is expected. This definition recognizes that all of us operate in an uncertain world. Whenever we try to achieve an objective, there's always the chance that things may not go according to plan. Every step has an element of risk that needs to be managed and every outcome is uncertain. Whenever we try to achieve an objective, we don't always get the results we expect. Sometimes we get positive results and sometimes we get negative results and occasionally we get both. Because of this, we need to reduce uncertainty as much as possible.

Uncertainty (or lack of certainty) is a state or condition that involves a deficiency of information and leads to inadequate or incomplete knowledge or understanding. In the context of risk management, uncertainty exists whenever the knowledge or understanding of an event, consequence, or likelihood is inadequate or incomplete. [3]

4.2 Definition of a failure

A component failure is an effect that degrades the efficiency of the component which is not reversed by normal operation or creates a safety issue. A purely cosmetic issue which does not have these consequences is not considered as a component failure. A component failure is relevant for the warranty when it occurs under conditions the component normally experiences.

4.3 Example of failures

Five selected sample components and the corresponding failure will be described in detail. Such a method aims to show the process of weighing risks as developed in the Solar Bankability project. The complete list of the failures can be found in Appendix A where each failure is defined. An agreed definition of failures is in fact beneficial for the industry as it should lead to a commonality in terminology and an improved failure data collection.

- Module – Delamination failure
- Inverter – Overheating failure
- Mounting structure – Module clamps incorrectly installed

- Cabling – Different types of connectors
- Connection and distribution boxes – Missing protection against electric shock

The selection of the failures is according to their frequency of detection and their impact in the PV plant. The failure description is divided into five sections:

First section: Brief and detailed description of the failure
In this section we provide a clear definition of the failure so that it can be used regardless of the expertise of the user. The objective is for this failure list to be an important step towards a standardized nomenclature for defects to a certain extent.

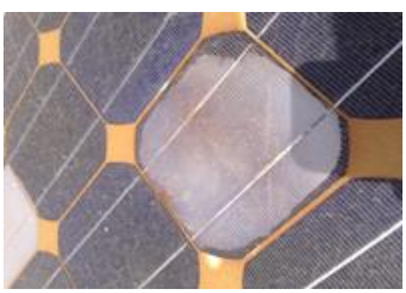
Second section: Root cause related to the PV plant phase
This section lists the different root causes which could lead to the failure and thus must be considered in the failure evaluation. For e.g. module glass breakage could be due to defective glass or mishandling of module during transportation or installation.

Third Section: Detection methods
Each failure is detected by different techniques and equipment. Incorrect detection methods or mistakes in the failure detecting process could result in longer time for the failure to be identified and rectified and thus most effective (time and cost) detection method should be always preferred.

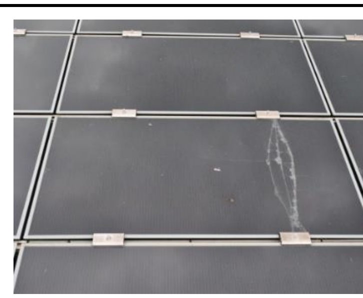
Forth section. Cost Priority Number (CPN)
For every risk a CPN is assigned for the assessment of the failure. The CPN was developed as part of the project and is described in detail in Chapter 5. This parameter is important for the evaluation of the risk with regards to its economic impact. The CPN given in the following tables is for base scenario given in Chapter 6.

Fifth section: Action
Taking into consideration all the previous points, this section is a proposal of the recommended actions after the detection and evaluation of the failures.

Component	**Module**			
Defect	**Delamination**			
Brief description	Delamination results due to the loss of adhesion and it is bright, milky area that stand out in color from the remaining cells.			
Detailed description	The adhesion between the glass, encapsulant, active layers and back layers can be compromised for many reasons. Delamination is more frequent and severe in hot and humid climates. Typically, if the adhesion is compromised because of contamination (e.g. improper cleaning of the glass) or environmental factors, delamination will occur, followed by moisture ingress and corrosion. Delamination at interfaces within the optical path will result in optical reflection and subsequent loss of current power from the modules. Delamination on cells led to decrease in Isc			
References	Review of Failures of Photovoltaic Modules, IEA - International Energy Agency. Study of Delamination in acceleration tested PV modules – Neelkanth G., Mandar B.			
Normative References	IEC 61215	IEC 61730	IEC 61446	
Causes	Installation: Mishandling	Product defects: Material defect	Maintenance: Environmental influence & Degradation	
Detection	Visual inspection			
CPN [€/kWp]	Time to detect (t_{td})	Time to repair/substitution ($t_{tr,ts}$)	Repair/substitution time (t_{fix})	Power loss (PL)
	8760 [h]	744 [h]	2 [h]	1 [%]
	Average cost of detection per component (C_{det})	Average substitution cost per component (C_{subs})	Average repair cost per component (C_{repair})	Average transport costs per component (C_{tran})
	0 [€]	108 [€]	0 [€]	10 [€]
Action	Modules with large delamination must be replaced.			

		
Delamination	Delamination	Browning and delamination of a module

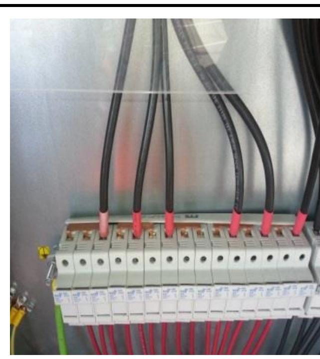
Component	**Inverter**			
Defect	**Overheating**			
Brief description	During temperature derating, the inverter reduces its power to protect components from overheating.			
Detailed description	Temperature derating protects sensitive inverter components from overheating. When the monitored components reach the maximum operating temperature, the device shifts it operating point to a lower power. During this process, power is reduced step-by-step. In the extreme case, the inverter switches off completely. As soon as the temperature of the threatened components falls below the critical value, the inverter returns to the optimal operating point. Temperature derating can occur for various reasons, e.g. when installation conditions interfere with the inverter's heat dissipation.			
References	UEN103910			
Normative References	IEC 62116	DIN VDE 0126	EN50530	
Causes	Installation: Improper installation	Product defects: Fan failure	Maintenance: Fan or dust is blocking heat dissipation	
Detection	Visual Inspection, Inverter Monitoring, Data logger			
CPN [€/kWp]	Time to detect (t_{td})	Time to repair/substitution ($t_{tr,ts}$)	Repair/substitution time (t_{fix})	Power loss (PL)
	8760 [h]	744 [h]	4 [h]	20 [%]
	Average cost of detection per component (C_{det})	Average substitution cost per component (C_{subs})	Average repair cost per component (C_{repair})	Average transport costs per component (C_{tran})
	0 [€]	0 [€]	377 [€]	10 [€]
Action	The filters and in general heat dissipation path should be clear.			
				
Soiled air filter	Soiled air filter	Ventilation failure		

Component	**Mounting structure**			
Defect	**Module clamp not fixed correctly**			
Brief description	Inadequate fixation or damage of the module or framework by the clamp.			
Detailed description	The most common mistake, regarding module clamps, is their improper installation that can lead to the damage of the module and sometimes to its dismounting. In addition the installation of wrong clamps can cause similar problems such as damage of the frame, glass breakage etc. The installation manuals of the module and mounting manufacturer must be carefully considered to avoid such failures.			
References	Module and mounting structure installation manuals			
Normative References	EN 1999-9	EN62446	EN 1090-3	
Causes	Installation: Improper installation	Product defects: Wrong combination of clamps - modules	Maintenance: Corrosion	
Detection	Visual inspection			
CPN [€/kWp]	Time to detect (t_{td})	Time to repair/substitution ($t_{tr,ts}$)	Repair/substitution time (t_{fix})	Power loss
	8760 [h]	744 [h]	48 [h]	0 [%]
	Average cost of detection per component (C_{det})	Average substitution cost per component (C_{subs})	Average repair cost per component (C_{repair})	Average transport costs per component (C_{tran})
	0 [€]	0 [€]	0 [€]	0 [€]
Action	All module clamps must be replaced.			
				
Improper installation	Wrong combination of clamps and modules	Damaged PV module due to improper clamping		

Component	**Cabling**			
Defect	**Different types of connectors**			
Brief description	Different interconnectors are combined. Problems of compatibility of materials as well as corrosion may occur during the lifetime of the PV plant.			
Detailed description	The practice of connecting different types of connectors is a significant blunder, with dire consequences e.g. burnt connectors, arcing. One of the most common failures is that no electricity at all will pass through the connection. However, this is not typically the case and the problems instead do not manifest themselves right away. Usually the cross-mated pair of connectors will connect together and pass electricity without any noticeable problems or losses. But the misalignment of connectors and material scheme over time can lead to losses or connection failure.			
References	Declaration TÜV Rheinland, G. Volberg			
Normative References	EN 62548	EN62446		
Causes	Installation: Different types	Product defects: Insulation	Corrosion: Maintenance	
CPN [€/kWp]	Time to detect (t_{td})	Time to repair/substitution ($t_{tr,ts}$)	Repair/substitution time (t_{fix})	Power loss (PL)
	8760 [h]	744 [h]	0,5 [h]	0 [%]
	Average cost of detection per component (C_{det})	Average substitution cost per component (C_{subs})	Average repair cost per component (C_{repair})	Average transport costs per component (C_{tran})
	0 [€]	1,5 [€]	0 [€]	1 [€]
Detection	Visual inspection			
Action	If compatibility assurance cannot be given, connectors should be changed.			

		
Wrong combination of connectors	Wrong combination of connectors	Wrong combination of connectors

Component	**Connection and distribution boxes**			
Defect	**Missing protection against electric shock**			
Brief description	The protection against electric shock is detached or missing.			
Detailed description	The Distribution & Connection boxes in order to provide effective protection against direct contact hazards must possess a degree of protection according to the standards. Moreover all the removable parts of the equipment (door, front panel, etc.) must only be detached or open by means of a key or tool provided for this purpose, after complete isolation or disconnection of the live parts in the enclosure. The metal enclosure and all metal removable screens must be connected to the protective earthing conductor of the installation.			
References	Schneider Electric			
Normative References	IEC61140	IEC60364-4-41	IEC62548	
Causes	Installation: Wrong planning or incomplete installation	Product defects: Material failure	Maintenance: Corrosion	
Detection	Visual inspection			
CPN [€/kWp]	Time to detect (t_{td})	Time to repair/substitution ($t_{tr,ts}$)	Repair/substitution time (t_{fix})	Power loss (PL)
	8760 [h]	744 [h]	1 [h]	0 [%]
	Average cost of detection per component (C_{det})	Average substitution cost per component (C_{subs})	Average repair cost per component (C_{repair})	Average transport costs per component (C_{tran})
	0 [€]	10 [€]	0 [€]	2 [€]
Action	The protection against electric shock must be intact for each terminal.			

		
Missing protection	Live parts are exposed	Live parts are exposed

5 MATHEMATICAL MODEL

The aim of risk analysis is to assess the economic impact of technical risks and how this can influence various business models and the LCOE (Levelized Cost Of Electricity). In this a cost-based FMEA (Failure Mode and Effect Analysis) is developed by introducing a Cost Priority Number (CPN) which would include cost consideration directly in the risk assessment. To do so, it is important to understand what the needs are from the LCOE and from the business model analysis point of view. A CPNs ranking could prioritize risks which have a higher economic impact.

For the analysis of the technical risks, one of the biggest challenges is to obtain reliable detailed statistics for each component based on the likelihood of failures over the lifetime of the PV plant. For some components such as inverters, the data may be more readily available due to the PV plant monitoring practice. For other components, the failure statistics may be not readily available, or such data may not exist altogether.

Keeping these challenges in mind, I have relied on data from TÜV Rheinland to perform the CPN exercise. This input data is statistically significant and based on a large evidence base. As a first step, the data has been analyzed, organized, and consolidated. A list of different failures associated with the selected PV components along with the different PV plant phases has been established in Table 1.

Table 1 the failure list of the modules along the different PV plant phases

Components / Project Phase	Product testing	PV plant planning / development	Installation / Transportation	Operation / Maintenance	Decommissioning
Modules	Insulation	Glass breakage	Module misshandling (Glass/cell breakage, defective backsheet)	Hotspot	Higher costs of different module technology
	Incorrect cell soldering	Soiling	Soiling	Delamination	Capacity to recycle module
	Failure on mechanical load	Shadow diagram	Breakage during transport and installation	Glass breakage	No product recycling procedure defined
	Cell mismatch	Modules mismatch	Modules fixing system	Soiling	
	Cell overlap	Modules not certified	Module frame damage	Shading	
	Bubbles	Flash report not available or incorrect	Module plug connectors substituted	Snail track	
	Undersized bypass diode	Modules weight	Incorrect connection of modules	Cell cracks	
	Junction box adhesion	Mechanical resistence	Short circuit or defect at modules	Defective backsheet	
	Delamination at the edges	No protection against back current	Scratches at front glass	Overheating junction box	
	Snail trails	Different types of modules	Special climatic conditions not considered (salt corrosion, ammonia, ...)	PID = Potential Induced degradation	
	Arcing spots on the module	Lack of experience in the field	Bad wiring without fixation	Failure bypass diode and junction box	
	Visually detectable hot spots	Special climatic conditions not considered (salt corrosion, ammonia, ...)		Corrosion in the junction box	
	Defective type label solar module	Incorrect assumptions of module degradation, Light induced degradation unclear		EVA discoloration	
	Module label inexplicit	Module quality unclear (lamination, soldering) (s. 22 Phase I)		Theft of modules	
	Junction box broken	Simulation parameters (low irradiance, temperature....) unclear, missing Pan files		Broken module	
	Solar cell broken			Slow reaction time for warranty claims, Vague or inappropriate definition of procedure for warranty claims	
	Potential induced degradation			Special climatic conditions not considered (salt corrosion, ammonia, hail, ...)	
	Manufacturer´s insolvency			Unfortunate sorting of module power	
	Lack of manufacturer´s experience in the field			Damage by snow	
	Incorrect assessment of module degradation			Corrosion of cell connectors	
	Incorrect power rating (flash test issue)			Unsufficient theft protection	
	Uncertified components or production line			Broken modules due to atmospheric agents (wind, hail, snow, etc)	
				Improperly installed	
				Module damaged due to fire	
				Missing modules	

5.1 Description of the statistical data

The statistical data derived from the technical reports after the inspection of the 112 PV plants in the last 4 years is shown in Table 5. The overall solar capacity of the inspected PV plants is more than 435 MWp and the average age of the installation is 4.17 years. For every PV plant the recorded information is shown in Table 2.

Table 2 necessary information for PV the plant recorded on-site and included in the database

Plant characteristics	Electrical characteristics
1. Site location	1. Nominal power of the PV plant
2. Yield	2. Module nominal power
3. Installation date	3. Number of modules per string
4. Type	4. Number of strings per table/tracker
a. Roof	5. Nominal power of inverters
b. Fixed	6. Nominal power of inverter
c. Tracker	
5. Inspection date	

The characteristics of the plant shown in Table 2 are necessary for assessment of the CPN value. For the plants where the information was inadequate, the quantity and variety of components have been calculated using the method shown in Table 3.

Table 3 parameters used for the model and calculation approach

Parameter	Formula
Overall yield	= (yield) * (the nominal power of the PV plant)
Years of operation	= (inspection date) – (the installation date)
Number of modules	= (nominal power of the PV plant) / (the nominal power of the module)
Number of strings	= (number of modules) / (the number of modules per string)
Number of inverters	= (nominal power of the PV plant) / (the nominal power of the inverter)

Number of combiner boxes	If the number of the combiner boxes is not available the following short algorithm has been developed according to case studies.
	if (nominal power of inverter) <40 kWp **then**
	(number of combiner boxes) = (number of inverters)
	elseif (nominal power of inverter) <140 kWp **then**
	(number of combiner boxes) = 3 * (the number of inverters)
	elseif (nominal power of inverter) <700 kWp **then**
	(number of combiner boxes) = 6 * (the number of inverters)
	else
	(number of combiner boxes) = 10 * (the number of inverters)

Number of trackers /tables	= (number of strings) / (number of modules per string)
Number of cables	= (number of strings) * 2

After the recording or calculation of the components in a PV plant the next step was the creation of statistical data of failures. In the Table 4 an example of how the statistical data have been recorded can be seen.

Table 4 example of recorded failures for the CPN model

COMPONENTS	RISK MATRIX FAILURE	ROOT CAUSE OF FAILURE (PROJECT PHASE)	SEVERITY	NUMBER OF CASES	PERCENTAGE OF COMPONE	N° OF CASES nfail
Mounting_Structures	Not proper installation	PV_plant_planning_development	Basic	Sporadic_1	1,00%	4
Modules	Defective backsheet	Operation_Maintenance	Severe	Sporadic_1	1,00%	214
Modules	Improperly installed	Installation_Transportation	Basic	General	100,00%	21343
Mounting_Structures	Corrosion of module clamps	Operation_Maintenance	Basic	Sporadic_1	1,00%	4
Modules	Hotspot	Product_development	Major	Numerous	10,00%	2135
Modules	Overheating junction box	Operation_Maintenance	Major	Sporadic_1	1,00%	214
Cabling	Conduit failure	Operation_Maintenance	Basic	General	100,00%	2664
Cabling	Broken cable ties	Operation_Maintenance	Basic	Numerous	10,00%	267
Cabling	improper installation	Installation_Transportation	Basic	Sporadic_1	1,00%	27
Cabling	Wrong wiring	Installation_Transportation	Basic	General	100,00%	2664
Cabling	Wrong wiring	Installation_Transportation	Basic	Numerous	10,00%	267
Connection_Distribution_Boxes	Broken, missing or corroded cover	Operation_Maintenance	Major	Sporadic_1	1,00%	2
Connection_Distribution_Boxes	Missing protection	PV_plant_planning_development	Basic	General	100,00%	146

5.2 Overview of the statistical data

An overview of the total amount of analyzed plants, components and detected failures is given in Table 5. In total 1,155,536 failure cases were included in the analysis of 112 PV plants including 2,183,841components. The database contains data of around 435 MWp of PV plants nominal power. An important characteristic of the data collected is, the average number of years of operation. In this case it is more than 4 years which is important since empirically the older the PV plant the more the detected failures.

Table 5 overview of the statistical data derived from the TÜV Rheinland inspection reports

Segment	Total number of plants	Total Power [kWp]	Average number of years
TOTAL	112	435.852,97	4,17
Components	**No. tickets**	**No. Cases**	**No. Components**
Modules	325	758246	1890289
Inverters	86	2224	9741
Mounting structures	198	15521	44751
Connection & Distribution boxes	189	12309	12175
Cabling	499	367443	226412
Transformer station & MV/HV	49	188	473
Total	1346	1155931	2183841

5.3 Description of CPN method

For the calculation of the economic impact of the PV plant technical risks, which are likely to occur during the implementation phase, namely during the plant operation and maintenance, the Occurrence and Severity were calculated in a dedicated table. The table was designed to allow generalization and flexibility in order to maximize the use of the methodology. Moreover, this approach does not constrain the analysis carried out in this thesis. The following parameters were considered:

- PV plant type (ground or roof-mounted)
- Specific yield (to account for latitude/geographic dependent analysis)
- Costs due to downtime (loss of feed-in tariffs, loss of electricity valorization, cost of reduced energy savings)
- Costs due to fixing the failure (cost of detection, cost of repair or substitution, cost of transport, labor cost)

The economic impact of a specific failure can be split into three categories:

Firstly, the economic impact due to downtime and/or power loss ($C_{down,f}$) and depends on:

- Failures might cause downtime or % in power loss (PL)
- Time to detect the failure (t_{td})
- Failures at component level which might affect other components (e.g. module failure might bring down the whole string.

Secondly, the economic impact due to repair of the failure ($C_{down,r}$) includes:

- Failures might cause downtime or % in power loss (PL)
- Time to repair or substitute and time to fix the failure ($t_{tr,ts}$ t_{fix})
- Failures at component level which might affect other components (e.g. module failure might bring down the whole string

Finally, the economic impact due to substitution costs (C_{fix}) includes:

- Cost of detection to account for various techniques (C_{det} IR for hotspots, EL for crack cells, visual inspection, monitoring systems, etc.)
- Cost of transportation of component (C_{transp})
- Cost of labor (C_{lab})
- Time to fix the failure (t_{fix})
- Cost of repair (C_{rep})
- Cost of substitution (C_{sub})

5.4 Overall cost due to failure losses

The overall costs due to failure losses are calculated considering the time to detection, (t_{td}), PL the performance loss due to the failure expressed in fraction (therefore PL =1 for failures causing total downtime), M is a multiplier to consider failures that cause problems at higher component level (e.g. 1 module takes down the whole array).

