PV Performance and Reliability

David Moser
Eurac Research is a private research centre founded in 1992 in Bolzano (South Tyrol).
The Institute for Renewable Energy at Eurac Research conducts applied research on how to produce energy using advanced energy systems based on sustainable energy sources, how to manage them and reduce their consumption.
We study and execute **products, technologies and solutions** for private businesses, utilities, public administrations, researchers and professionals working in **several sectors**.

**Sustainable Heating and Cooling Systems**

**Photovoltaic Energy Systems**

**Energy efficient buildings**

**Energy Retrofit of Historic Buildings**

**Urban and Regional Energy Systems**
~ 100 collaborators
~ 50 projects and consultancies
7 labs
Photovoltaic Energy System group: Our topics
Quality and Sustainability of the PV sector

Performance & Reliability

PV in buildings

PV in grids

Solar Resource Assessment

Solar economics
Impact strategy
European PV Technology and Innovation Platform
Member of the steering committee

Contribution on ad-hoc groups:
BIPV
LCOE
Grid integration
Quality

The Association of the European Renewable Energy Research Centres

Pushing renewables and energy efficiency in the EC agenda

PVPS TASK 13
PVPS TASK 15

Performance and Reliability
BIPV

PEARL PV

Performance and Reliability
Quality
BIPV
Grid integration

WG1 TC82

Norms and standardisation
The Quest for Quality
Does quality have a real impact on the LCOE?
- quality in PV has a leverage effect with the benefits that can clearly offset the added costs
- bankability is a variable concept depending on stakeholders and context while quality is an absolute value
- feedback loop from downstream to upstream is essential to define what is really needed in terms of quality checks of PV components
- large scale performance data are much needed to be able to better assess and improve the assumptions in business models
The journey: quality, performance and reliability

PV performance database

Failure review in the field

Uncertainty framework

Technical risk framework

Technical risk framework

CPN methodology

PV performance database

Industry 4.0 + IoT platform

Big data analytics
IEA PVPS Task 13: ST2 activities

Shared Data

Advanced diagnostics

Soiling

Performance Loss Rate

Climatic rating

Yield assessments

Plant availability

Predictive models

Climate dependent performance

Shared Methodologies
Technical risks framework
Tracking defects in the field

**TASK13: Review of Failures of Photovoltaic Modules, M. Köntges et al**

Failure description → Failure mechanisms and detection → Performance loss

Majority of returns associated with failures that can be detected visually (underestimation of other type of failures?)

Systematic use of visual inspection → Large dataset of failures

Large datasets available from:
- Field inspections
- O&M ticketing system
- Insurance claims
- Third party review

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**Claims expenditure (Cause)**
- Storm: 15%
- Lightning/Surge: 25%
- Fire: 6%
- Theft: 41%
- Solar Pressure: 19%
- Hail: 7%
- Animal Bite: 7%
- Others: 7%

**Claims number (Cause)**
- Storm: 49%
- Lightning/Surge: 28%
- Fire: 17%
- Theft: 7%
- Solar Pressure: 7%
- Hail: 7%
- Animal Bite: 7%
- Others: 7%

**Claims number (Components)**
- Storm: 43%
- Lightning/Surge: 26%
- Inverter: 13%
- Module: 11%
- Cabling: 7%
- Monitoring: 7%
- Others: 7%
Risk assessment

The risks stay with the owner/operator of the system. Risks can be vastly reduced and transferred.
Technical risk framework

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tr>
<td>A</td>
<td>Risk identification</td>
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<td>B</td>
<td>Risk assessment</td>
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<tr>
<td>C</td>
<td>Risk management</td>
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<tr>
<td>D</td>
<td>Risk controlling</td>
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www.solarbankability.eu
### Technical Risks Matrix

<table>
<thead>
<tr>
<th>Product Development</th>
<th>Assessment of PV Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product testing</strong></td>
<td><strong>Planning</strong></td>
</tr>
<tr>
<td><strong>Transportation / installation</strong></td>
<td><strong>O&amp;M</strong></td>
</tr>
<tr>
<td><strong>Decommissioning</strong></td>
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#### Modules
- Insulation test
- Incorrect cell soldering
- Undersized bypass diode
- Junction box adhesion
- Delamination at the edges
- Arcing spots on the module
- Visually detectable hot spots
- Incorrect power rating (flash test issue)
- Uncertified components or production line