The steps that lead to the downtime costs ($C_{down,f}$) are the following:

$$t_{down,fail} = t_{td} \cdot PL \cdot M \quad (1)$$

- calculation of total downtime ($t_{down,f}$) for n number of failures (hours) normalized by the number of years

$$t_{down,f} = t_{down,fail} \cdot n_{fail}/n_{years} \tag{2}$$

- calculation of total downtime ($t_{df,comp}$) normalized by components (hours/component)

$$t_{df,comp} = t_{down,f}/n_{comp} \tag{3}$$

- calculation of occurrence over a time (t_{ref}) (%)

$$O_f = t_{df,comp}/t_{ref} \tag{4}$$

(t_{ref}) is the equivalent hours (specific yield) i.e., the total number of hours per year. Maximum impact is achieved when we consider that the downtime due to failure when the plant is working at the nominal power.

- calculation of energy losses, L, due to downtime (kWh)

$$L_f = O_f \times Ener_{expec} \tag{5}$$

The energy expected ($Ener_{expec}$) is calculated as the total plant(s) production over one year in absence of failures.

- calculation energy expected ($Ener_{expec}$) over one year (kWh)

$$Ener_{expec} = P_{nom} * y \tag{6}$$

The nominal power of the plant (P_{nom}) and (y) is the specific yield

- calculation of downtime costs

$$C_{down,f} = L \times FIT \tag{7}$$

Where FIT is the Feed in Tariff (€/kWh)

Combining the Equations (1), (2), (3), (4), (5), (6), (7) and dividing by the nominal power of the PV plant (P_{nom}) we obtain Equation 8.

$$C_{down,f} = \frac{t_{td} * PL * M * n_{fail} * FIT * P_{nom} * y}{P_{nom} * n_{years} * t_{ref} * n_{comp}} \ (€/kWp/a) \tag{8}$$

Table 6 overview of the parameters used for the calculation of the cost due to losses

Parameters that derived from the database	Parameter calculated or assumptions
$\boldsymbol{n_{fail}}$: number of failures $\boldsymbol{P_{nom}}$: nominal power of the PV plant (kWp) $\boldsymbol{n_{years}}$: number of years $\boldsymbol{y}$: specific yield (kWh/kWp) $\boldsymbol{n_{comp}}$: number of components $\boldsymbol{FIT}$: feed in tariff (€/kWh)	t_{td} : time to detect (hours) PL : performance loss due to the failure % t_{ref}: 8760 (hours)

5.5 Cost due to reparation downtime

The concept of the calculation of the losses during reparation time ($C_{down,r}$) is similar to the calculation of calculation of the losses due to the failure ($C_{down,f}$) but instead of the parameter time to detect (t_{td}), the time to repair or substitute ($t_{tr,ts}$) and the time to fix the failure (t_{fix}) are required. The losses during reparation are important especially for failures such as failures for inverters that the time to detect the failure is short but the time to repair is long due to lack of inverters, or spare parts etc. Time to fix (t_{fix}) is the time that is needed for the engineer on-site to fix the failure which has a great influence when the number of failures is high.

The steps that lead to the downtime costs ($C_{down,r}$) are the following:

$$t_{down,repair} = (t_{tr,ts} + t_{fix}) \cdot PL \cdot M \tag{9}$$

- calculation of total downtime during reparation ($t_{down,r}$) for the n number of failures (hours) normalized by the number of years

$$t_{down,r} = t_{down,repair} \cdot n_{fail}/n_{years} \tag{10}$$

- calculation of total downtime during reparation ($t_{dr,comp}$) normalized by components (hours/component)

$$t_{dr,comp} = t_{down,r}/n_{comp} \tag{11}$$

- calculation of occurrence over a time (t_{ref}) (%)

$$O_r = t_{dr,comp}/t_{ref} \tag{12}$$

(t_{ref}) is the equivalent hours (specific yield) i.e., the total number of hours per year. Maximum impact is achieved when we consider that the downtime due to failure when the plant is working at the nominal power

- calculation of energy losses, L, due to reparation down time (kWh)

$$L_r = O_r \times Ener_{expec} \tag{13}$$

The energy expected ($Ener_{expec}$) is calculated as the total plant(s) production over one year in absence of failures.

- calculation energy expected ($Ener_{expec}$) over one year (kWh)

$$Ener_{expec} = P_{nom} * y \tag{14}$$

The nominal power of the plant (P_{nom}) and (y) is the specific yield

- calculation of downtime costs

$$C_{down,r} = L \times FIT \tag{15}$$

Combining the Equations (8), (9), (10), (11), (12), (13), (14), (15) and dividing by the nominal power of the PV plant (P_{nom}) we obtain Equation (16).

$$C_{down,r} = \frac{(t_{tr,ts} + t_{fix}) * PL * M * n_{fail} * FIT * P_{nom} * y}{P_{nom} * n_{years} * t_{ref} * n_{comp}} \ (€/kWp/a) \tag{16}$$

Table 7 overview of the parameters used for the calculation of the cost due to reparation time

Parameters that derived from the database	Parameter calculated or assumptions
$\boldsymbol{n_{fail}}$: number of failures $\boldsymbol{P_{nom}}$: nominal power of the PV plant (kWp) $\boldsymbol{n_{years}}$: number of years $\boldsymbol{y}$: specific yield (kWh/kWp) $\boldsymbol{n_{comp}}$: number of components $\boldsymbol{FIT}$:feed in tariff (€/kWh)	$t_{tr,ts}$: time to repair or substitute (hours) t_{fix} : time to fix (hours) PL : performance loss due to the failure % t_{ref} : 8760 (hours) M : multiplier

5.6 Cost due to substitution of the components

The costs related to fixing the failure results from the sum of the costs of repair/substitution, the costs of detection, the costs of staff, the costs of transport, and the cost of labor.

- calculation of labor cost

$$C_{labor} = \frac{t_{fix} * C_{lab} * n_{fail}}{P_{nom} * n_{years}} \ (€/kWp/a) \tag{17}$$

- calculation of detection, substitution and transportation cost

$$C_{sub} = \frac{\left(C_{det} + C_{rep} + C_{sub} + C_{transp}\right) * n_{fail}}{P_{nom} * n_{years}} \ (€/kWp/a) \tag{18}$$

The total cost to fix (C_{fix}) the failure is the sum of the labor (C_{labor}) and substitution (C_{sub}) cost

$$C_{fix} = \frac{\left(C_{det} + C_{rep} + C_{sub} + C_{transp}\right) * n_{fail} + t_{fix} * C_{lab} * n_{fail}}{P_{nom} * n_{years}} \ (€/kWp/a) \tag{19}$$

Table 8 overview of the parameters used for the calculation of the cost to fix

Parameters that derived from the database	**Parameter calculated or assumptions**
$\boldsymbol{n_{fail}}$: number of failures $\boldsymbol{P_{nom}}$: nominal power of the PV plant (kWp) $\boldsymbol{n_{years}}$: number of years $\boldsymbol{C_{lab}}$: Labor cost (€) $\boldsymbol{C_{det}}$: Cost to detect the risk $\boldsymbol{C_{rep}}$: Cost to repair the component (€) $\boldsymbol{C_{sub}}$: Cost to substitute the component (€) $\boldsymbol{C_{transp}}$: Transportation cost (€)	t_{fix} : time to fix (hours)

5.7 Cost Priority Number

The Cost Priority Number (CPN) will be generated for all the failures and will take into consideration $C_{down,f}$ that is calculated in the Formula (8), $C_{down,r}$ which derives by Formula (16) and C_{fix} calculated by Equation (19). This way, the segregation of risks with high failure losses will be highlighted and on the other hand risks with high repair cost are derived as well. This method makes the assessment of the risks more accurate and more efficient concerning the mitigation steps.

$$CPN_{plant,f} = C_{down,f} + C_{down,r} + C_{fix} \ (€/kWp/a) \tag{20}$$

Where:

$CPN_{plant,f}$: The CPN value for one plant and one specific failure

The calculated CPN in Equation (20) is for one type of failure in one PV plant and the value is quite high since it has already occurred.

It is important to have an average CPN value that will demonstrate the risk of the error in general considering all the cases whether influenced or not. In order to have that, first the calculated CPNs need to be weighted by a factor related to the nominal power of the PV plant and the average nominal power of all PV plants. Hence, small capacity PV plants will not influence the final CPN value as much as big scale PV plants.

$$P_{aver} = \frac{\sum_{1}^{n_{plants}} P_{nom}}{n_{plants}} \ (kWp) \tag{21}$$

Where:

P_{aver} : The average power of all PV plants in the database

n_{plants} : Number of plants in the database

$$CPN_{plantw,f} = CPN_{plant,f} * \frac{P_{nom}}{P_{aver}} \ (€/kWp/a) \qquad (22)$$

Where:
$CPN_{plantw,f}$: The weighted CPN value of a failure for one specific PV plant

Since the weighted CPN value for each failure for each plant has been calculated in order to have a better overview of the magnitude of the general CPN value, it is of great interest to calculate the average value the weighted CPNs.

$$CPN_{w,f} = \frac{\sum_{1}^{n_{cases,f}} CPN_{plantw,f}}{n_{cases,f}} \ (€/kWp/a) \qquad (23)$$

Where:
$CPN_{w,f}$: The average CPN value of a risk for all influenced PV plants
$n_{cases,f}$: Number of cases with a specific failure

The value computed in the Equation (23) is important since it demonstrates the impact of a risk in the profitability of the PV plant when a specific failure has been detected. According to $CPN_{w,f}$ PV administrators will be able to assess the risk and decide which mitigation measure to apply. However, another important parameter it is to know the CPN value for each risk regardless the detection of the failure. Then the occurrence ($O_{plants,f}$) of the failure needs to be considered in order to have a value derived from all PV plants influenced or not.

$$O_{plants,f} = n_{plants,f}/n_{plants} \ (\%) \qquad (24)$$

Where:
$n_{plants,f}$: The number of plants that the specific error has been detected
n_{plants}: Total number of plants

Consequently the

$$CPN_{totalw,f} = CPN_{w,f} * O_{plants,f} \ (€/kWp/a) \qquad (25)$$

Where:
$CPN_{totalw,f}$: The CPN value for a risk for all PV plants

5.8 Comparison between the approaches in this thesis and solar bankability report

The main difference with the approach of the Solar Bankability project is that the approach in this thesis is project oriented instead of failure-rate oriented which is in solar bankability approach. In the Table 9 some the parameters and their differences can be seen

Table 9 differences between approach in the solar bankability and in this report

Parameters	failure - rate oriented	project oriented
n_{fail}	Total number of specific failures recorded for all PV plants. e.g. detected hotspots failures in all PV plants	Total number of specific failures recorded for one PV plant. e.g. detected hotspots failures in one PV plants
n_{years}	Average number of years of operation of all the PV plants	Years of operation of the specific PV plant
y	Average specific yield of all the PV plants	Specific yield of the PV plant
n_{comp}	Total number of a specific component for all PV plants e.g. Total number of inverters	Total number of specific component for a specific plant
FIT	0.25 €/kWh	According to the PV plant
C_{lab}	Constant e.g. Germany 100 €/hour	According to the country

The advantage of this approach is that it is more accurate since it is project oriented. On the other hand, the disadvantage is that most of the times not all the information is available and assumed values must be used. In the Figure 4 the differences between the two CPN values is it shown regarding PV modules.

To conclude, if the necessary information of the plant is available then the proposed approach in this master thesis is more accurate. Additionally, the PV plants can be categorized into groups according to the country of origin. This method can neglect the availability of information such as labor cost and specific energy yield.

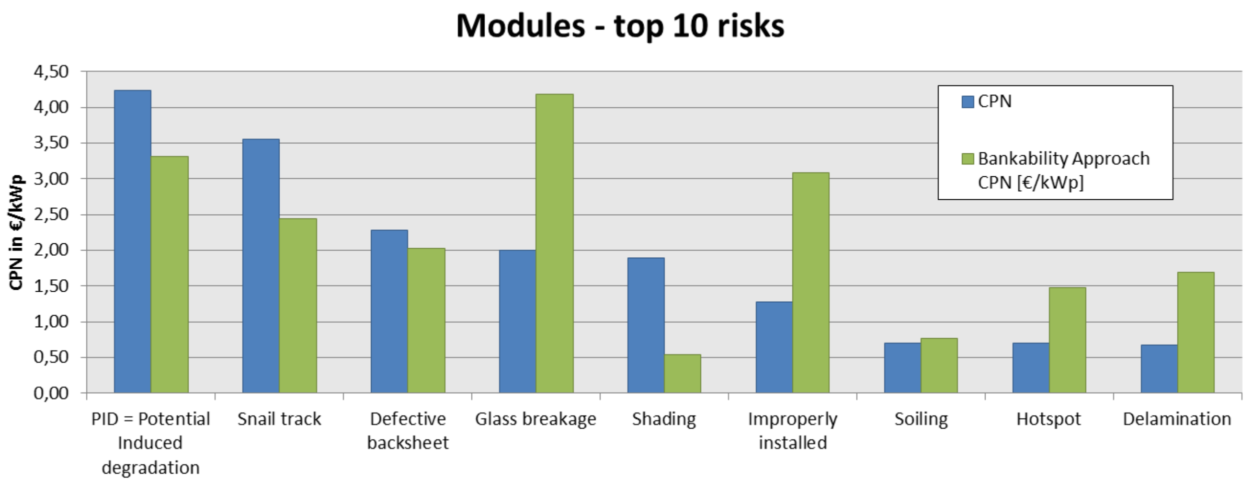


Figure 4 comparison of solar bankability approach for PV modules failures

The differences between the two methods can be generated from the difference in the labor cost or specific yield that is not considered in the bankability approach. Concerning cabling risks shown in Figure 5 for both approaches, the trend line of the risks is similar can be concluded. In addition, both approaches have the same risk ranking.

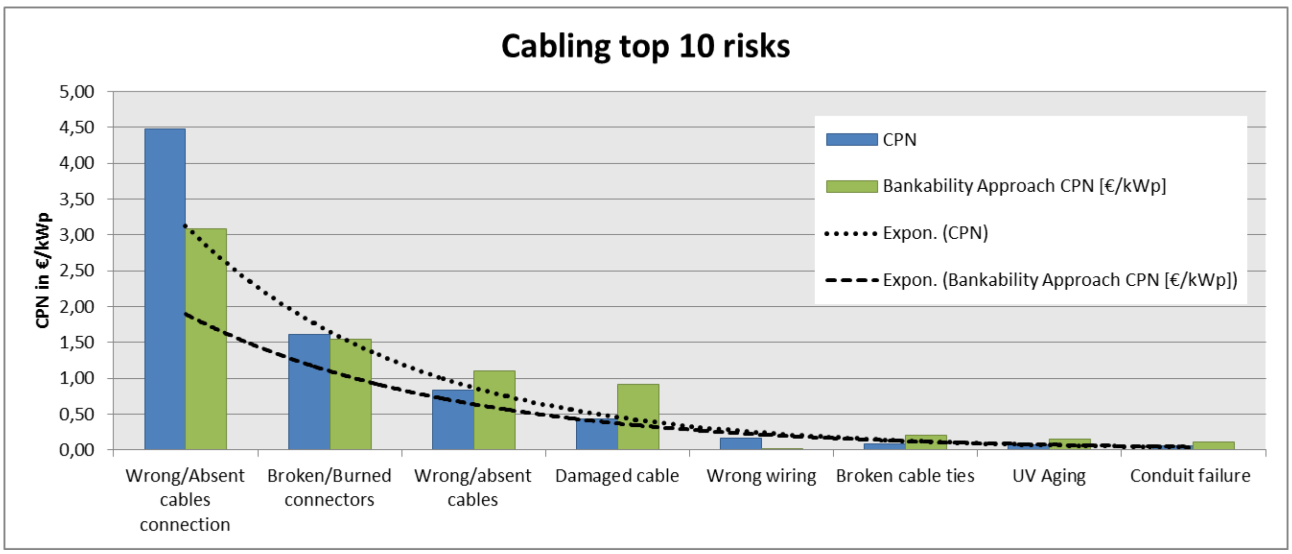


Figure 5 comparison of solar bankability approach for cabling risks

6 RESULTS OF THE MODEL

In this chapter the results from the approach described in the Chapter 5 are given. Moreover some of the results in the Solar Bankability approach are commented as well. Furthermore, results for different segments of PV plants regarding PV modules are considered, however these outcomes have been derived from the solar bankability report since the data for the commercial or residential segments are not allowed to be used for this thesis.

The following components will be discussed:

- Modules
- Inverters
- Cabling
- Combiner boxes

For each component the occurrence of each failure is mentioned, the weighted CPN value for the influenced plants is given as well as the final CPN for the risks for all PV plants. The analysis is based on the described CPN method in Chapter 5. The parameters such as downtime cost, fixing cost and reparation cost for each failure can be found in Appendix A. Therefore, all developed results are strongly depending on the database and the defined conditions and assumptions.

6.1 Definition of costs

In order to apply the CPN methodology the values of the parameters described in Chapter 5 must be defined. In the Appendix A the assumption used for this model can be seen. These values were derived from standard market costs and serve for the base scenario as input. If a certain project with known cost figures shall be analyzed, these values can be adjusted accordingly. For the base scenario the following conditions are taken into consideration:

- No monitoring system installed
- No O&M contract or on-site inspection
- No surveillance
- No spare parts stored

6.2 Analysis of risks detected on the PV modules

The most critical components in a PV plant are the modules since the cost to substitute all of them is almost equal to the cost of the entire PV project. Thus, risks related to the PV modules must be seriously taken into account. The most important risks regarding PV modules are examined and analyzed. Furthermore results from solar bankability are also included.
In Figure 6 the ranking of the most essential risks according to CPN value is shown.

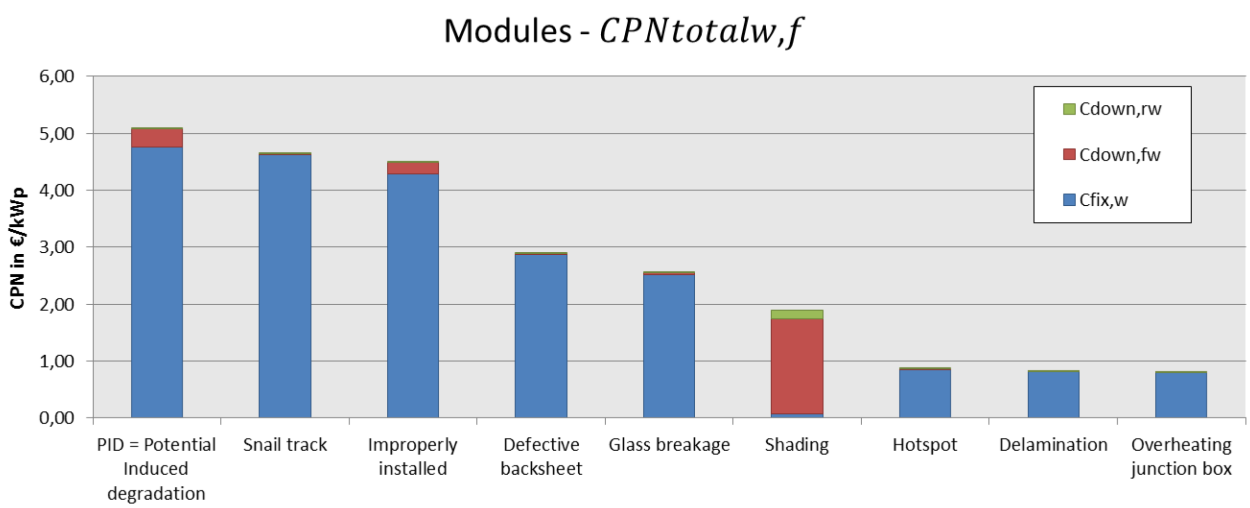


Figure 6 CPNtotalw,f diagram for the PV modules risks

According to Figure 6 the risks can be split into two groups of failures

- ➢ One group of failures that have a great influence in the production like shading and soiling and the repair cost is too low compare to the losses. In such cases the risk should be repaired as soon as possible.
- ➢ The other group includes risks that do not greatly influence the production and the cost to repair is really high. This is because PV modules cannot be repaired and only replaced.

The evaluation of this type of risks is not easy since the development of the failure is unclear and the future years of the operation should also be considered. In the Figure 7 the CPN for worst case scenario regarding losses and for the period of three years is shown. In this scenario the time to detect and reference time parameters are considered for three years. In addition the assumptions that have been used for the Performance losses after three years are shown Appendix B.