- Soiling
- Shadow diagram
- Modules mismatch
- Modules not certified
- Flash report not available or incorrect
- Special climatic conditions not considered (salt corrosion, ammonia, ...)
- Incorrect assumptions of module degradation, light induced degradation unclear
- Module quality unclear (lamination, soldering)
- Simulation parameters (low irradiance, temperature…) unclear, missing PAN files

- Module mishandling (glass breakage)
- Module mishandling (cell breakage)
- Module mishandling (defective backsheets)
- Incorrect connection of modules
- Bad wiring without fasteners

- Hotspot
- Delamination
- Glass breakage
- Soiling
- Shading
- Snail tracks
- Cell cracks
- PID
- Failure bypass diode and junction box
- Corrosion in the junction box
- Theft of modules
- Module degradation
- Slow reaction time for warranty claims, vague or inappropriate definition of procedure for warranty claims
- Spare modules no longer available, costly string reconfiguration

- Undefined product recycling procedure
## Technical Risks Matrix

### Product Development

- **Assessment of PV Plants**

### Product testing

<table>
<thead>
<tr>
<th>Modules</th>
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#### List of failures

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### Uncertainty

20
## Technical Risks Matrix

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### List of failures

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- Shadow diagram
- Modules mismatch
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**Uncertainty**

**List of failures**
## Modules
- Inverter
- Mounting structure
- Connection & distribution boxes
- Cabling
- Potential equalization & grounding, LPS
- Weather station, communication, monitoring
- Infrastructure & environmental influence
- Storage system
- Miscellaneous

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- Module mishandling (glass breakage)
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### Assessment of PV Plants

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### Assessment of PV Plants

- Hotspot
- Delamination
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- Theft of modules
- Module degradation
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- Spare modules no longer available, costly string reconfiguration

### Quantifiable impact

**List of failures:**

- **Product Development**
- **Assessment of PV Plants**

**O&M**
## Technical Risks Matrix

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- Soiling
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### Indirect impact
Classification of technical risks

- Category of risk
- Common nomenclature
- Standardised quantification

Risk Matrix

- Year 0 risks
- Uncertainty
- Precursors
- Indirect impact

Impact
- on uncertainty (exceedance Probability)
- on CAPEX
- on CPN (O&M)
| A | Risk identification |
| B | Risk assessment     |
| C | Risk management     |
| D | Risk controlling    |
FMEA approach

<table>
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<tr>
<th>Severity</th>
<th>Criteria</th>
<th>Ranking</th>
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<tr>
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<td>No effect, Performance loss &lt; 0.5%</td>
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<tr>
<td>Low</td>
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<tr>
<td></td>
<td>Performance loss &lt; 3 %</td>
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<tr>
<td>Moderate</td>
<td>Performance loss &lt; 5 %</td>
<td>4</td>
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<tr>
<td></td>
<td>Performance loss &lt; 10 %</td>
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<tr>
<td>High</td>
<td>Performance loss &lt; 25 %</td>
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<tr>
<td></td>
<td>Performance loss &gt; 25%</td>
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<tr>
<td>Safety risk without performance loss</td>
<td>Safety risk without performance loss</td>
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<td>Safety risk with performance loss</td>
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</tr>
<tr>
<td>Death, fire, total loss</td>
<td>Safety hazard</td>
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RPN = S x O x D

In Solar Bankability we have created a cost based FMEA methodology
Quantification of the economic impact of technical risks

- Risks to which we can assign an uncertainty (e.g. irradiance) → Impact on financial exceedance probability parameters

- Risks to which we can assign a Cost Priority Number CPN (e.g. module and inverter failure) given in Euros/kWp/year → Impact on cash flow
Quantification of the economic impact of technical risks

- Risks to which we can assign an uncertainty (e.g. irradiance) → Impact on financial exceedance probability parameters
Calculation of uncertainty

Uncertainties in PV System Yield Predictions and Assessments

Christian Reise, Alexandra Schmid, Björn Müller, Daniela Dimberger, Nils Reich, Giorgio Belluardo, David Moser, Philip Ingenhoven, Mauricio Richter, Joshua S. Stein, Clifford W. Hansen, Anton Driesse, Lyndon Frearson, Bert Herteleer

IEA PVPS Task 13, Subtasks 2.3 & 3.1 Report IEA-PVPS T13-12:2018 April 2018
Irradiance measurements and solar resource assessment: irradiance variability and trends

IEA PVPS Task 13, Subtasks 2.3 & 3.1 Report IEA-PVPS T13-12:2018 April 2018
Irradiance measurements and solar resource assessment: G_POA, decomposition and transposition models

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<td></td>
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<td>3.0%</td>
<td>4.2%</td>
<td>3.1%</td>
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GHI
Diffuse HI
Direct HI
Reflected HI
GTI
Temperature: environmental conditions and module temperature calculation

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<tr>
<th>nr</th>
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<th>Stratigraphy</th>
<th>Frame</th>
<th>$K_{mod}$ ($^\circ$C/W)</th>
<th>RMSE$k_{mod}$</th>
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<tr>
<td>1</td>
<td>CIGS3</td>
<td>CIGS</td>
<td>glass-glass (G-G)</td>
<td>WF</td>
<td>0.037</td>
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<td>mc-Si-back</td>
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<td>WF</td>
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<td>mc-Si3</td>
<td>mc-Si</td>
<td>glass-tedlar (G-T)</td>
<td>WF</td>
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<td>4</td>
<td>mc-Si1</td>
<td>mc-Si</td>
<td>glass-glass (G-G)</td>
<td>NF</td>
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<tr>
<td>5</td>
<td>mc-Si2</td>
<td>mc-Si</td>
<td>glass-glass-black sheet (G-C_b)</td>
<td>NF</td>
<td>0.035</td>
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<td>glass-tedlar (G-T)</td>
<td>WF</td>
<td>0.031</td>
<td>1.7</td>
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Maturi L., BiPV System Performance and Efficiency Drops: Overview on PV Module Temperature Conditions of Different Module Types, Energy Procedia 48 2014 1311-1319
Performance Loss Rate
State of the art
State of the art
State of the art
State of the art

\[ y = -0.88x + 0.91 \]
Work in progress

Factors affecting the overall PLR

• Data quality
• Filtering
• Metrics
• Methodologies

3 approaches to assess PLR results

• Shared algorithms/filtering used on shared data
• Confidential algorithms/filtering used on shared data
• Shared algorithms/filtering used on confidential data
Work in progress

First step is to benchmark different existing methodologies to see initial differences in the final results.
Work in progress

Benchmark will be extended to several PV plants to understand shortcomings of certain methodologies.

“Low” quality data
- pre-processed
- given PR/Power/Energy production
- Low resolution
- used only to compare PLR methods

“High” quality data
- Unfiltered PV system time series of high resolution
- can be used to compare performance models
- and filtering criteria
Work in progress (Task 13)

Benchmark will be extended to several PV plants to understand shortcomings of certain methodologies.

Is the selection of accurate methodologies dependent on the prevailing climate?
Performance Loss Rates of PV systems of Task 13 database, Sascha Lindig, David Moser, Alan Curran and Roger French, IEEE PVSC Chicago 2019
IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

PVPS TASK 13

Package in R Functions:
• Pre-defined filters
• Modelling of module temperature (NOCT and Sandia)
• PR calculation, temperature correction, monthly aggregation
• PLR calculation by applying STL and SLR
• Download of satellite irradiance & transposition to POA
Work in progress

Is a linear PLR realistic?
Work in progress

$PL_{\text{seg1}} = 0.95\%/\text{a}$  
36 months

$PL_{\text{seg2}} = -1.39\%/\text{a}$  
60 months
Quantification of the economic impact of technical risks

Shading problems due to nearby object / bad planning
Quantification of the economic impact of technical risks

161 deviations in 73 factory inspections carried out in around 2 years were identified, resulting in an average of 2.2 deviations per inspection.