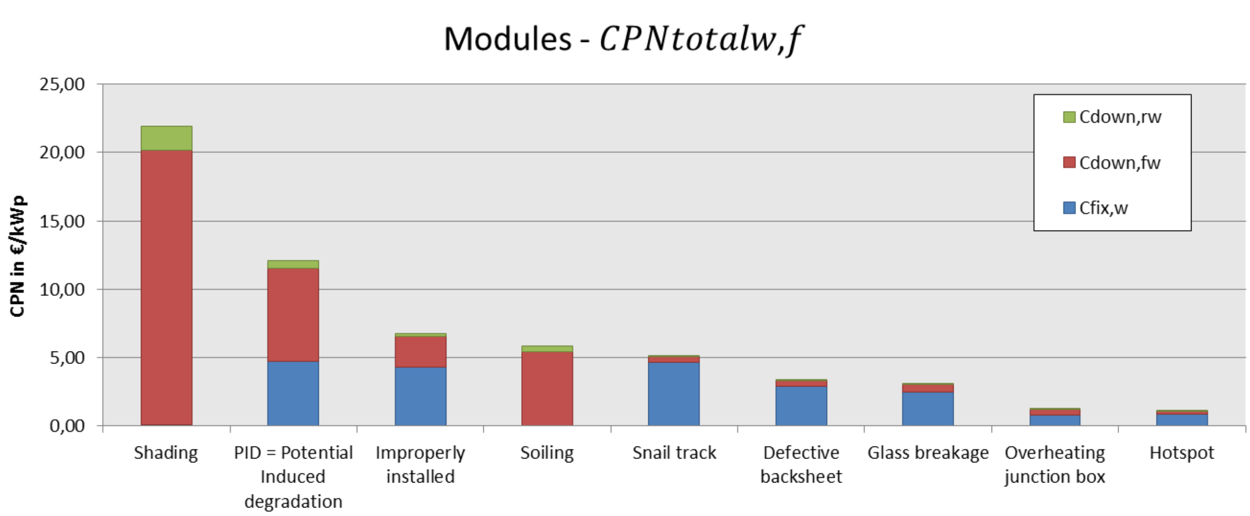


Figure 7 CPNtotalw,f diagram for the PV modules risks with worst case losses and 3 years of duration

Comparing Figure 6 and Figure 7, it can be concluded that failures during the first year do not have such a great influence and no correction action can be a possible approach. However, only after two years of no correction actions the failures have been considerably developed and the repair or substitution of the components is mandatory according to the profitability of the PV plant.

Furthermore, the occurrence ($O_{plants,f}$) of the failures is important in order to be evaluated. In the Figure 8 it is demonstrated the likelihood of a plant to have one of the followings risks according to the given database.

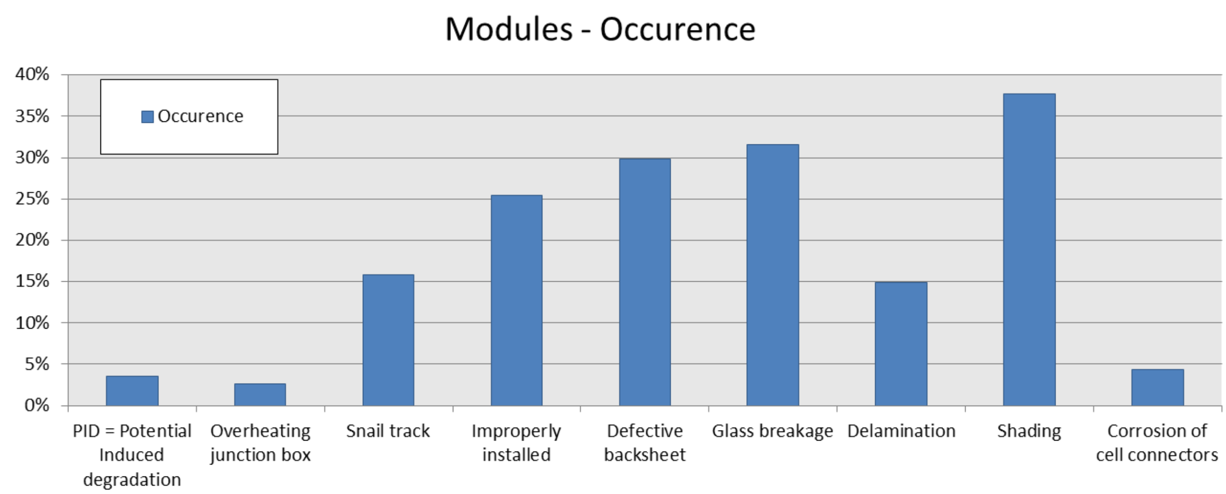


Figure 8 occurrence of failures in the PV plants concerning PV modules

Additionally, what is of the utmost importance is the impact of the failures on the profitability of the PV plants that these failures have been occurred and detected. For such case the average CPN value of the risk for the influenced plants ($CPN_{plantw,f}$) has been calculated and is shown in the Figure 9. The CPN values are significant for cases that the risk has been detected on the PV plant and measures must be taken. The CPN values of the failures in Figure 9 have derived without taking into consideration the occurrence ($O_{plants,f}$).

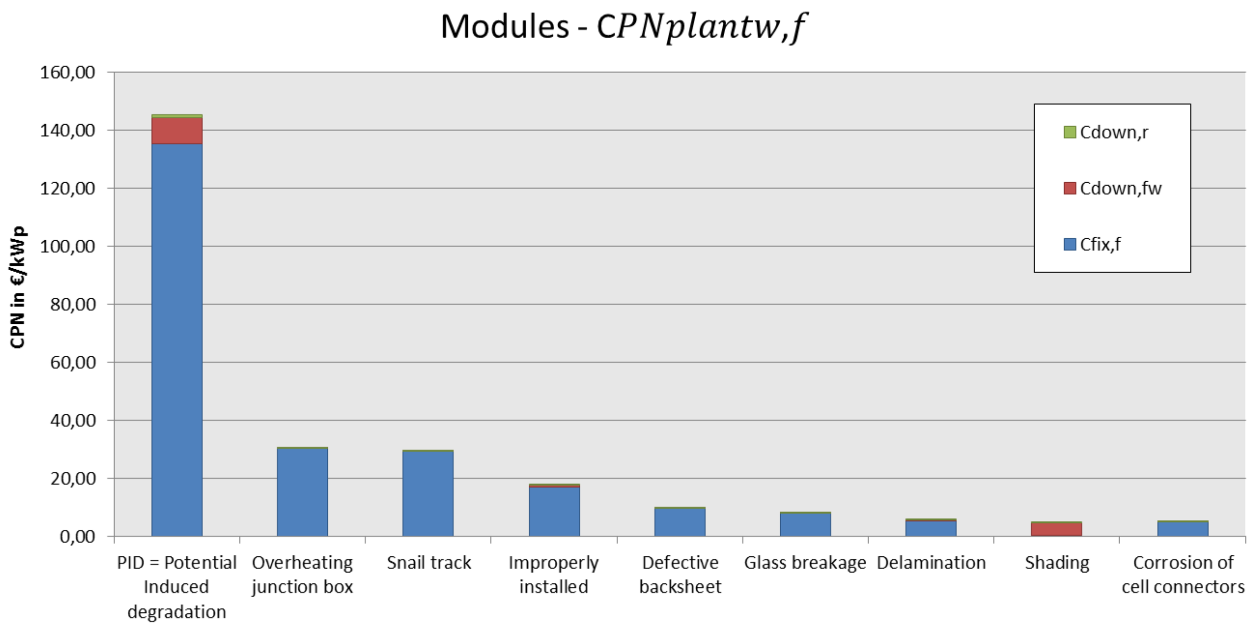


Figure 9 CPNplantw,f diagram for the PV modules risks only for the influenced PV plants

As it is shown in the Figure 9 and Figure 6 the deviation of CPN vales of influenced PV plants and all PV plants is great. This fact demonstrates how important it is for the owner of the PV plant to acknowledge the risks existing in his PV plant.

Finally, concerning the commercial and residential segments only the failures detected by visual inspection have been recorded according to solar bankability report. Additionally, the results shown in Figure 10 can be interpreted as the majority of the residential PV installations have never been inspected and the risk of these investments is really high because of the uncertainty resulting from the lack of knowledge of the existing risks.

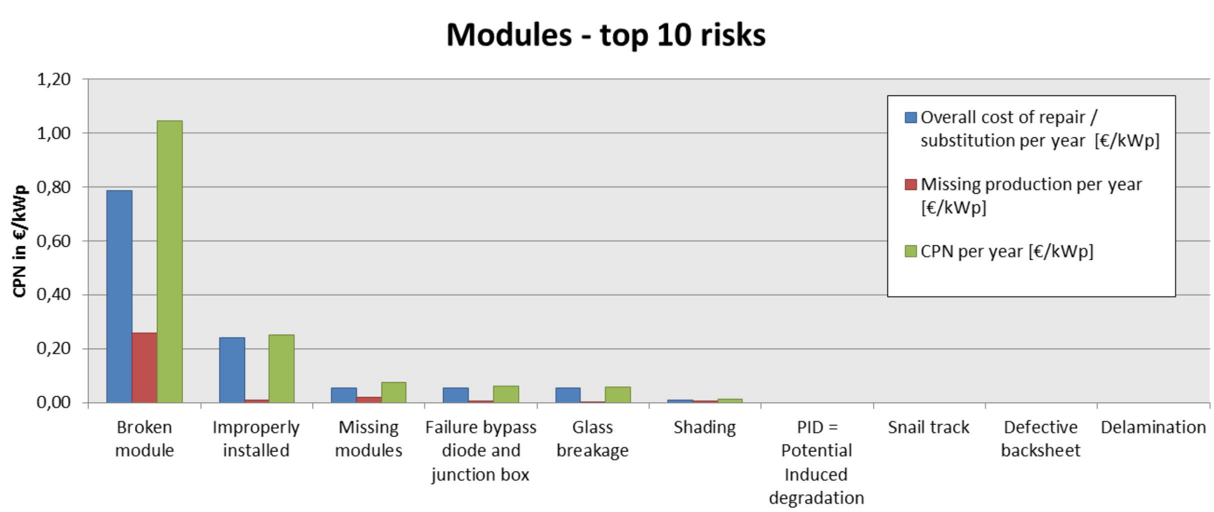


Figure 10 CPN value for PV modules failures only in the residential segment graph from the solar bankability project

6.3 Analysis of risks detected on the inverters

The same approach with PV modules is considered. The overview and the ranking of the risks according to the total CPN value it is shown in the Figure 11. The comparison of the risk pattern concerning the costs for the PV modules failures and inverters demonstrates the difference of the failures. For instance, the PV modules risks do not influence the efficiency of the PV plant as much as the inverters and on the other side the cost to fix the failure of the inverters is not as high as the cost to fix related to PV module failures.

Furthermore, the risks of the inverters, according to the Figure 11, can be divided into two groups:

- The failures with pattern of high repair cost and high losses such as wrong installation and fan failure. In this case the repair cost is high since a component of the inverter or the inverter itself must be substituted. The assessment of these risks is not as clear as the other risks related to the inverters and further examination is necessary. However, the general case of risks resulting from the inverters is to be repaired as soon as possible.
- The failures with pattern of almost zero repair cost and high losses such as inverter not operating etc. In such a case the evaluation of the risks is not complex and the failure should be fixed as soon as possible.

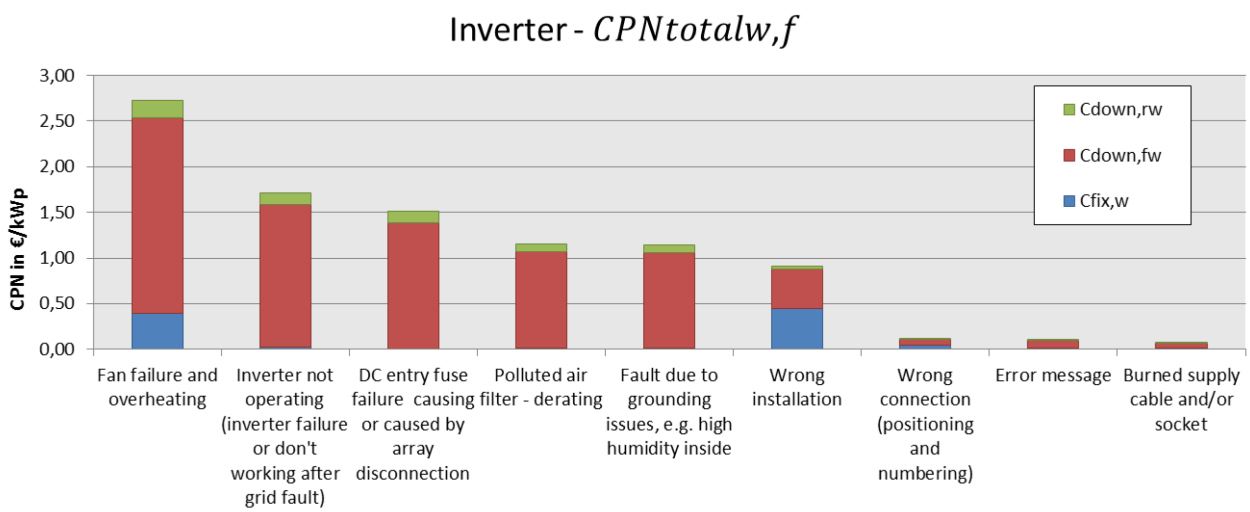


Figure 11 CPNtotalw,f diagram for the risks related to inverters

Additionally, it is important to take into account the impact of the failures on the profitability of the PV plants that these failures have been occurred and detected. For such case the average CPN value of the risk for the influenced plants ($CPN_{plantw,f}$) has been calculated and is shown in the Figure 12. The CPN values are significant for cases that the risk has been detected on the PV plant and measures must be taken. The CPN values of the failures in Figure 12 have derived without taking into consideration the occurrence ($O_{plants,f}$).

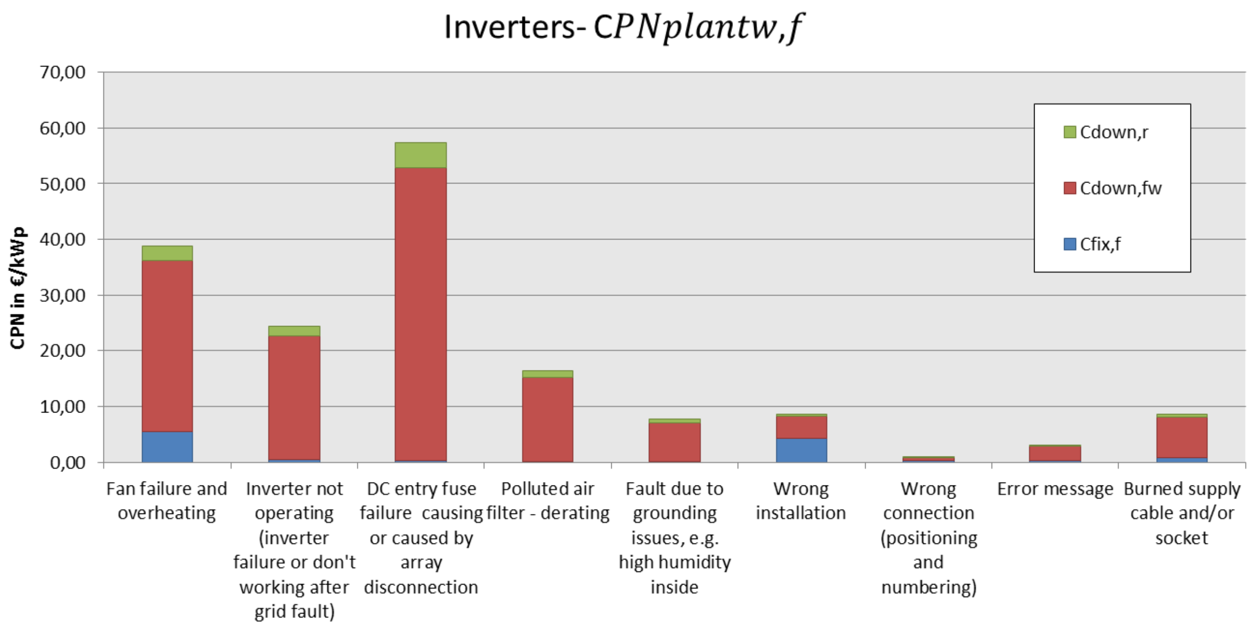


Figure 12 CPNplantw,f diagram for the risks related to inverters

According to the $CPN_{plantw,f}$ the cost for each specific failure can be evaluated or estimated. In order for the cost to be calculated for one specific PV plant the model must be run for the specific plant. An example of the utilization of the model is given in the Chapter 6.6. Furthermore, according to the Solar Bankability report which takes into consideration different segments the improper installation of the inverters is one of the most common detected failures which demonstrates the lack of expertise during the installation.

The occurrence of the failures can be seen in the Figure 13. It should be mentioned that the database extracted from the reports of TÜV Rheinland is not optimum for such failures because most of the failures have been detected and repaired before the inspection.

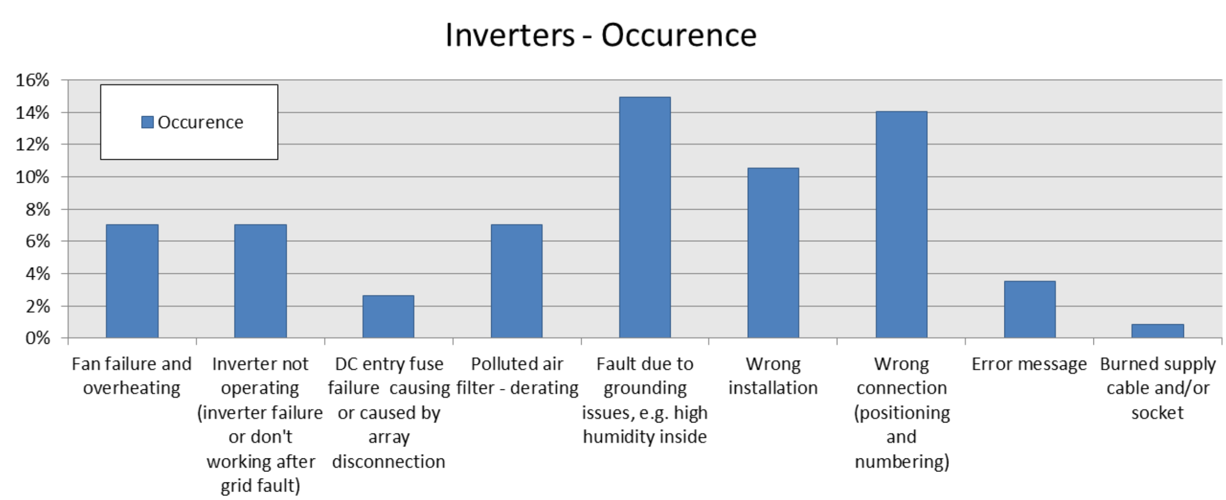


Figure 13 occurrence of failures in the PV plants concerning inverters

6.4 Analysis of risks detected on the cables

In a PV installation, two types of cables can be found AC and DC. The DC cables are used for the interconnection of the modules and inverters and the AC cables for the interconnection of the inverters with the AC combiner boxes or the Transformer. However, here only the DC cables will be considered.

Regarding the AC cables the failures can be summarized to design failures which can cause an increased likelihood of the cable to not function properly. Additionally, installation failures that can cause the mechanical damage of the cables. The CPN values of the AC cables failures are really high since the losses, if a failure will occur, are high as well.

In the Figure 14 the ranking of the risks it is shown. The highest according to the database and the model is the wrong connection of the cables which includes also failures such as installation of different type of connectors.

According to the Figure 14 the failures can be divided into three groups:

- The failures that do not impact the performance of the plant but the cost to fix it is really high. These failures most probably will never be replaced or fixed unless the losses are great enough. This pattern follows the failure e.g. wrong wiring.
- The other group consists of failures that the cost to fix is really low compared to the losses. These kinds of failures should be replaced as soon as possible. These types of failures are: Wrong/Absent cables connection and broken burned connectors.
- The third group consists of failures that are more complex and their assessment requires further considerations such as damaged cables.

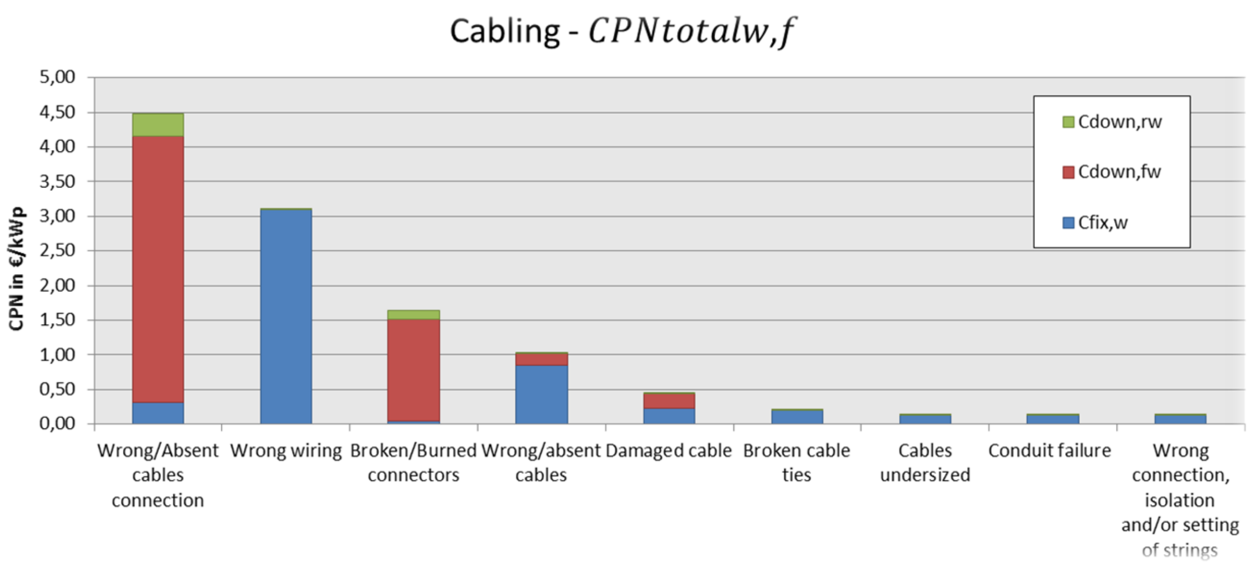


Figure 14 CPNtotalw,f diagram for the risks related to cabling

The comparison of the Figure 15 and Figure 14 demonstrates the importance of the occurrence of a failure in the model since as regards the Wrong/Absent cables connection $CPN_{totalw,f} = CPN_{plantw,f}$ since it has been detected in every plant. Additionally, in the Figure 15 the impact of damaged cables is clear and the valuation of the risk is easier.

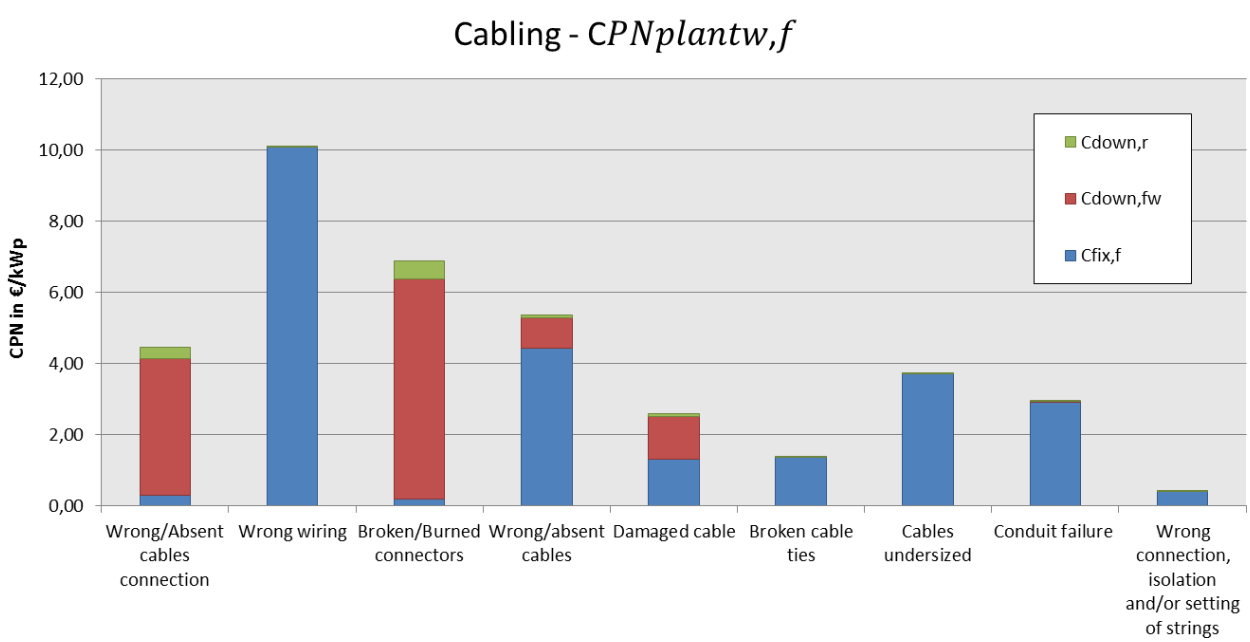


Figure 15 CPNplantw,f diagram for the risks related to cabling

Taking into consideration DC cables and according to the database provided by TÜV Rheinland, failures related to the installation have been detected in every plant as it is shown in the Figure 16. For these types of failures, the root cause is improper installation. It has been often detected because normally the installation company is also responsible for the maintenance of the PV plant.

Consequently, since they did not notice the failure during the installation and fix it they will not do it afterwards. Accordingly, when another third party institution do the inspection of the PV installation all the failures done in the installation phase will be noticed and acknowledged for the first time. However there are failures that have occurred because of no alternative choice e.g. different type of connectors. A lot of companies due to the lack of connectors in the market have installed different types of connectors together which is not allowed according to the standards.

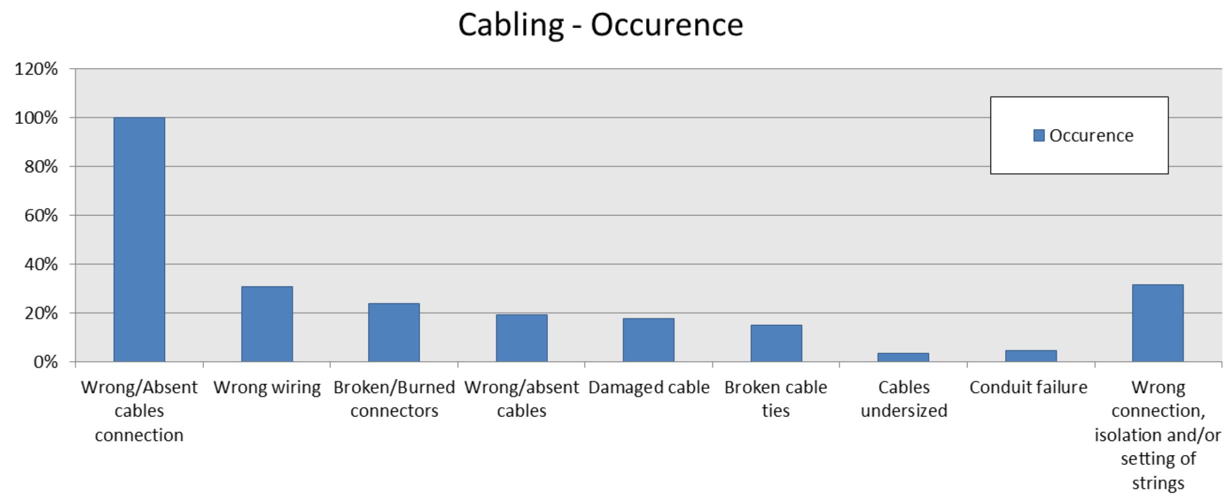


Figure 16 occurrence of failures in the PV plants concerning cables

6.5 Analysis of risks detected on the combiner boxes

The ranking of the risks in combiner boxes is shown in the Figure 17. The risks have the same pattern with the other failures of the other components. In general, most of the failures that have been detected occured during the design and installation phase.

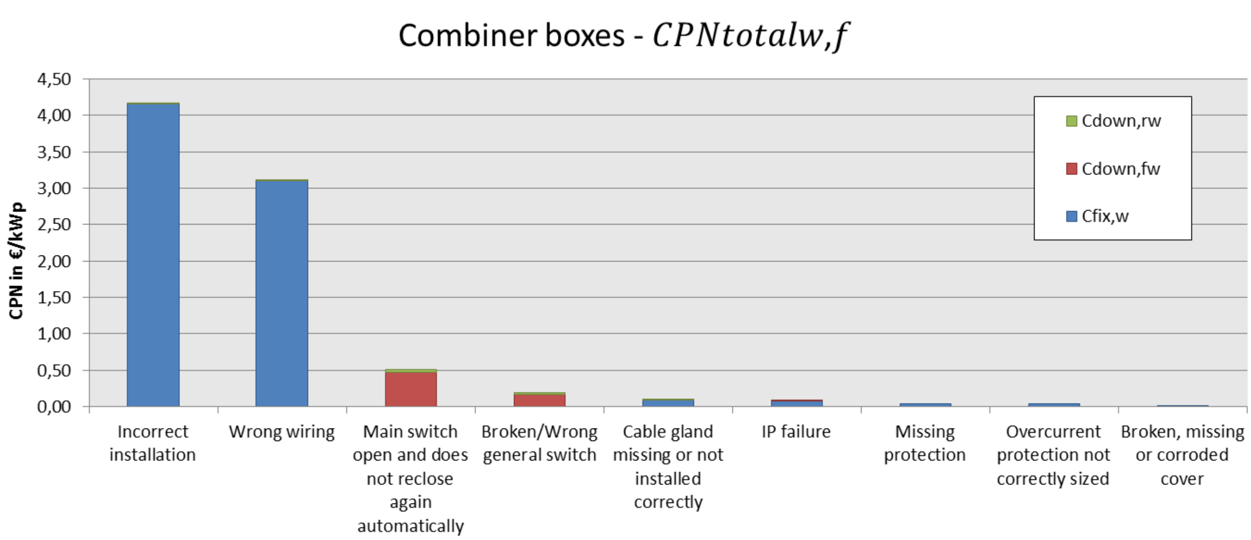


Figure 17 CPNtotalw,f diagram for the risks related to combiner boxes

In Figure 17 the failures:

- main switch open and does not reclose
- broken/wrong switch

have a low $CPN_{totalw,f}$ value but their $CPN_{plantw,f}$ is more than 40 times as it is shown in the Figure 18. This represents the great impact of the failures when they occur.

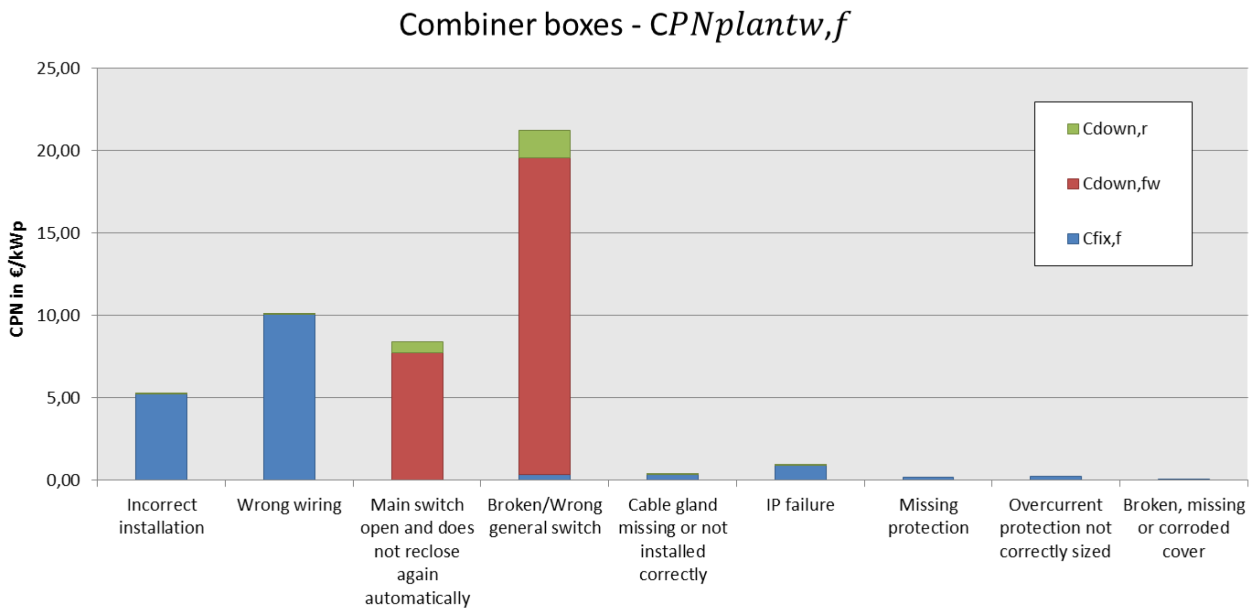


Figure 18 CPNplantw,f diagram for the risks related to combiner boxes

Except the incorrect installation risk which is generally detected, the occurrence of the other risks does not follow any specific pattern as it is shown in the Figure 19.

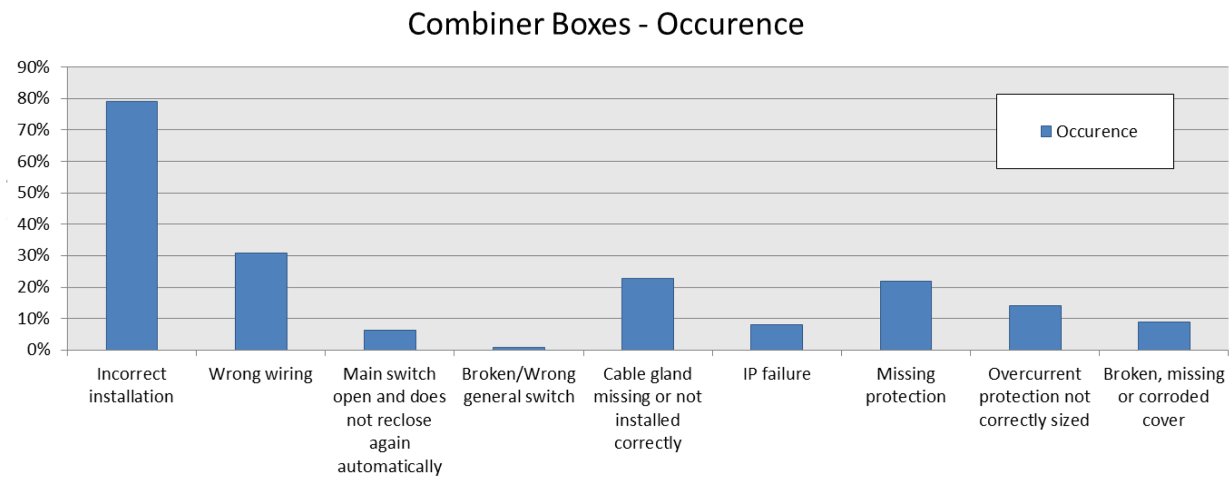


Figure 19 occurrence of failures in the PV plants concerning combiner boxes

6.6 Example of model utilization for a PV plant

In this section an example of how to utilize the proposed model will be given. The purpose of this example is to demonstrate the flexibility of the model and how it can be adjusted automatically to any PV plant.

The PV plant that would be considered has the following features:

- Year of installation: 2012
- Fixed – ground mounted PV Installation
- Location: Germany
- Nominal Power: 3268 kWp
- Spec. Yield : 1000 kWh/kWp

The PV plant consists of:

Number of PV Modules	Number of Combiner Boxes	Number of Inverters	Number of cables	Number of Mounting Structures
14208	150	150	2076	222

In the Figure 20 the detected risks for the PV plant of 3.3 MWp are shown. The improper installation of the Mounting Structure has the greatest risk since the cost to fix it really high.

According to the Figure 20 the overall CPN Value of the PV plant is equal to 158.45 €/kWp. That means that the cost of this specific plant to be fixed is equal to:

$$3268\ \mathrm{kWp} * \frac{158.45€}{\mathrm{kWp}} = 517816€$$

The 517816€ represent the additional costs for the PV plant due the failures in the Figure 20. This amount is the maximum since it has been calculated without any mitigation measures and in case that all failures must be fixed and it includes both the cost to fix and losses.

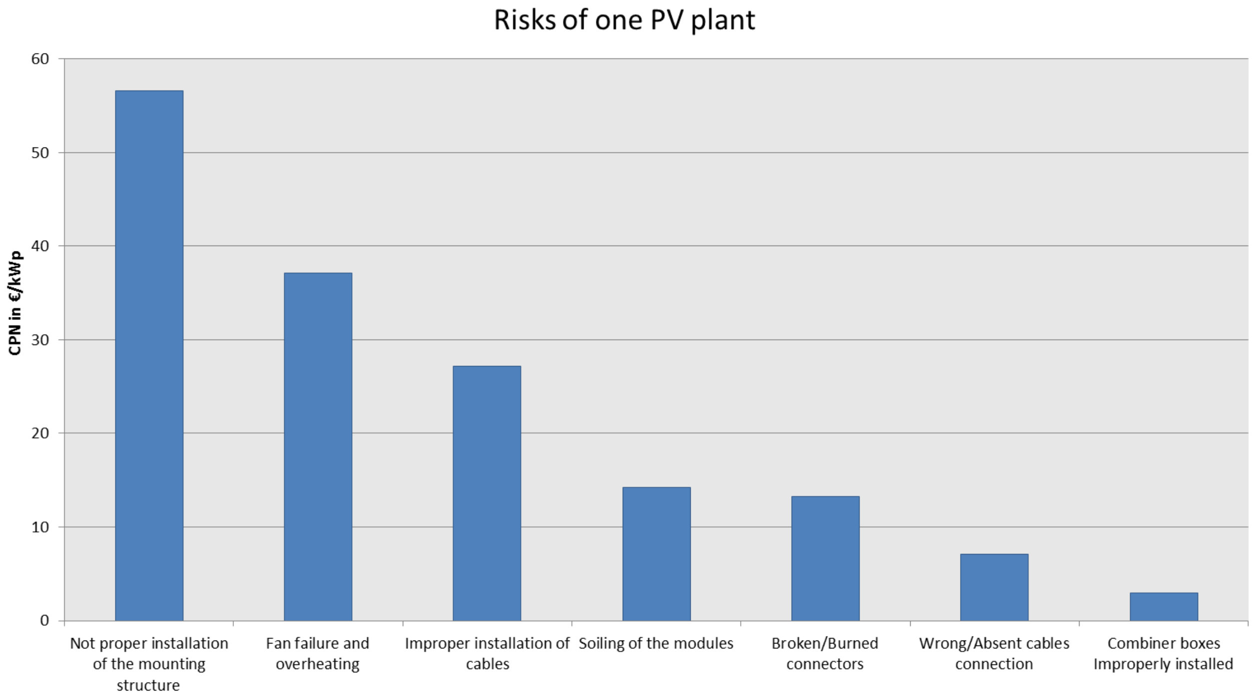


Figure 20 example of CPN values for one PV plant

According to the costs that have been described in the Chapter Results of the model6 and Figure 20 the assessment of the risk would have been divided into two groups:

- The first group consists of failures that will not be fixed because of the high cost to fix it and the losses are not high e.g.
  - Improper installation of the mounting structure.
  - Combiner boxes improperly installed and improper installation of the modules.

However as long as the failures have not been fixed, the respective risks remain as well and in the future the losses might increase at a point that the repair of the failures will be the only option.

- The other group consists of the failures that should be repaired as soon as possible e.g.
  - Fan failure and overheating.
  - Soiling of the modules.
  - Broken/burned connectors.

The cost to fix it is equal to the C_{fix} parameter from the model.

7 MITIGATION OF THE FAILURES/RISKS

In this chapter the mitigation measures regarding the failures described in the previous chapter is given. There is a great variety of mitigation measures but in this thesis measures that have the highest positive impact on the CPN are taken into account. The measures are divided into two groups:

- Preventive measures: that must be applied before the occurrence of the failure.
- Corrective measures: that are taken after the occurrence of the failure.

A compromise between the cost of the mitigation measures and the risk of the PV project should be found. Concerning Figure 21, in order to reduce the risk of the PV project the initial investment is greater because the capital expenditure (CAPEX) and operating expense (OPEX) are more demanding. This fact can reduce the attractiveness of the PV plants.

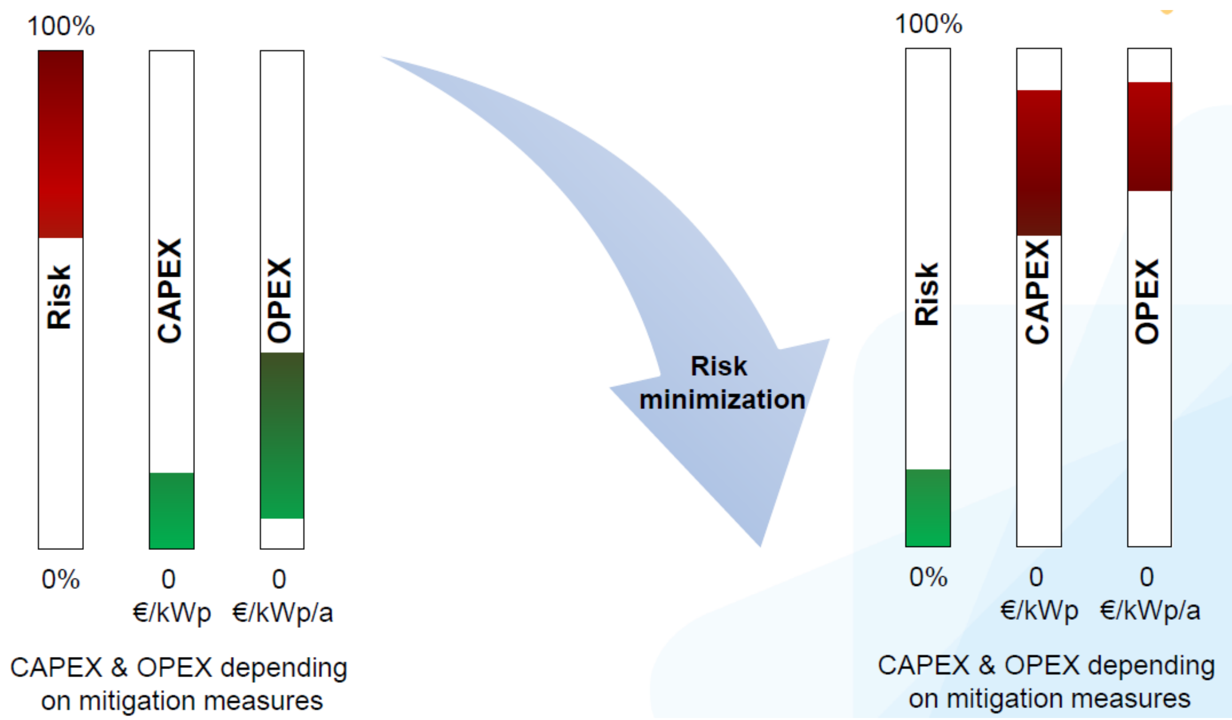


Figure 21 the relation between risk, capex and opex[2]

7.1 Preventive measures

In this group of measures, two main mitigation measures that can greatly reduce the risk of the PV investment have been distinguished i.e.:

[2] www.solarbankability.org

- inspection during the design and planning phase
- testing of the modules in the laboratory

These measures are described in detail and examples of real cases (claims) accordingly are given.