Many deviations are related to determination of Pn. Overestimation of output power is a problem.
Typical uncertainty range in LTYA

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Range</th>
<th>Effect</th>
<th>Overall uncertainty range (1 STD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar resource</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climate variability</td>
<td>±4% - ±7%</td>
<td>Insolation variability</td>
<td>± 4-7% (see 5.1.1 in [1])</td>
</tr>
<tr>
<td>Irradiation quantification</td>
<td>±2% - ±5%</td>
<td>POA transposition model</td>
<td>± 2-5% (see 5.1.1 in [1])</td>
</tr>
<tr>
<td>Conversion to POA</td>
<td>±2% - ±5%</td>
<td>Temperature coefficients and temperature effects</td>
<td>± 0.02%/°C (5% relative error for crystalline silicon based modules) (lab measurements)</td>
</tr>
<tr>
<td>PV modeling</td>
<td>1°C - 2°C</td>
<td>Temperature deviation due to environmental conditions</td>
<td>1-2 °C (± 0.5-1%) (see 5.1.3 in [1]) Up to ±2% if environmental conditions are not included</td>
</tr>
<tr>
<td>PV array model</td>
<td>±1% - ±3%</td>
<td>PV array and inverter model</td>
<td>±0.2% to ±0.5% (see 5.1.3 in [1]) for the inverter model</td>
</tr>
<tr>
<td>PV inverter model</td>
<td>±0.2% - ±0.5%</td>
<td>Soiling Mismatch</td>
<td>±0.25-2% (see 5.1.2 in [1], [2])</td>
</tr>
<tr>
<td>Other</td>
<td>±5% - ±6%</td>
<td>Degradation</td>
<td>± 0.25-2% (see 5.1.2 in [1], [2])</td>
</tr>
<tr>
<td>Soiling Mismatch Degradation Cabling Availability...</td>
<td></td>
<td>Shading</td>
<td>Site dependent</td>
</tr>
<tr>
<td>Other</td>
<td>±5% - ±6%</td>
<td>Soiling Mismatch</td>
<td>±2% (see 5.1.3 in [1]) (Also site dependent)</td>
</tr>
<tr>
<td>Other</td>
<td>±5% - ±6%</td>
<td>Spectral Mismatch (modelled)</td>
<td>± 0.01% - 9% (depending on PV technologies, [3])</td>
</tr>
<tr>
<td>Other</td>
<td>±5% - ±6%</td>
<td>Nominal power</td>
<td>± 1% to ±1.5% for c-Si</td>
</tr>
<tr>
<td>Overall uncertainty on estimated yield</td>
<td>±5% - ±10%</td>
<td>Overall uncertainty on estimated yield</td>
<td>± 5-10%</td>
</tr>
</tbody>
</table>

**Typical uncertainty values (irradiance, temperature, soiling, shading, etc): ±5-10%**

• Risks to which we can assign an uncertainty (e.g. irradiance) → Impact on financial exceedance probability parameters
Objectives:
- More precise estimation of uncertainty in yield estimation
- Reduction of uncertainty

22% difference in terms of yield used in the business model
Task 13 YA exercise

Location: Bolzano, Italy
Data available since August 2010
Technology: polycrystalline-Si

Real Yield Assessments (anonymized) provided by T13 partners will be analysed and benchmarked. Uncertainty scenarios will be created to show impact on P90/P50.
Yield assessment on selected sites

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Given Latitude/Longitude, tilt angle and azimuth</td>
</tr>
<tr>
<td>Irradiance and transposition</td>
<td>Each independent YA will use their favourite database</td>
</tr>
<tr>
<td>Temperature</td>
<td>Each independent YA will use their favourite database</td>
</tr>
<tr>
<td>Technology and mismatch</td>
<td>Technology Given, each YA will apply their own considerations</td>
</tr>
<tr>
<td>Inverter</td>
<td>Given</td>
</tr>
<tr>
<td>Shading</td>
<td>Given shading diagram</td>
</tr>
<tr>
<td>Soiling</td>
<td>Each independent YA will apply their own considerations</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Each independent YA will use their favourite database</td>
</tr>
<tr>
<td>Long term insolation effects</td>
<td>Each independent YA will apply their own considerations</td>
</tr>
<tr>
<td>Degradation</td>
<td>Each independent YA will apply their own considerations</td>
</tr>
<tr>
<td>Snow loss / snow fall</td>
<td>Each independent YA will apply their own considerations</td>
</tr>
<tr>
<td>Availability</td>
<td>Each independent YA will apply their own considerations</td>
</tr>
<tr>
<td>Uncertainties</td>
<td>Please provide uncertainties for each parameter (when possible) and for the yield (compulsory). Also please provide the type of assumed distribution for each parameter (when available) and for the Yield (compulsory)</td>
</tr>
</tbody>
</table>
## Initial Yield Assessment

### PV Power Plant | Energy Yield

![Graph showing energy yield vs. probability of exceeding the estimated value.]