7.1.1 Inspection during the design and planning phase

One of the most important mitigation measures that should be an inextricable part of the future projects is the inspection during planning and installation phase from a third party institution. This mitigation measures includes:

- The review of the designs
- The evaluation of the energy analysis of the PV plant
- The review of the implementation studies
- Inspection during the installation phase
- Final electrical measurements
- Final commissioning

This preventive measure is one of the most crucial because of two reasons:

- Most of the failures recorded in the statistical data are related with the design and installation phase of the PV project
- It reduces the (n_{fail}) number of failures and the cost to fix the failure in this phase of the project is almost 0 €/kWp.

The earliest the failure is detected the less the cost to repair it. According to the Figure 22 the cost for reparation of defects increases from product idea phase to customer phase exponentially. This phenomenon is called “rule-of-ten” because the cost to fix the failure is multiplied by 10 in every phase of the project.

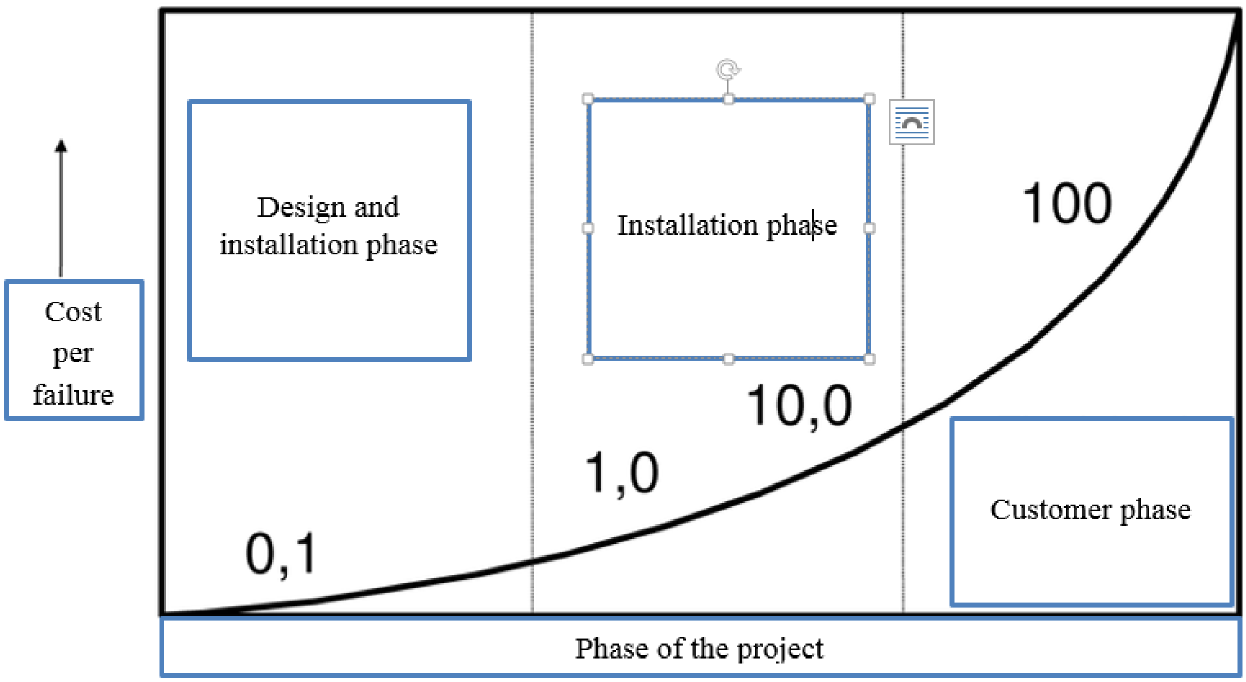


Figure 22 the rule of 10 for the failures through the different phases of the project

According to the model developed in Chapter 5 once this mitigation measure will be applied the parameter n_{fail} is greatly reduced. According to a market research the average cost of the inspection during the planning and installation phase is 10 €/kWp. In the Appendix D an example of the costs regarding the mitigation measures is given.

The sum of the CPN values of all the failures and all PV plants without any mitigation measure is 167.94 €/kWp. After applying the mitigation measure sum is 58.71 €/kWp. This means that if the inspection during the planning and installation phase was a common practice the sum of the risks of the PV investments would have dropped more than 65%. This is a great example how important is the expertise of the EPC company and how future investors should draw their focus on how to reduce risks in advance. In the Figure 23 the influence of the mitigation measure in the CPN values is shown.

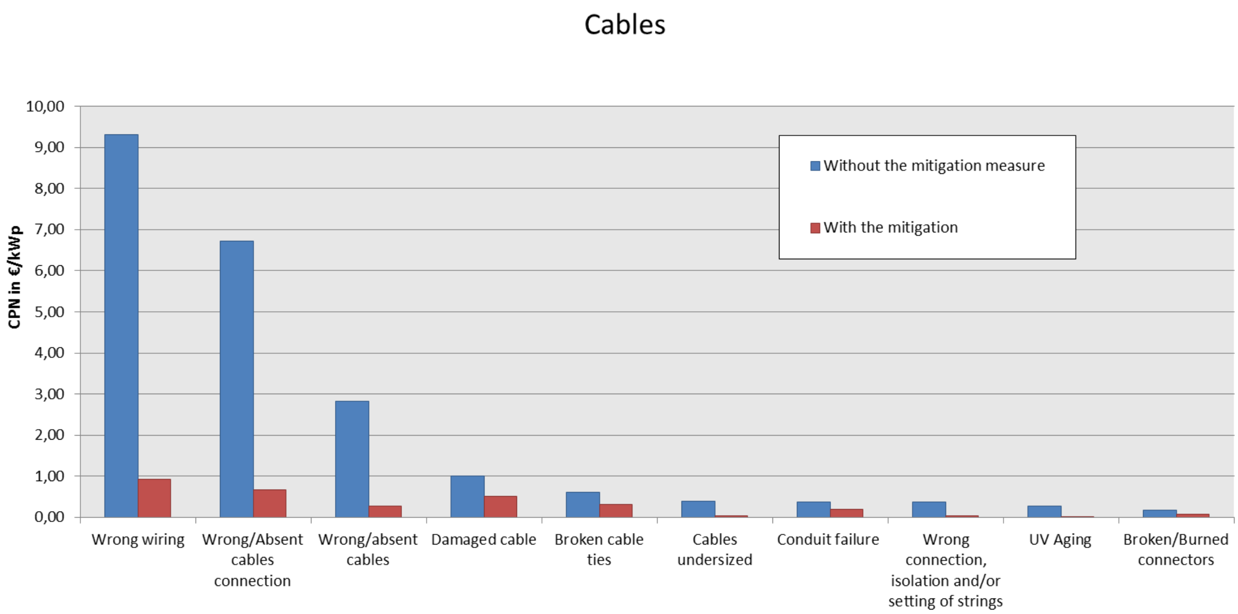


Figure 23 an example of the influence in the CPN values of failures regarding the cables with and without the mitigation measures.

7.1.2 Real cases of failures due to mistakes during planning phase

The first example is a failure concerning the sizing of the inverters i.e. optiprotect switches have failed due to higher currents and temperatures than expected. This failure causes the disconnection of the PV modules and the losses are great. The example that is shown in Table 10 is a common example that can occur due to different reasons e.g.

- wrong design
- misunderstanding between engineers and people responsible for the procurement
- quality of the component

In this case the cost to repair the defect is 28 €/kWp and could have been avoided applying the described mitigation which costs 10 €/kWp. For the specific example the losses due to this failure are unknown therefore not considered.

Table 10 example of a failure due to wrong sizing of the inverters and the financial impact[3]

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

The second failure is regarding the site of the PV plant. The quality and the status of PV plant site are two parameters that are considered given by the EPCs and PV owners. Consequently, they do not pay the required attention and sometimes the required studies have not been conducted which can lead to failures such as the one described in Table 11.

In this example, the EPC contractor has not considered the possibility of ground subsidence and the accumulation of water in the area where the inverter have been installed. In order to fix the failure, the isolation of the inverter has been improved and the inverter has been lifted by few centimeters.

The cost for this reparation was 16.4 €/kWp (if one inverter station is equal to 1 MW) unfortunately the losses during the reparation are not known therefore not considered. The cost have been paid by the owner of the PV plant since the warranty of the EPC contractor had expired. The owner could have avoided this cost if he had invested 10 €/kWp. It should be mentioned that almost all the failures that have been caused by the EPC have been detected after the EPC warranty of construction has expired. Because during the warranty period, the EPC is looking after the PV plant and ensures the normal operation of it. However after the warranty period of the construction or if the EPC does not exist anymore, and if another company will inspect the PV plant all the failures during planning and installation phase will be detected.

[3] Technical Risk Assessment during the Planning and Construction of PV plants/solar parks, Ingo Klute from Yuwi http://www.solarbankability.org/

Table 11 example of a failure due to wrong installation of the inverters and the financial impact[4]

Failure		Photographic demonstration
Risk	Wrong installation of the inverters	
Description	Water ingress in cable cellar of inverter station due to surface water	
Performance losses	N/A %	
Mitigation	Inspection during the design and planning phase	
Detection method	Inspection of the PV Plant	
Reparation method	Jack the inverter station higher	
Cost of reparation	16.4 €/kWp (if one inverter station is equal to 1 MW)	
Cost of mitigation measure	10 €/kWp	

The last example from this section is regarding the PV modules (please see Table 12). The failure for this case is the wrong installation of the modules due to the small bending radius of the module cables. This failure can cause the void of warranty of the modules in case the cable is damaged. Furthermore, it can influence the insulation of the junction box which can consequently cause other failures. In this case all the cables must be checked for any visual damage and if their electrical characteristics have changed. The cost of the reparation for this failure have been 3 €/kWp but could have been avoided with a 5 €/kWp investment.

Table 12 example of the a failure regarding the radius of module cable and the financial impact[5]

Failure		Photographic demonstration
Risk	Wrong installation of the modules	
Description	The bending radius of the module cable is below the limit	
Performance losses	N/A %	
Mitigation	Inspection during the design and planning phase	
Detection method	Inspection of the PV Plant	
Reparation method	Rearranging of the cabling	
Cost of reparation	3 €/kWp	
Cost of mitigation measure	5 €/kWp	

[4] Technical Risk Assessment during the Planning and Construction of PV plants/solar parks, Ingo Klute from Yuwi http://www.solarbankability.org/
[5] Technical Risk Assessment during the Planning and Construction of PV plants/solar parks, Ingo Klute from Yuwi http://www.solarbankability.org/

7.1.3 Testing of the modules in a laboratory

Another important preventive mitigation measure is the testing of the modules in a laboratory. A series of test should be conducted in order to ensure the quality of the modules after the transportation and before the installation e.g.

- STC power measurements: it is reducing the uncertainty regarding the characteristics of the modules. Also, this measurement can be used for future evaluation of the modules regarding their efficiency.
- PID testing: important for PV modules that PID failures have been detected in other plants.
- Electroluminescence Imaging: in order to identify failures after the transportation of the modules i.e. cell cracks
- Insulation measurements: especially for modules installed in areas with high humidity.

The cost of this mitigation measure is 3 €/kWp according to the Appendix D and the CPN value has been reduced by 6% which means 10.16 €/kWp according to the model. Comparing the two mitigation measures it can be concluded that the testing of the modules is not as crucial as the previous mitigation measure. However, this is not true because of the different characteristics of the failures that each mitigation measure influences. In the Figure 24 the impact of the mitigation measure can be seen.

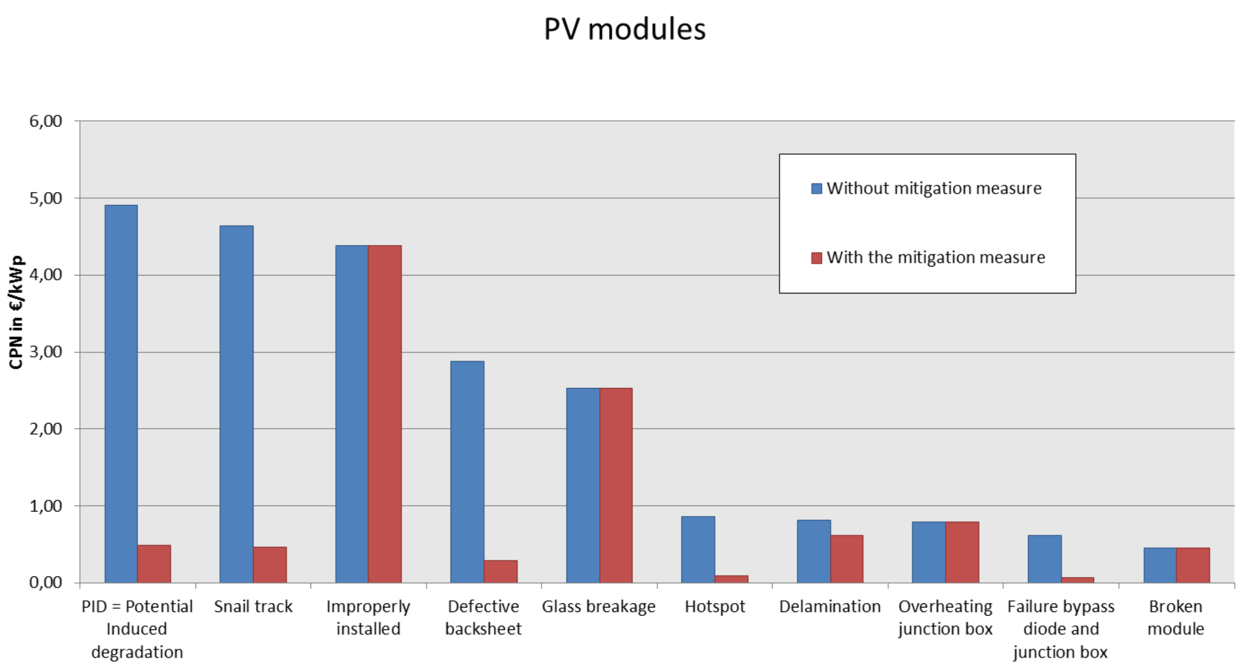


Figure 24 the difference in the CPN value of the risks regarding the PV modules with and without the testing of the PV modules as a mitigation measure

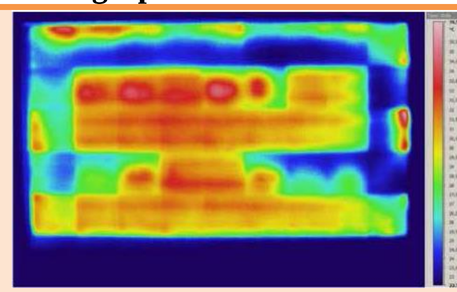
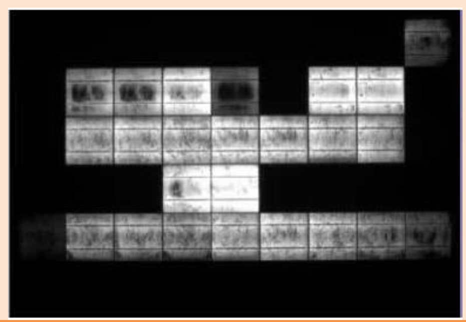
7.1.4 Real cases of failures due to low quality of PV modules

The example for the quality of the modules that is analyzed is the failure due to PID phenomenon. This failure has an extensive impact in the profitability of the plant and can be mitigated if the modules would have been tested before installation. However, the testing of the modules would have increased the investment by 3 €/kWp. Taking into consideration the example in the Table 13 the total cost of the failure has been 117 €/kWp and derives from:

- The cost of repair 61 €/kWp which includes the cost of transportation, accommodation, traveling, cost of PV Offset Boxes, installation etc.
- The downtime losses due to the failure is 56 €/kWp and includes the losses due to the performance loss from the moment that the failure have been detected till repaired.

The 61 €/kWp have been covered from the warranty of the modules and the 56 €/kWp are the losses of the owner during the claim period. This examples is similar to the CPN calculation (see Figure 9).

Table 13 example of a failure regarding PID cable and the financial impact

Failure		Photographic demonstration
Risk	PID	 
Description	Potential induced degradation is potential induced performance degradation in photovoltaic modules, caused by so-called stray currents.	
Performance losses	15% - 56 €/kWp	
Mitigation	Inspection during the design and planning phase	
Detection method	Inspection of the PV Plant	
Reparation method	Installation of PV Offset Boxes	
Cost of reparation	61 €/kWp	
Cost of mitigation measure	3 €/kWp	

7.2 Corrective measures

These measures unfortunately are applied after the occurrence of the failures and their impact on the CPN is not as great as the preventive measures, since they do not influence the number of failures. However, they can reduce dramatically the time to detect a failure (t_{td}) parameter and/or time to repair ($t_{tr,ts}$) parameter.

7.2.1 Monitoring as a corrective maintenance

Almost all the PV plants have a monitoring system installed. Monitoring is crucial for the detection time of the failures but not for the occurrence. Especially when the monitoring is combined with an O&M contract the CPN can be greatly reduced. In the Figure 25 the global market of the monitoring companies can be seen.

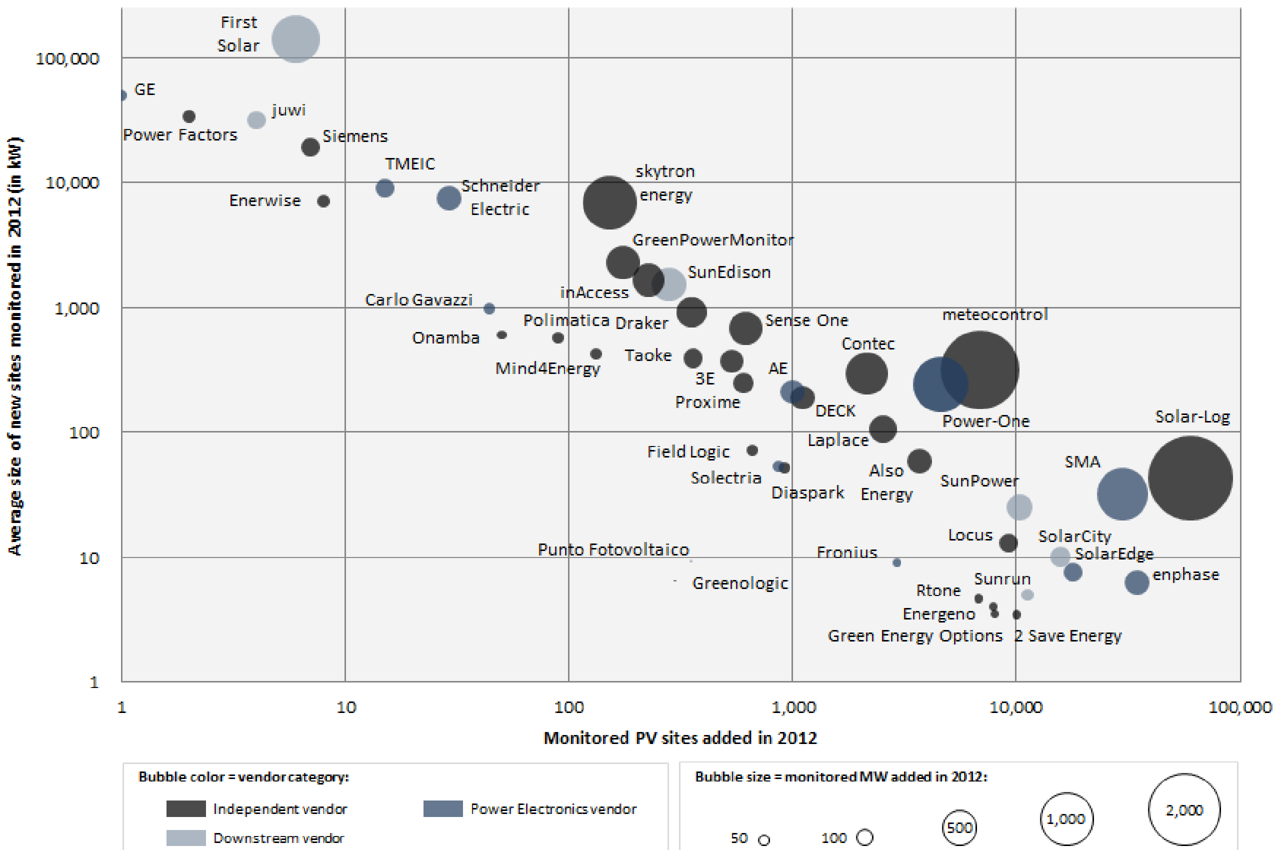


Figure 25 global PV monitoring market according to the new sites monitored in 2012 and the size of the plant[6]

The monitoring is related to the model described in Chapter 5 as it has a great impact on time to detect parameter (t_{td}). For instance the time to detect in case of inverter failure for a PV plant without monitoring is 744 (hours) and a PV plant with monitoring system is 24 (hours). Because in such failures the operator will receive immediately a notification regarding the failure. Another fact which makes monitoring important is that failures with great impact in the productivity of the PV plant are detectable by the monitoring. However, monitoring is not sufficient for the detection of all failures in a PV plant since failures e.g. hotspot, delamination etc. cannot be detected from the monitoring system. In such a case the failures can be detected after on-site inspection. In the Figure 26 the difference between the CPN values of the inverter failures with and without monitoring system can be seen.

[6] www.greentechmedia.com

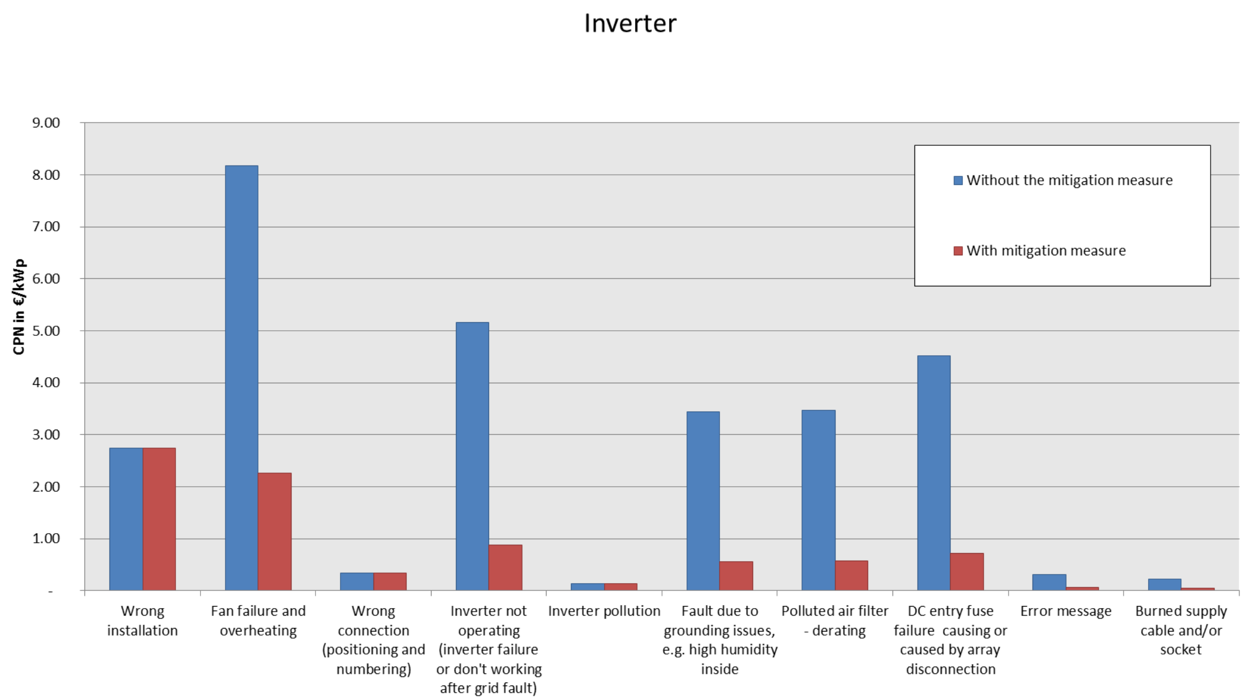


Figure 26 the difference in the CPN value of the risks regarding the inverters with and without monitoring as a mitigation measure

According to the model described in the Chapter 5 the sum of CPN values for all PV failures is:

- without mitigation measures: 167.94 €/kWp
- with monitoring as a mitigation measure: 139,72 €/kWp

The risks have been reduced by 17 % which is equal 28 €/kWp.

Moreover, in Figure 27 the importance of the monitoring is shown. The performance ratio of the PV plant with monitoring system is 4% greater than PV plants without monitoring. This performance loss can be translated to a CPN value. For instance a PV plant with the following characteristics:

- Yield : $y = 1500\ (kWh/kWp)$
- Feed-in-Tariff : $FIT = 0.25\ (€/\mathrm{kWh})$

Then the losses would have been 15 €/kWp since they are equal to:

$$Losses = y * FIT * PL = \ 1500 * 0.25 * 0.04 = 15\ (€/kWp).$$

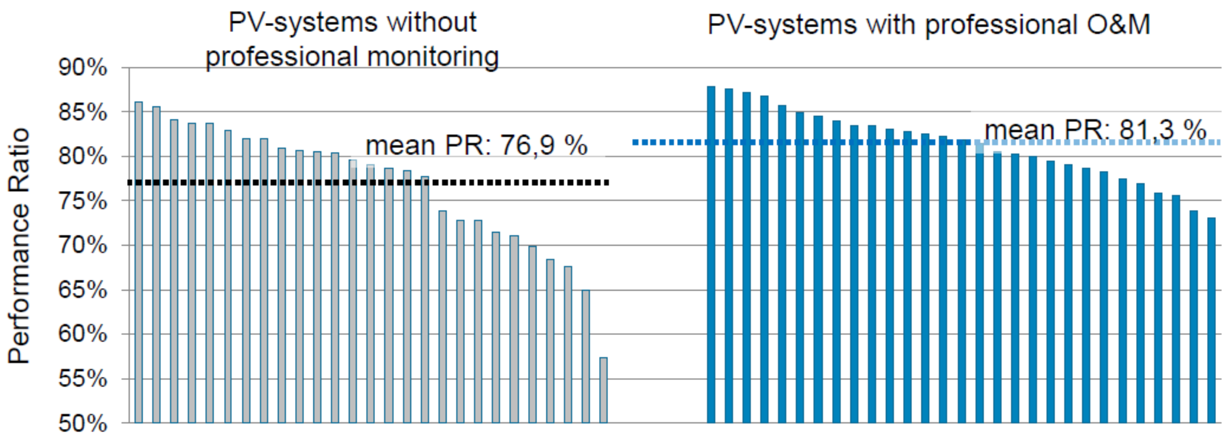


Figure 27 deviation in the performance ratio between PV plants with and without monitoring[7]

In addition one reason that demonstrates why almost all PV plants have a monitoring system installed is:

- 4% is translated to 15 €/kWp (for a PV plant with yield 1500 kWh/kWp and FIT = 0.25 €/kWh)
- according to the Appendix D the cost for the monitoring is 3 €/kWp

which means by investing 3 €/kWp they save 15 €/kWp.

7.2.2 O&M / Inspection as a mitigation measure

The O&M operator is responsible for the uninterruptible operation of the PV plant and maximize the profitability. Nevertheless, to achieve this goal a number of things are required from the O&M operator. As is shown in Figure 28 the operator is responsible for three main points:

- The monitoring of the PV plant and corrective maintenance. It requires excellent communication between the engineers in the control room and the O&M manager who is responsible for the reparation of the failures as soon as possible.
- Preventive maintenance.
- Spare parts – management, it is significantly important especially for failures regarding inverters and their availability

[7] How to minimize risks and maximize yield, Martin Schneider from Meteocontrol
http://www.solarbankability.org/

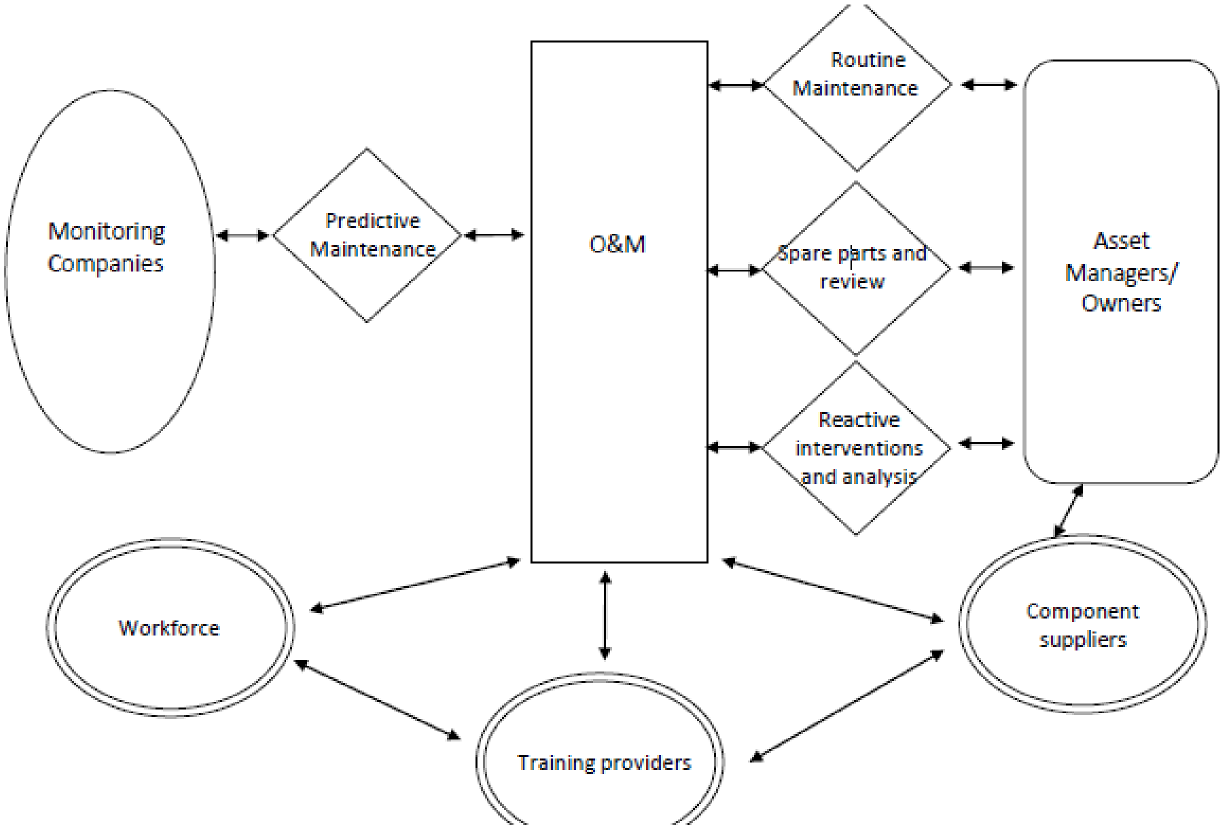


Figure 28 O&M operator and the dependencies with the other stakeholders of the PV plant

In order for a PV plant to meet the lifetime expectancy of 20 years, O&M is an important factor. Especially for components where maintenance is a requirement by the manufacturer and it is a prerequisite for the warranty e.g.

- medium and low voltage substations
- inverters
- combiner boxes
- transformers
- PV modules

For instance, a PV plant with oil-filled transformers without the regular check of the oil level in the transformer can cause the failure of the transformer and maybe its substitution would lead to great losses.

O&M has a great influence regarding the profitability of the PV plant as well. Taking into account the influence of soiling and trimming, the importance of maintenance is underlined (see Figure 29).

Figure 29 example of soiling on PV modules and plants causing shadow on the modules

It is quite difficult to quantify the losses due to soiling. However taking into account Figure 30 the losses due to soiling are greater than 28% for the specific example. The losses due to soiling in one day period of time, for big-scale PV plants, are sufficient to exceed the cost to clean the PV modules.

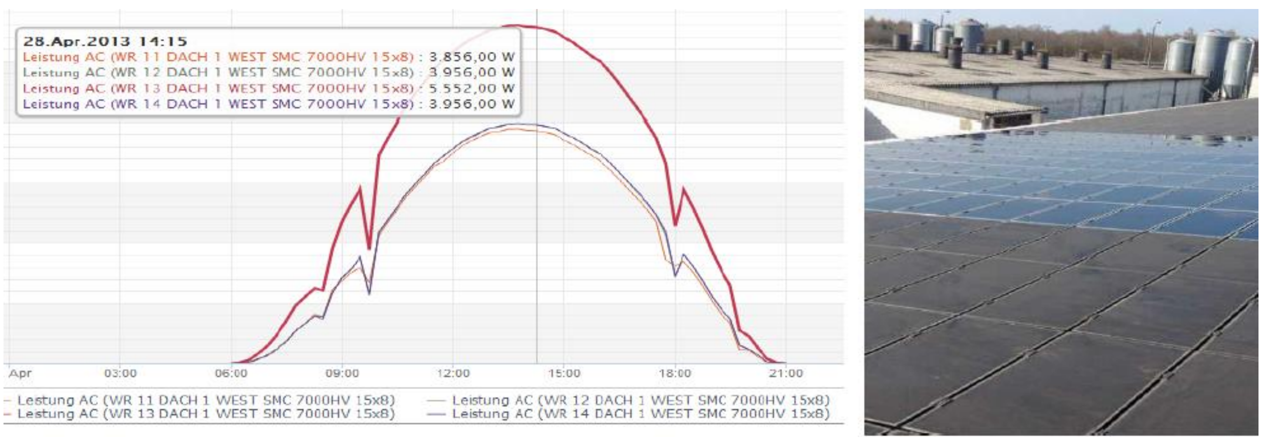


Figure 30 the deviation of the generated power during the day between dirty and clean PV modules[8]

As it is already mentioned above, it is quite challenging to quantify O&M and calculate CPN values for the failures. Nonetheless, according to the model described in the Chapter 5 the sum of CPN values for all PV failures is:

- without mitigation measures: 167.94 €/kWp
- with O&M as a mitigation measure: 141.41 €/kWp

The risks have been reduced by 16 % which is equal to 26.53 €/kWp.

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[8] How to minimize risks and maximize yield, Martin Schneider from Meteocontrol
http://www.solarbankability.org/

In Figure 31 the impact of the O&M mitigation measure on the failures regarding the inverters is shown.

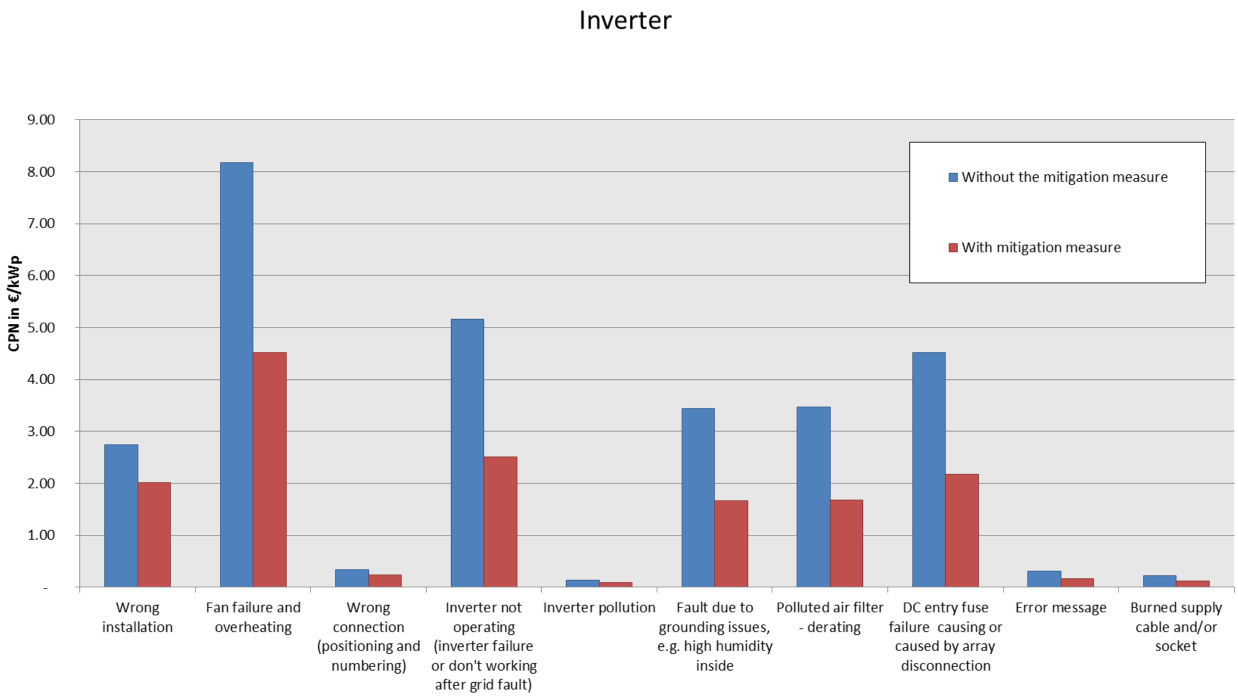

Figure 31 the difference in the CPN value of the risks regarding the inverters with and without O&M as a mitigation measure

7.3 All four mitigation measures together

Taking into consideration the statistical data and the recorded failures the following 4 measures have been proposed as the best combination to mitigate the risk on the PV plants:

- Inspection during design and installation phase: to reduce total number of recorded failures (n_{fail})
- Testing of the PV modules: to reduce the uncertainty regarding the electrical characteristics and to have a reference measure for future module efficiency assessment. Additionally, the number of PV module failures will be reduced dramatically.
- Monitoring: to reduce the time to detect (t_{td}) parameter for failures that are possible to be detected from monitoring
- O&M contract: in order to reduce the time to detect (t_{td}) parameter for failures that are not possible to be detected from the monitoring system, time to repair/substitute ($t_{tr,ts}$) and time to fix (t_{fix}).

With these four mitigation measures almost all the failures detected in the 112 reports used for the database can be tackled to an extend that is sufficient to ensure the high performance of the plant and payoff.

Regarding the CPN values for all the failures and components:

- The sum of the CPN values without any mitigation measure is 167.94 €/kWp
- With the proposed mitigation measures is 46.45 €/kWp including the cost of the measures

The risks have been dropped by 72% which is considered a significant change in the PV industry and attractiveness of the PV plants.

8 CONCLUSIONS

In this thesis the most important technical risks related to PV projects were identified. The prioritization of the risks was not estimated by following a classical FMEA but by developing a methodology that was never previously applied to PV systems, a cost based FMEA with Cost Priority Numbers. CPNs are given in €/kWp or in €/kWp/a and can thus directly give an estimation of the economic impact of a technical risk.

The CPN methodology was defined in order to assess three main economic impacts of a specific failure: impact due to downtime, impact due to repair time and substitution cost. For the calculation of the downtime ($C_{down,f}$), parameters such as time to detection, time to repair, repair time were considered. While for the cost to fix ($C_{fix,f}$), cost for detection, labour cost, cost of repair / substitution, cost of transportation were included. The methodology also considers the year of installation, the year of failure and the nominal power in order to evaluate the distribution of failure probability once the available data in the database reaches statistical relevance to this type of granularity. The methodology also takes into account other statistical parameters such as the number of affected plants and the number of components in affected plants. In this way it is possible to understand the magnitude of the risks in the influenced plants.

The objective of this master thesis was to identify and evaluate the most important risks on the PV plants. Thus, more than 100 inspection reports have been taken into consideration in order to create a database able to apply the mathematical model described in the Chapter 5. According to the model and the database a CPN value for every risk has been generated and the most important risks related to PV projects have been identified. According to CPN value of the risks, results have been presented for every component as well as mitigation measures in order to reduce the risk.

The risks on the PV projects cannot be reduced to zero however the costs of the three main parameters of the proposed model, losses due to the failures ($C_{down,f}$), cost to repair the failure ($C_{down,r}$) and cost to fix the failures (C_{fix}) can drop more than 70% applying mitigation measures.

According to the Chapter 7 the mitigation measures:

- inspection during the design and installation phase and
- testing of the modules in laboratory

have shown the greatest positive impact on PV projects. On the other hand these two mitigation measures are increasing the cost of the installation (CAPEX) of the PV projects. Nevertheless, according to the PV plants that have been considered these two preventive measures can minimize the number of failures and losses respectively. Thus, can compensate the initial cost by increasing the profitability of the PV plant.