- **Partner 1**
  - P50: 1325 kWh/kWp
  - σ (k=2): 8.40%
  - P90: 111 kWh/kWp
  - P90/P50 ratio: 0.89

- **Partner 2**
  - P50: 1095 kWh/kWp
  - σ (k=2): 7.00%
  - P90: 77 kWh/kWp
  - P90/P50 ratio: 0.91

- **Partner 3**
  - P50: 1406 kWh/kWp
  - σ (k=2): 7.30%
  - P90: 103 kWh/kWp
  - P90/P50 ratio: 0.91

- **Partner 4**
  - P50: 1213 kWh/kWp
  - σ (k=2): 1.90%
  - P90: 23 kWh/kWp
  - P90/P50 ratio: 0.98

**Partner 4 used a specific year.**

No use of multiple irradiance sources.
### Derating factors

**Partner 3**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizon shading</td>
<td>100</td>
</tr>
<tr>
<td>Row shading</td>
<td>99</td>
</tr>
<tr>
<td>Object shading</td>
<td>99</td>
</tr>
<tr>
<td>Soiling</td>
<td>98.5</td>
</tr>
<tr>
<td>Reflection losses</td>
<td>96.4</td>
</tr>
<tr>
<td>Spectral losses</td>
<td>95.5</td>
</tr>
<tr>
<td>Irradiation-dependent losses</td>
<td>94.3</td>
</tr>
<tr>
<td>Temperature-dependent losses</td>
<td>89.2</td>
</tr>
<tr>
<td>Mismatch losses</td>
<td>88.5</td>
</tr>
<tr>
<td>DC cable losses</td>
<td>87.7</td>
</tr>
<tr>
<td>Inverter losses</td>
<td>84.1</td>
</tr>
<tr>
<td>Inverter power limitation</td>
<td>84.1</td>
</tr>
<tr>
<td>Additional consumption</td>
<td>84.1</td>
</tr>
<tr>
<td>AC cable losses low voltage</td>
<td>83.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>83.6</td>
</tr>
</tbody>
</table>

**Partner 4**

<table>
<thead>
<tr>
<th>Effective Irradiation on collectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Padding Loss</td>
</tr>
<tr>
<td>-10.6%</td>
</tr>
<tr>
<td>Stacking Loss</td>
</tr>
<tr>
<td>-2.0%</td>
</tr>
<tr>
<td>Occlusion Loss</td>
</tr>
<tr>
<td>-1.0%</td>
</tr>
<tr>
<td>Temperature Loss</td>
</tr>
<tr>
<td>0.0%</td>
</tr>
<tr>
<td>Hot Spot Loss</td>
</tr>
<tr>
<td>0.0%</td>
</tr>
<tr>
<td>Module Mismatch Loss</td>
</tr>
<tr>
<td>0.0%</td>
</tr>
<tr>
<td>Inverter Loss</td>
</tr>
<tr>
<td>0.0%</td>
</tr>
<tr>
<td>**Array Nominal Energy (at STC eff)</td>
</tr>
<tr>
<td>1,315 kWh</td>
</tr>
</tbody>
</table>

**PR:** 0.836

### Additional Diagrams

- **Horizontal global irradiation**
  - Global incident in col. plane
  - Global incident below threshold
  - Far Shading / Horizon
  - IAM factor on global
  - Soiling loss factor

- **Effective Irradiation on collectors**
  - PV conversion
  - Array nominal energy (at STC eff)
  - PV Loss due to irradiance level
  - PV Loss due to temperature
  - Module quality loss
  - LID • Light induced degradation
  - Mismatch loss, modules and strings
  - Ohmic wiring loss
  - Array virtual energy at MPP