Furthermore, two more mitigation measures are proposed in this thesis:

- O&M contract
- Monitoring

Applying these two mitigation measures the factors regarding the required period of time to detect and repair a failure are significantly influenced. These two mitigation actions are increasing the annual cost of the PV project (OPEX). Nonetheless, as it proven in Chapter 7, most probably the cost for the mitigation measures is going to return to the investor by increasing the availability and efficiency of the PV plant.

Furthermore, another important parameter of the PV plants nowadays is the after-sales value of the PV plants. Therefore, PV plants with the proposed preventive and corrective measures have higher after-sales price. Additionally, these mitigation measures or just an inspection of the PV plant are mandatory by the stakeholders before they purchase an already installed PV plant. Thus, future PV projects must take into account this parameter during the planning phase.

8.1 Further steps

The goal was to demonstrate a technique how to identify the highest risks on PV plants and mitigate them. For that purpose and due to the short available time period, of 6 months, and lack of data some parameters of the model have been assumed or have been extracted from the experience here in TÜV. Thus, the model described in the Chapter 5 can be further developed and improved regarding its accuracy.

Furthermore, parameters such as Performance Loss (PL) or time to detect (t_{td}), etc. should be further developed by including more data such as measures of losses for different types of failures etc. In addition, the data collected from TÜV Rheinland throughout the last 5 years are biased since failures occurred during the operations or failures of one PV plant throughout the years have not been considered. Thus a point of view from an O&M company is necessary for the improvement of the statistical data.

In the next years it will be important to build large databases with potentially a uniform method to increase the confidence level of the statistical analysis and thus increase the accuracy of the model and reduce the perceived risks from investors.

9 BIBLIOGRAPHY

[1] "Solar bankability," 2016. [Online]. Available: http://www.solarbankability.org/home.html.

[2] "SNAPSHOT OF GLOBAL PHOTOVOLTAIC MARKETS," Report IEA PVPS T1-29:2016, 2015.

[3] "ISO 31000 - Risk management".

[4] S. P. Europe, "Global Outlook Market for Solar Power".

[5] I. I. E. AGENCY, "Review of Failures of Photovoltaic Modules," 2014.

[6] M. E. J. Solorzano, "Hot-spot mitigation in PV arrays with distributed MPPT (DMPPT)," 2013.

[7] G. H. J.Gallon, "PV Module Hotspot Detection".

[8] B. M. Chris Deline, "A Performance and Economic Analysis of Distributed Power Electronics in Photovoltaic Systems," 2011.

[9] L. P. K.-A. W. M. K. M. K. Cornelia Peike, "Towards the origin of photochemical EVA discoloration," 2013.

[10] F. J. PERN, "FACTORS THAT AFFECT THE EVA ENCAPSULANT DISCOLORATION RATE UPON ACCELERATED EXPOSURE," 1994.

[11] D. W. C. A. N. K. John Wohlgemuth, "Failure Modes of Crystalline Si Modules," 2010.

[12] M. B. P. Neelkanth G.Dhere, "STUDY OF DELAMINATION IN ACCELERATION TESTED PV MODULES," 2001.

[13] T. Shioda, "Delamination failures in long-term field aged PV modules from point of view of encapsulant," Mitsui Chemicals, 2013.

[14] SMA, "Temperature Derating".

Appendix A Assumptions used for the base model (no monitoring, O&M company, Inspection)

	Failures	Time to detect [h]	Time to repair/substitution [h]	Repair/substitution time [h]	Power loss [%]	Multiplier
Modules	Hotspot	8760	744	2	2,00%	1
	Delamination	8760	744	2	1,00%	1
	Glass breakage	8760	744	2	10,00%	1
	Soiling	8760	744	0,01	10,00%	1
	Shading	8760	744	0,01	10,00%	1
	Snail track	8760	744	2	1,00%	1
	Cell cracks	8760	744	2	1,00%	1
	Defective backsheet	8760	744	2	1,00%	1
	Overheating junction box	8760	744	2	1,00%	1
	PID = Potential Induced degradation	8760	744	2	10,00%	1
	Failure bypass diode and junction box	8760	744	2	33,00%	1
	Corrosion in the junction box	8760	744	2	1,00%	1
	EVA discoloration	8760	744	0	0,00%	1
	Theft of modules	8760	744	0,5	100,00%	1
	Broken module	8760	744	2	100,00%	1
	Damage by snow	8760	744	2	100,00%	1
	Corrosion of cell connectors	8760	744	2	1,00%	1
	Improperly installed	8760	744	2	5,00%	1
	Missing modules	8760	744	2	100,00%	1
Inverter	Fan failure and overheating	8760	744	4	20,00%	1
	Switch failure/damage	8760	744	4	100,00%	1
	Inverter firmware issue	8760	744	4	0,00%	1
	Polluted air filter - derating	8760	744	4	20,00%	1
	Inverter pollution	8760	744	4	1,00%	1
	Data entry broken	8760	744	4	0,00%	1
	Display off (broken or moisture inside of it	8760	744	4	0,00%	1
	Wrong connection (positioning and numbe	8760	744	4	5,00%	1
	Burned supply cable and/or socket	8760	744	4	100,00%	1
	Inverter wrongly sized	8760	744	4	10,00%	1
	Wrong installation	8760	744	4	10,00%	1
Mounting structure	Tracker failure	8760	744	5	50,00%	1
	Not proper installation	8760	744	48	0,00%	1
	Corrosion of module clamps	8760	744	0,5	0,00%	1
	Disallignment caused by ground instability	8760	744	48	1,00%	1
	Corrosion	8760	744	24	0,00%	1
	Oil leakage	8760	744	5	0,00%	1
Combiner Boxes	IP failure	8760	744	24	0,00%	1
	Main switch open and does not reclose aga	8760	744	1	100,00%	1
	Broken/Wrong general switch	8760	744	1	100,00%	1
	Wrong wiring	8760	744	24	0,01%	1
	General switch off	8760	744	1	100,00%	1
	Wrong/Missing labeling	8760	744	1	0,00%	1
	Incorrect installation	8760	744	24	0,00%	1
	Overcurrent protection not correctly sized	8760	744	4	0,00%	1
	Broken, missing or corroded cover	8760	744	1	0,00%	1
Cabling	UV Aging	8760	744	2	1,00%	1
	Theft cables	8760	744	24	100,00%	1
	Broken cable ties	8760	744	1	0,01%	1
	Wrong connection, isolation and/or setting	8760	744	0,5	0,01%	1
	Broken/Burned connectors	8760	744	0,5	100,00%	1
	Wrong/Absent cables connection	8760	744		5,00%	1
	Wrong wiring	8760	744	0,5	1,00%	1
	Cables undersized	8760	744	48	1,00%	1
	Damaged cable	8760	744	1	15,00%	1
	improper installation	8760	744	1	1,00%	1
	Conduit failure	8760	744	2	0,10%	1
	Broken transformer	8760	744	48	100,00%	1

	Failures	Rm (average cost of detection/component) [€]	Rsu (average substitution cost /component or unit) [€]	Rr (average repair cost/component) [€]	Rp (average transport costs per component) [€]
Modules	Hotspot	0,00 €	108,00 €	0,00 €	10,00 €
	Delamination	0,00 €	108,00 €	0,00 €	10,00 €
	Glass breakage	0,00 €	108,00 €	0,00 €	10,00 €
	Soiling	0,00 €	0,00 €	0,26 €	10,00 €
	Shading	0,00 €	0,00 €	0,08 €	10,00 €
	Snail track	0,00 €	108,00 €	0,00 €	10,00 €
	Cell cracks	0,00 €	108,00 €	0,00 €	10,00 €
	Defective backsheet	0,00 €	108,00 €	0,00 €	10,00 €
	Overheating junction box	0,00 €	108,00 €	0,00 €	10,00 €
	PID = Potential Induced degradation	0,00 €	108,00 €	0,00 €	10,00 €
	Failure bypass diode and junction box	0,00 €	108,00 €	0,00 €	10,00 €
	Corrosion in the junction box	0,00 €	108,00 €	0,00 €	10,00 €
	EVA discoloration	0,00 €	0,00 €	0,00 €	0,00 €
	Theft of modules	0,00 €	108,00 €	0,00 €	10,00 €
	Broken module	0,00 €	108,00 €	0,00 €	10,00 €
	Damage by snow	0,00 €	108,00 €	0,00 €	10,00 €
	Corrosion of cell connectors	0,00 €	108,00 €	0,00 €	10,00 €
	Improperly installed	0,00 €	108,00 €	0,00 €	10,00 €
	Missing modules	0,00 €	0,00 €	0,00 €	0,00 €
Inverter	Fan failure and overheating	0,00 €	0,00 €	0,00 €	0,00 €
	Switch failure/damage	0,00 €	108,00 €	0,00 €	10,00 €
	Inverter firmware issue	0,00 €	0,00 €	377,00 €	10,00 €
	Polluted air filter - derating	0,00 €	0,00 €	377,00 €	10,00 €
	Inverter pollution	0,00 €	0,00 €	377,00 €	10,00 €
	Data entry broken	0,00 €	0,00 €	377,00 €	10,00 €
	Display off (broken or moisture inside of	0,00 €	3.770,00 €	0,00 €	150,00 €
	Wrong connection (positioning and numl	0,00 €	3.770,00 €	0,00 €	150,00 €
	Burned supply cable and/or socket	0,00 €	0,00 €	377,00 €	10,00 €
	Inverter wrongly sized	0,00 €	0,00 €	377,00 €	10,00 €
	Wrong installation	0,00 €	0,00 €	377,00 €	10,00 €
Mounting structure	Tracker failure	0,00 €	0,00 €	377,00 €	10,00 €
	Not proper installation	0,00 €	0,00 €	100,00 €	0,00 €
	Corrosion of module clamps	0,00 €	300,00 €	100,00 €	50,00 €
	Disallignment caused by ground instabili	0,00 €	300,00 €	100,00 €	50,00 €
	Corrosion	0,00 €	300,00 €	100,00 €	50,00 €
	Oil leakage	0,00 €	0,00 €	0,00 €	0,00 €
Combiner Boxes	IP failure	0,00 €	0,00 €	2,00 €	0,50 €
	Main switch open and does not reclose a	0,00 €	20,00 €	30,00 €	10,00 €
	Broken/Wrong general switch	0,00 €	50,00 €	0,00 €	20,00 €
	Wrong wiring	0,00 €	2,00 €	0,00 €	0,50 €
	General switch off	0,00 €	10,00 €	0,00 €	2,00 €
	Wrong/Missing labeling	0,00 €	100,00 €	0,00 €	10,00 €
	Incorrect installation	0,00 €	0,00 €	5,00 €	1,00 €
	Overcurrent protection not correctly size	0,00 €	0,00 €	0,00 €	0,00 €
	Broken, missing or corroded cover	0,00 €	0,00 €	0,00 €	0,00 €
Cabling	UV Aging	0,00 €	0,00 €	10,00 €	2,00 €
	Theft cables	0,00 €	10,00 €	0,00 €	2,00 €
	Broken cable ties	0,00 €	50,00 €	0,00 €	20,00 €
	Wrong connection, isolation and/or setti	0,00 €	50,00 €	0,00 €	10,00 €
	Broken/Burned connectors	0,00 €	50,00 €	0,00 €	10,00 €
	Wrong/Absent cables connection	0,00 €	10,00 €	0,00 €	1,00 €
	Wrong wiring	0,00 €	50,00 €	0,00 €	10,00 €
	Cables undersized	0,00 €	0,00 €	0,00 €	0,00 €
	Damaged cable	0,00 €	1,50 €	0,00 €	1,00 €
	improper installation	0,00 €	1,50 €	0,00 €	1,00 €
	Conduit failure	0,00 €	0,00 €	0,00 €	0,00 €
	Broken transformer	0,00 €	50,00 €	0,00 €	10,00 €

Appendix B Development of the Performance Loss of the failure after 3 years

Failures	Power loss [%]	Max power loss [%]
Hotspot	2.00%	20.00%
Delamination	1.00%	30.00%
Glass breakage	10.00%	50.00%
Soiling	10.00%	30.00%
Shading	10.00%	40.00%
Snail track	1.00%	8.00%
Cell cracks	1.00%	15.00%
Defective backsheet	1.00%	20.00%
Overheating junction box	1.00%	33.00%
PID = Potential Induced degradation	10.00%	70.00%
Failure bypass diode and junction box	33.00%	33.00%
Corrosion in the junction box	1.00%	33.00%
EVA discoloration	0.0%	10.0%
Theft of modules	100.00%	100.00%
Broken module	100.00%	100.00%
Slow reaction time for warranty claims, Vague or inappropriate definition of procedure for warranty claims	100.00%	100.00%
Special climatic conditions not considered (salt corrosion, ammonia, hail, ...)	10.00%	10.00%
Unfortunate sorting of module power	2.50%	5.00%
Damage by snow	100.00%	100.00%
Corrosion of cell connectors	1.00%	15.00%
Unsufficient theft protection	0.00%	100.00%
Improperly installed	5.00%	20.00%
Module damaged due to fire	100.00%	100.00%
Missing modules	100.00%	100.00%

Appendix C Costs and FIT per country

Country	Labor Cost [€]	Specific prod. [kWh/kWp]	FIT [€/kWh]
Germany	31,43 €	936	0,25 €
Italy	28,30 €	1326	0,25 €
Spain	21,27 €	1600	0,25 €
Portugal	25,00 €	1500	0,25 €
France	34,58 €	1100	0,25 €
UK	22,31 €	970	0,25 €
Netherlands	34,04 €	950	0,25 €
Romania	4,63 €	1200	0,25 €
Malaysia	25,00 €	1500	0,25 €
Ukraine	25,00 €	1500	0,25 €
Greece	25,00 €	1500	0,25 €
Bulgaria	25,00 €	1500	0,25 €
Czech Republik	25,00 €	1500	0,25 €

Appendix D Example of the costs of the mitigation measures (3 MWp PV plant)

Measure	Cost
Component testing • PID Testing -1000 V, 25°C, 168 hours • Electroluminescence Imaging • STC Power measurements	**3€ /kWp** • 0,6 €/kWp • 0,6 €/kWp • 1,2 €/kWp
Design verification • Site evaluation • Shadow	**5 €/kWp** • 0,4 €/kWp • 0,16 €/kWp
Transportation and construction monitoring • Construction monitoring	**5 €/kWp?** • 2,8 €/kWp
Plant commissioning • Review of project documentation • Shadow	**4.1 €/kWp** • 0,2 €/kWp • 0,16 €/kWp
O&M • Trimming • Soiling • Inspection of the PV plant	**3,5 €/kWp/a?** • 0,08 €/kWp/a • 0,26 €/kWp/a • 1 €/kWp/a
Performance monitoring • Monitoring of the PV plant • Monitoring platform	**3 €/kWp/a?** • 1 €/kWp/a? • 2 €/kWp/a?

Appendix E Detailed description of mitigation errors

			Before detection		After detection	
Component	Project phase	Risk	Mitigation Measure	Detection type / Actions	Mitigation Measure2	Actions
A. MODULES	Product testing / development	1. Failed insulation test - modules with failed or skipped insulation test can cause dispersive and dangerous currents, leading to safety risks.	Component testing	1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Retest or reject component	1. Retest or reject 2. Warranty claim and substitution of modules
A. MODULES	Product testing / development	2. Incorrect cell soldering - imperfections in cell soldering can lead, amongst others, to corrosion, undesired electrical resistances and bad current transmission.	Component testing	1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Retest or reject component	1. Retest or reject 2. Warranty claim and substitution of modules
A. MODULES	Product testing / development	3. Undersized bypass diode - increases chances of hotspots (overheating of cells) or the damage of the bypass diode itself.	Component testing	Testing part of the modules in laboratory 1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Reject and replace component	Warranty claim and substitution of modules
A. MODULES	Product testing / development	4. Junction box adhesion - incorrect adhesion of the junction box can cause, amongst others, blocked connections interrupting module current, humidity ingress with subsequent corrosion leading to performance losses and increasing risk of electrical arcing and subsequent initiation of fire.	Component testing	1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Reject and replace component	Warranty claim and substitution of modules
A. MODULES	Product testing / development	5. Delamination at the edges - water can ingress causing humidity, oxidation, corrosion leading to performance losses and increasing risk of electrical arcing and subsequent initiation of fire.	Component testing	1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Reject and replace component	Warranty claim and substitution of modules
A. MODULES	Product testing / development	6. Arcing in a PV module - caused by damaged cell, can cause fire during the operation of the module.	Component testing	1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Reject and replace component	Warranty claim and substitution of modules
A. MODULES	Product testing / development	7. Visually detectable hotspots - cells are overheating, which has a negative impact on the energy production of the module (module degradation).	Component testing	1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Retest or reject component	1. Retest or reject 2. Warranty claim and substitution of modules
A. MODULES	Product testing / development	8. Incorrect power rating (flash test issue) - sorting of the modules by performance will not be possible, PV modules mismatch losses undefined. High uncertainty of the nominal power of the PV plant and thus uncertainties of specific yield and performance ratio (PR).	Component testing	1. Visual Inspection 2. Electroluminescence Imaging 3.Insulation measurements (wet leakage) 4.Determination of EVA Gel Content Backsheet Peel Test 5.Determination of light induced degradation (LID) after 20 kWh 6. PID Testing -1000 V, 25°C, 168 7. Hours Low light measurements 200,400,600,800 (Optional)	Retest or reject component	Warranty claim and substitution of modules
	Product testing / development	9. Uncertified components or production line - life cycle, reliability and quality of PV modules can be significantly reduced.	Component testing	1. Module technical assessment 2. Production audit 3.The manufacturing process should be according to EU and International standards	Get certification or change component	1. Test modules in independent laboratory 2. warranty claim and substitution of components
A. MODULES	PV plant planning / development	1. Soiling losses - less energy production due to soiling caused, amongst others, by pollution, bird droppings, and accumulation of dust and/or pollen. Its impact is strongly site dependent.	Design verification	1. Inspection of planning phase 2. Anti-bird construction 3. Special soiling condition must also consider e.g. landfill 4. Installation of water collection system	Preventive maintenance scope	1. Cleaning planning 2. Anti-bird construction 3. Installation of water collection system 4. Conservative soiling losses in yield estimate
A. MODULES	PV plant planning / development	2. Shadow diagram - needed to design the right layout of the PV plant. Shadowed modules can have negative impact on the production.	Design verification	1. Inspection of planning phase 2. On-site visit and 3D Modelling of the PV Plant 3. Simulation and minimization of losses	Re-design	1. Detailed 3D simulation of near and far objects 2. Rearranging of the modules 3. Remove items causing shadow if possible. 4 Reconfiguration of inverters MPPT and strings 5. Testing part of the modules in laboratory 6. Warranty claim
A. MODULES	PV plant planning / development	3. Modules' mismatch - caused by interconnection of solar cells or modules without identical electrical properties or conditions (due to soiling, shadow, etc.).	Design verification	1. Inspection of planning phase 2. Sorting of the modules 3. O&M contract 3. 3D modeling and simulation in order to minimize the losses	Re-design	1. Module binning after flash test 2. Remove items causing shadow if possible. 3 Reconfiguration of inverters MPPT and strings 4. Cleaning planning