- **Energy output**
  - 5,305 kWh
  - 5,066 kWh
  - 5,986 kWh

- **Energy injected into grid**
  - 5,305 kWh
  - 5,066 kWh
  - 5,986 kWh

**PR:** 0.75
LTYA / LTYP

Measured AC values

8.4%  5.4%

Measured AC values averaged over previous years
Repeat benchmarking exercise for other location with other climate related / technology related features (e.g. soiling, bifacials, etc)
Based on the findings of the benchmarking exercise we will show how uncertainty plays a role for various parameters.
Quantification of the economic impact of technical risks

• Risks to which we can assign a Cost Priority Number CPN (e.g. module and inverter failure) given in Euros/kWp/year → Impact on cash flow
Procedure for the calculation of a Cost Priority Number (CPN)

a) Economic impact due to downtime and/or power loss (kWh to Euros)
- Failures might cause downtime or % in power loss
- Time is from failure to repair/substitution and should include: time to detection, response time, repair/substitution time
- Failures at component level might affect other components (e.g. module failure might bring down the whole string)

b) Economic impact due to repair/substitution costs (Euros)
- Cost of detection (field inspection, indoor measurements, etc)
- Cost of transportation of component
- Cost of labour (linked to downtime)
- Cost of repair/substitution

Creating a cost-based Failure Modes and Effects Analysis (FMEA) for PV

Income reduction
Savings reduction

Increase in maintenance costs
Reduction of reserves
Technical Risks collection

CPN = $C_{\text{down}} + C_{\text{fix}}$

CPN is given in Euros/kWp/year
It gives an indication of the economic impact of a failure due to downtime and investment cost

Tickets from O&M operators as corrective or periodic maintenance in paper or electronic form

Visual and detailed inspection
Technical Risks collection

CPN is given in Euros/kW/year. It gives an indication of the economic impact of a failure due to downtime and investment cost.

\[ CPN = C_{down} + C_{fix} \]

<table>
<thead>
<tr>
<th>Components</th>
<th>Total number of plants</th>
<th>Total Power [kWp]</th>
<th>Average number of years</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>772</td>
<td>441676</td>
<td>2.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Components</th>
<th>No. tickets</th>
<th>No. Cases</th>
<th>No. Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>473</td>
<td>67801</td>
<td>205821</td>
</tr>
<tr>
<td>Inverters</td>
<td>476</td>
<td>2548</td>
<td>11967</td>
</tr>
<tr>
<td>Mounting structures</td>
<td>420</td>
<td>15809</td>
<td>43057</td>
</tr>
<tr>
<td>Connection &amp; Distribution boxes</td>
<td>221</td>
<td>12343</td>
<td>20372</td>
</tr>
<tr>
<td>Cabling</td>
<td>614</td>
<td>367724</td>
<td>238546</td>
</tr>
<tr>
<td>Transformer station &amp; MV/HV</td>
<td>53</td>
<td>220</td>
<td>558</td>
</tr>
<tr>
<td>Total</td>
<td>2257</td>
<td>1077445</td>
<td>2373222</td>
</tr>
</tbody>
</table>

- Tickets from O&M operators from preventive and corrective maintenance
- Visual and detailed PV plant inspections
Definition of scenarios

- **Never detected (CPN_{ndet})**
  
  Failure is undetected. **Losses due to downtime** over a time $t_{td}$

- **Failure fix (CPN_{failfix})**
  
  Failure is detected. 1 Month of lead time to repair/substitution

- Failures are equally distributed over time
- No increase in Performance Losses over time
- Yield is considered as an average at national level (not site specific)
- The real scenario would be a combination of the two
### Technical Risks collection: some statistics

<table>
<thead>
<tr>
<th></th>
<th>no. cases</th>
<th>no. components</th>
<th>Years</th>
<th>Share of failures</th>
<th>Share of failures/ year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>678,640</td>
<td>2,058,721</td>
<td>2.68</td>
<td>33%</td>
<td>12%</td>
</tr>
<tr>
<td>Inverters</td>
<td>2,474</td>
<td>11,967</td>
<td>2.68</td>
<td>21%</td>
<td>8%</td>
</tr>
</tbody>
</table>

#### Module Failure share

- Soiling: 23.4%
- Shading: 16.8%
- EVA discoloration: 11.6%
- Glass breakage: 6.5%
- PID: 5.0%