A. MODULES	PV plant planning / development	4. Modules not certified - no quality warranty, modules of unknown origin	Design verification	1. Inspection of planning phase 2. Only certified modules must be installed 3. Inspection of the modules before the installation	Get certification or change component	1. Inspection and evaluation of the modules 2. Request for modules certifcation 3. Test modules in independent laboratory 4. Bankability assessment 5. Substitution of the modules
A. MODULES	PV plant planning / development	5. Flash test report not available or incorrect - sorting of the PV modules not possible, mismatch losses undefined.	Design verification	1. To be specified during procurement phase 2. Inspection of planning phase 3. Use updated product datasheet specification 4. Minimize the mismatch losses from the design	Perform laboratory testing and/or Re-design	1. If flash tests not available, get it from manufacturer; if incorrect test modules in independent laboratory 2. Conduct an inquiry with the manufacturer 3. Adapt mismatch losses based on flash test data 4. Minimize the mismatch losses from the design
A. MODULES	PV plant planning / development	6. Special climatic conditions not considered (salt corrosion, ammonia, etc.) - can have a negative impact on the lifecycle of all components of the PV plant.	Design verification	1. Inspection of planning phase 2. Reference projects from the same area	Re-design	1. Get certification for scpecific environment 2. Substitution of the components 3. Possible quality enhancement of the components
A. MODULES	PV plant planning / development	7. Incorrect assumptions of module degradation - Light induced degradation unclear may lead to high uncertainty of energy production.	Design verification	1. Inspection of planning phase 2. Testing part of the modules in laboratory 3. Evaluation of the meteo data	Perform laboratory testing and/or Re-design	1. Testing part of the modules in order to evaluate the electrical characteristics of the modules 2. Substitution of the modules if necessary 3. Re-calculation of expected yield 4. Check contractual agreement
A. MODULES	PV plant planning / development	8. Quality of module production unclear (lamination, soldering, etc.)	Design verification	1. Inspection of planning phase 2. Testing part of the modules in laboratory	Perform laboratory testing and/or Re-design	1. Testing part of the modules in order to evaluate the electrical characteristics of the modules 2. Production audit 3. Substitution of the modules if necessary
A. MODULES	PV plant planning / development	9. Simulation parameters (low irradiance, temperature, etc.) unclear - missing module or inverter files for simulation software (e.g. module PAN files or inverter OND files for PVSYST) - data should be reliable and certified.	Design verification	1. Inspection of planning phase 2. Testing part of the modules in laboratory 3. Evaluation of the meteo data 4. Reference PV plant from the same area	Re-design	1. Re-calculation of expected yield by a third-party institution using validated assumptions 2. Evaluation of the simulation results. 3. Replanning of the investment
A. MODULES	Transportation / installation	1. Module mishandling (Glass breakage) - incorrect transportation - logistics may lead to damaged module components.	Transportation and construction monitoring	1. Testing part of the modules in laboratory before installation 2. Sensor for the mechanical load due to transportation 3. tracking system 4. Construction monitoring	Replace component	1. Testing part of the modules in laboratory 2. Evaluation of the results 3. Claim of warranty 4. Substitution of the modules if necessary
A. MODULES	Transportation / installation	2. Module mishandling (Cell breakage) - incorrect transportation - logistics may lead to damaged module components.	Transportation and construction monitoring	1. Testing part of the modules in laboratory before installation 2. Sensor for the mechanical tension due to transportation 3. tracking system 4. construction monitoring	Replace component	1. Testing part of the modules in laboratory 2. Evaluation of the results 3. Claim of warranty 4. Substitution of the modules if necessary
A. MODULES	Transportation / installation	3. Module mishandling (Defective backsheet) - incorrect transportation - logistics may lead to damaged module components.	Transportation and construction monitoring	1. Testing part of the modules in laboratory before installation 2. Sensor for the mechanical load due to transportation 3. tracking system 4. Construction monitoring	Replace component	1. Testing part of the modules in laboratory 2. Evaluation of the results 3. Claim of warranty 4. Substitution of the modules if necessary
A. MODULES	Transportation / installation	4. Bad wiring without fasteners - mechanical tension that may lead to loose connections and even permanent disconnection of modules/strings causing subsequent performance loss and safety risks.	Construction monitoring and plant commissioning	1. Inspection of the installation phase	Reinstall component	1. Re- Installation of the cables 2. Substitution of damaged components
A. MODULES	Operation / maintenance	1. Hotspot - overheating of cells etc. can cause burn marks. Temperature difference between neighbour cells should not be over 30°C. Infrared cameras can be used for imaging the defects of the modules. Hotspots can also identified by visual inspection from the rear side of the module.	O&M plan	Inspection of the PV Modules - IR Images	Replace component	1. Determination of root cause by testing the modules in the laboratory 2.Warranty claim and substitution of the modules
A. MODULES	Operation / maintenance	2. Delamination - separation of cells from tedlar, usually caused by insufficient lamination process e.g. too short lamination times. Humidity can be induced and cause oxidation, corrosion etc.	O&M plan	Inspection of the PV Modules - Visual Inspection	Replace component	1. Testing of modules in Laboratory and warranty claim 2. Substitution of the modules if necessary
A. MODULES	Operation / maintenance	3. Glass breakage - during operation due to thermal shock, mishandling by the operator, etc.	O&M plan	Inspection of the PV Modules - Visual Inspection	Replace component	1. Determination of root cause by testing the modules in the laboratory 2.Warranty claim and substitution of the modules
A. MODULES	Operation / maintenance	4. Soiling losses - due to operational conditions: e.g. smog, sand particles, bird droppings, etc. Its impact is strongly site dependent.	O&M plan	1. Advanced monitoring 2. Water availability on site 3. Clarification of soiling detection procedure	Preventive maintenance scope	1. Cleaning of the modules
A. MODULES	Operation / maintenance	5. Shading losses - during operation due to growing vegetation on the front side of the module, object recently installed.	O&M plan	1. Advanced monitoring 2. Damages due to trimming must be covered by the O&M company	Preventive maintenance scope	1. Trimming of nearby vegetation

A. MODULES	Operation / maintenance	6. Snail track - discoloration effect, mainly caused by micro cracks in solar cells. Can be only detected by visual inspection or electroluminescence (EL) of the PV modules.	O&M plan	Inspection of the PV Modules - Visual Inspection	Preventive maintenance scope	1. Inspection of the failures and warranty claim or module replacement if applicable
A. MODULES	Operation / maintenance	7. Cell cracks - due to mechanical or thermal loads. It can be detected during EL image inspection of the module.	O&M plan	Inspection of the modules - Electro Luminescence test	Preventive maintenance scope	1. Inspection of the failures and warranty claim or module replacement if applicable
A. MODULES	Operation / maintenance	8. PID = Potential Induced degradation - when the charged atoms are driven, from voltage potential and leakage currents, between the semiconductor material and other components of the module e.g. frame, glass etc. Low fill factor measurement might indicate PID phenomenon.	Performance monitoring	1. Recurrent monitoring reporting 2. Inspection of the P/V modules - thermography	Corrective maintenance scope	1. Testing of modules in Laboratory and warranty claim 2. Application of corrective measures 2. Substitution of the modules if necessary
A. MODULES	Operation / maintenance	9. Failure of bypass diode and junction box - may cause heating of the cells, or reduce the generated energy. The defective diode can be detected by opening the junction box or by measuring the open circuit voltage of the module.	O&M plan	1. Advanced monitoring 2. Inspection of the P/V modules - thermography	Replace component	1. Testing of modules in Laboratory and warranty claim 2. Substitution of the modules if necessary
A. MODULES	Operation / maintenance	10. Corrosion in the junction box - may cause defective bypass diodes leading to a significant reduction of the produced energy and increasing risk of electrical arcing and subsequent initiation of fire.	O&M plan	1. Inspection of the P/V modules	Replace component	1. Testing of modules in Laboratory and warranty claim 2. Substitution of the modules if necessary
A. MODULES	Operation / maintenance	11. Theft or vandalism of modules - significant reduction in the energy production.	O&M plan	1. Advanced monitoring 2. Visual inspection 3. Insurance contract 4. CCTV	Insurance	1. Payout from insurance company 2. Install/improve security system
A. MODULES	Operation / maintenance	12. Module degradation - may lead to lower energy production than predicted.	Performance monitoring	1. Recurrent monitoring reporting 2. Inspection of the P/V modules - electrical characteristics, IR image, EL test	Preventive maintenance scope	1. Testing of modules in Laboratory and warranty claim (Module manufacturer, EPC or O&M depending on root cause) 2. Substitution of the modules if necessary
A. MODULES	Operation / maintenance	13. Slow reaction time for warranty claims, vague or inappropriate definition of procedures for warranty claims.	Component supply agreement	1. Module supply agreement 2. Availability contract	Spare parts stock management	1. Spare parts stock management, 2. Payout from O&M company (penalty on performance/availability)
A. MODULES	Operation / maintenance	14. Spare PV modules not available or module manufacturer no longer existing or producing - costly string reconfiguration may contribute to additional costs for repair.	O&M plan	1. During the planning phase spare modules must be considered	Spare parts stock management	1. Spare parts stock management, 2. O&M penalty on performance/availability 3. Substitution of the damaged modules with modules with similar electrical characteristics
A. MODULES	Decommissioning	1. No product recycling procedure defined or implemented.	Environmental study	1 .Implementation of environmental study	Plan decommissioning phase	1. Disposal of PV-Waste according legislation
B. INVERTERS	Product testing / development	1. Inverter derating might start at approximately 40 °C working temperature - Temperature derating occurs when the inverter reduces its power in order to protect the sensitive semiconductor components from overheating. The power is reduced in steps and in extreme cases the inverter will shut down completely. This procedure is working properly if the temperature sensors and DC operating voltage are properly set up in the device software during the manufacturing process.	Component testing	1. Inverter type test 2. Inspection of the design and sizing phase 3. Sizing of the inverters from the manufacturer	Replace component	1. Investigation of the failure and detection of the root cause 2. Reconfiguration of the inverter 3. Substistution of the inverters
B. INVERTERS	Product testing / development	2. Maximum Power Point Tracker (MPPT) issues - During the manufacturing process and certification of the inverter the software architecture does not fulfil the technical requirement. As a consequence the inverter's software is not able to properly run the MPPT procedure. This leads to inaccuracy when following the Maximum Power Point, in case of variable weather conditions or different relative Maximum Power Points.	Component testing	1. Inverter type test 2. Manufacturing process must be certified 3. All the components of the inverter must be certified as well	Replace component	1. Investigation of the failure and detection of the root cause 2. Reconfiguration of the inverter 3. Substistution of the inverters
B. INVERTERS	PV plant planning / development	1. Inverter wrongly sized - Not properly considered during the planning of the electrical characteristics of the conversion group. The maximum voltage of the PV module string has to be calculated not only at nominal temperature of 25 °C, but also considering the temperatures at operating conditions. This is especially important for the early hours in the morning. Wrong dimensioning of the inverter may lead to dangerous over voltages and to the breakdown of the device or void of warranty.	Design verification	1. Inspection of the design and sizing phase 2. Sizing of the inverters from the manufacturer	Re-design	1. Proper inverter sizing considering operating conditions 2. Reconfiguration of the inverter 3. Substistution of the inverters
B. INVERTERS	PV plant planning / development	2. No protection against overvoltage - Overvoltage protection serves to prevent damage to the inverters as a result of excessive voltages. It is intended to prevent damage to buildings and the photovoltaic system due to lightning strikes. Overvoltage protection is strictly required in case of photovoltaic plants installed on buildings and in any case, it is recommended to carry out a risk analysis for ground mounted PV plants.	Design verification	1. Inspection of the design and sizing phase 2. Order inverters with surge protection devices 3. Order surge protection devices independently from the inverter	Re-design	1. Add surge protection devices in the inverterer if it is possible 2. Install a combiner boxes with surge protection devices 3. Replacement of the inverter

B. INVERTERS	PV plant planning / development	3. IP number does not comply with installation conditions - The IP codification defines the operating conditions of electrical devices. As a component of a PV installation the inverter could be installed outside or inside the building, room, cabinet, etc. For the same device, mainly inverters, it could have both configurations indoor/outdoor, following the technical requirements of the inverter installation.	Design verification	1. Inspection of the design and sizing phase 2. Protect inverter against weather conditions	Re-design	1. Additional structure for the protection of the inverter against weather conditions 2. Select different inverter
B. INVERTERS	PV plant planning / development	4. Inverter cabinet not sufficiently ventilated - Air is supplied through the fan grills inside the inverter to cool down its operating temperature. The exhaust air is emitted through the ventilators and must be ducted away from the device to avoid power derating and possible thermal damage which may lead to short circuits. Inverter manufacturers recommend a sufficient airflow around the device and, especially for central inverters, the installation of a ventilation system into the inverter cabinet. On-site measures must be taken to ensure that supply air and exhaust air are ducted separately and that there is always an adequate supply of fresh air.	Design verification	1. Inspection of the design and sizing phase 2. The installation manual of the manufacturer must be strictly taken into consideration	Re-design	1. Re-configuration of the inverter's cabinet 2. Outdoor installation of the inverters if it is possible 3. Select different inverter
B. INVERTERS	PV plant planning / development	5. Inverter wrongly sized - excessive derating. Low performance operating area - The optimal sizing ratio according to specific yield will vary from system to system, based on the designers' allowances for the various derating factors. It is common in industry to oversize the PV array by using a PV array/inverter sizing ratio of around 1.15. Oversizing the array ensures that the inverter is driven always to its maximum output, at least during the best sun hours of the day. Going above a limit value of 1.3 bring the inverter to the limit operating conditions with consequences of overheating and a power derating.	Design verification	1. Inspection of the design and sizing phase 2. The installation manual of the manufacturer must be strictly taken into consideration	Re-design	1. Re-sizing of the inverters with a view of optimal sizing ratio considering manufacturer's allowances for the varios derating factors 2. Re-arranging of the modules if necessary 3. Select different inverter
B. INVERTERS	PV plant planning / development	6. Inverter exposed to direct sunlight - Derating - To prevent overheating, power derating caused by exposure to direct sunlight must be avoided. Typical examples are: inverters installed in locations exposed to direct sunlight, locations without air circulation and inverters installed one above the other. These situations lead to a localised increase in operating temperature.	Design verification	1. Inspection of the design and sizing phase 2. The installation manual of the manufacturer must be strictly taken into consideration	Re-design	1. Additional structure for the protection of the inverter against weather conditions. 2 Select different inverter
B. INVERTERS	PV plant planning / development	7. Non-availability of spare parts - Especially for large PV installations, the probability of one failure during 20 years' lifetime should be considered. Therefore, it is recommended to consider already in the planning phase the availability of a minimum number of spare parts or components. This will lead to a significant reduction of the plant downtime.	Design verification	1. Warehouse - spair parts 2. Availability contract with the manufacturer of the inverter 3. In case of design with string inverter additional spair inverters must be considered during the desing phase 4. Availability of certified technician must be also taken into account	Preventive maintenance scope	1. Foresee spare parts 2. Manufacturer warranty 3. Select different inverter
B. INVERTERS	PV plant planning / development	8. Special climatic conditions not considered (altitude, temperature, salt mist near the sea, etc.) - the installation manual of the inverter must be respected; void of warranty is possible.	Design verification	1. Inspection of the design and sizing phase 2. The installation manual of the manufacturer must be strictly taken into consideration	Re-design	1. Select inverter considering special site-specific conditions 2. Additional structure for the protection of the inverter against weather conditions
B. INVERTERS	PV plant planning / development	9. Simulation parameters (low irradiance, temperature dependencies, etc.) unclear - this might lead e.g. to wrong sizing of the inverter and hence to reduced production.	Design verification	1. Inspection of the design and sizing phase 2. Sizing of the inverters from the manufacturer	Re-design	1. Re-calculation of expected yield (use third party certified simulation parameters) 2. Reconfiguration of the inverters 3. Select different inverters if necessary
B. INVERTERS	PV plant planning / development	10. PID Degradation is a potential induced performance degradation in crystalline PV modules. The cause of the harmful leakage currents, besides the structure of the solar cell, is the voltage of the individual PV modules to the ground. The installation of an inverter with transformer can be considered as mitigation measure for the PID phenomenon. On the other hand, the trade-off with the inverter efficiency and the cost of the inverter must be taken into account.	Design verification	1. Inspection of the design and sizing phase 2. Consideration of special weather conditions 3. Consideration of PID failures for the specific combination of modules and invterters	Re-design	1. Inverter with transformer 2. Installation of additional devices for the elimination of the PID 2. Galvanic isolation using an isolation transformer

B. INVERTERS	Transportation / installation	1. Inverter configuration (e.g. parallel versus independent MPP tracker, global MPP tracking) - the configuration must be according to manufacturer and parallel MPP tracker must be avoided if it is possible.	Construction monitoring and plant commissioning	1. Inspection of the installation phase 2. The installation manual of the manufacturer must be strictly taken into consideration 3. Sizing of the inverter from the manufacturer	Reinstall component	1. Reconfiguration of the inverter following manufacturer instructions 2. Substistution of the inverters if necessary
B. INVERTERS	Transportation / installation	2. Fuse is not adapted to the cross-section - this might cause the damage of the cable or the damage of the fuse	Construction monitoring and plant commissioning	1. Inspection of the installation phase 2. The installation manual of the manufacturer must be strictly taken into consideration 3. Sizing of the inverter from the manufacturer	Replace component	1. Substitution of the fuses 2. Testing the quallity of the cables
B. INVERTERS	Transportation / installation	3. Missing contact protection - due to missing parts or forgotten to be installed. Dangerous situation for the personnel working at the PV plant.	Construction monitoring and plant commissioning	1. Inspection of the installation phase 2. The installation manual of the manufacturer must be strictly taken into consideration 3. The installation must be fullfil all the safety requirements	Install missing component	1. Installation of the components for the contact protection
B. INVERTERS	Transportation / installation	4. Inverter does not include surge protection - damage of the electronic equipment of the inverter might occur. If there are no SPDs in the DC and AC side of the inverter, due to wrong PV planning development, great loss of production might occur	Construction monitoring and plant commissioning	1. Inspection of the installation phase 2. Order inverters with surge protection devices 3. Order surge protection devices independently from the inverter	Install missing component	1. Add surge protection devices in the inverterer if it is possible 2. Install a combiner boxes with surge protection devices 3. Replacement of the inverter
B. INVERTERS	Operation / maintenance	1. Fan failure and overheating - may cause the temperature derating and reduce the production. Following the inverters' error message, appropriate measures must be taken immediately.	O&M plan	1. Advanced monitoring 2. Inspection of the inverter	Corrective maintenance scope	1. Replacement of inverter fan if permisible 2. Warranty claim
B. INVERTERS	Operation / maintenance	2. Switch failure/damage - due to many operations or defect from the manufacturer, etc. The disconnection of the inverter or the PV modules connected to it (for maintenance or troubleshooting purposes), requires more complex procedures leading to safety risks.	O&M plan	1. Advanced monitoring 2. Inspection of the inverter	Corrective maintenance scope	1. Substitution of the switch if permissible 2. Warranty claim
B. INVERTERS	Operation / maintenance	3. Inverter theft or vandalism - Theft or vandalism are frequent events concerning PV installations, especially in ground-mounted systems installed in remote areas. These criminal acts can force the plant to stop for several weeks and are extremely difficult to prevent. Beside the technical replacement of the stolen electrical components, there is a non-negligible work updating the plant documentation with new inverter datasheet or serial number	O&M plan	1. Advanced monitoring 2. Visual inspection 3. Insurance contract 4. CCTV	Replace component	1. Payout from insurance company 2. Install/improve security system
B. INVERTERS	Operation / maintenance	4. Fault due to grounding issues, e.g. high humidity inside the inverter.	O&M plan	1. Advanced monitoring 2. Inspection of the inverter	Corrective maintenance scope	1. Investigation of the failure and detection of the root cause 2. Reconfiguration of the inverters to correct grounding 3. Substistution of the inverters or defective part if necessary
B. INVERTERS	Operation / maintenance	5. Inverter firmware issue - updating the firmware for technical reasons and to update the system to new standards/grid technical requirements.	O&M plan	1. Advanced monitoring 2. Inspection of the inverter	Corrective maintenance scope	1. Verification of documentation of changes 2. Reconfiguration of the inverter 3. Warranty claim
B. INVERTERS	Operation / maintenance	6. DC entry fuse failure causing PV array disconnection - due to undersizing of the fuse or oversizing of the PV array.	O&M plan	1. Advanced monitoring 2. Inspection of the inverter	Corrective maintenance scope	1. Substitution of the fuses if permissible 2. Testing the quality of the cables 3. Warranty claim
B. INVERTERS	Operation / maintenance	7. Inverter not operating (inverter failure or inverter stops working after grid fault) - due to wrong configuration or malfunction of the inverter.	O&M plan	1. Advanced monitoring 2. Inspection of the inverter	Corrective maintenance scope	1. Investigation of the failure and detection of the root cause 2. Reconfiguration of the inverters 3. Substistution of the inverters if necessary 4. Warranty claim
B. INVERTERS	Operation / maintenance	8. Inverter damage due to lightning strike - European standards require the protection of metallic structures and electronic devices against lightning strike. The anti-lighting system protection can protect the plant for being stopped for several weeks and substitution of expensive components	O&M plan	1. Advanced monitoring 2. Inspection of the inverter 3. Insurance contract against force majeure 4. Installation of SPDs and lighting strike systems.	Corrective maintenance scope	1. Payout from insurance company 2. Replacement of damaged components 3. installation of protection against direct and indirect lighting strike
B. INVERTERS	Operation / maintenance	9. Slow reaction time for warranty claims, vague or inappropriate definition of procedure for warranty claims -. The definition of clear procedures in case of theft, vandalism, component breakdown, is fundamental to act quickly and efficiently, replacing or repairing system components. Clear definition of subjects involved at different levels and their responsibility (ownership, system installer, O&M, component/service supplier) should help to elaborate and close the claim in a short time period.	Component supply agreement	1. Inverter supply agreement 2. Availability contract	Spare parts stock management	1. Spare parts stock management 2. Extended service agreement 3. O&M penalty on performance/availability 4. Payout from manufacturer or O&M company
B. INVERTERS	Decommissioning	1. Inverter size and weight - The standard WEEE (Waste of electric and electronic equipment), defines the inverter as electrical device. The sustainable decommissioning has to be considered technically and economically. Parameters such as easy access to the device, device locations in the PV system, inverter size and weight, become relevant planning input	Environmental study	1. Environmental study including the decommisioning proposals	Plan decommissioning phase	1. Responsible companies for such waste must be contacted