#### Inverter Failure share

- Fan failure and overheating: 21.8%
- Fault due to grounding issues: 4.9%
- Inverter firmware issue: 3.8%
- Burned supply cable and/or socket: 2.2%
- Polluted air filter: 3.3%
- Inverter pollution: 1.5%

### OCPN from the cost-based FMEA (power loss)

<table>
<thead>
<tr>
<th>occurrence</th>
<th>portfolio</th>
<th>affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>modules</td>
<td>1.010%</td>
<td>14.958%</td>
</tr>
<tr>
<td>inverters</td>
<td>2.687%</td>
<td>22.046%</td>
</tr>
<tr>
<td>Mounting structure</td>
<td>0.206%</td>
<td>10.820%</td>
</tr>
<tr>
<td>Connection &amp; Distribution boxes</td>
<td>0.145%</td>
<td>15.175%</td>
</tr>
<tr>
<td>Cabling</td>
<td>2.765%</td>
<td>6.855%</td>
</tr>
<tr>
<td>Transformer station &amp; MV/HV</td>
<td>0.452%</td>
<td>0.393%</td>
</tr>
</tbody>
</table>
CPN Results - Components and Market Segments

- PV modules - Utility scale

- Highest risk consists of a group of installation failures (mishandling, connection failures, missing fixation, etc.)

- Variety of failures detected by different techniques (VI, IR, EL, IV-Curves)
CPN results - Comparison studies

- Affected components vs total components: CPN ratio

Failures calculated over the whole database

Failures calculated over the affected plants
CPN results - Comparison studies

- Some failures do not occur very often and are not equally spread over the portfolio but when they do, the economic impact is very high

- High CPN ratio for product failures or non-technical factors

![Graph showing CPN results](image-url)
CPN Results - Components and Market Segments

- Inverters
## Technical risk framework

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Risk identification</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Risk assessment</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Risk management</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Risk controlling</td>
<td></td>
</tr>
</tbody>
</table>

- **Risk Mitigation**
- **Risk Transfer**

www.solarbankability.eu
Risk mitigation

CAPEX & OPEX depending on mitigation measures

\[ \Sigma \text{CPNs} = \sim \text{XX Euros/kW/y} \]

Who bears the cost? Who bears the risk?

CAPEX & OPEX depending on mitigation measures

\[ \Sigma \text{CPNs} = \sim \text{120 Euros/kW/y} \]
Mitigation Measure Approach

List of 8 defined MMs, their mitigation factors and affected parameters

<table>
<thead>
<tr>
<th>Mitigation Measure Affected Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component testing – PV modules</td>
</tr>
<tr>
<td>Design review + construction monitoring</td>
</tr>
<tr>
<td>Qualification of EPC</td>
</tr>
<tr>
<td>Advanced monitoring system</td>
</tr>
<tr>
<td>Basic monitoring system</td>
</tr>
<tr>
<td>Advanced inspection</td>
</tr>
<tr>
<td>Visual inspection</td>
</tr>
<tr>
<td>Spare part management</td>
</tr>
</tbody>
</table>

- **Preventive measures**
- **Corrective measures**
Impact of Applied Mitigation Measures

New CPN results of mitigation measure combinations for different cost scenarios compared to CPN without mitigation measures

Preventive measures have higher impact
From theory to practice
PV4.0: Use of Industry 4.0 and IoT logics in the PV sector
Different market segments

• Medium/Large PV systems: facilitate due diligence and hand-over in the secondary market / create a benchmark to compare PV plants

• Small PV systems: log every maintenance intervention to keep track of the health status of the plants and to facilitate O&M
The overall objective of the project is to develop a concept for the effective management of the activities of various stakeholders (asset managers, O&M companies, etc) inspired by Industry 4.0 and so to optimise the decision process minimising time and operational costs.
Before

.time to detection: no monitoring system or warning thresholds too broad or inaccurate (up to months to detect deviations)
.time to response: time required to organise repair or substitution.
.Time to understand the appropriate action.
.time to repair: assessment of situation only once on site

After (PV4.0ed)

.time to detection: use of advance diagnostics and predictive monitoring / big data analytics
.time to response: use of self-learning Decision Support System (DSS) to suggest actions based on techno-economic analysis
.time to repair: use of DSS to optimise spare parts management
Develop a BIM inspired system to have a 3D visualisation of PV plants

Component log

01/06/2018 Module cleaned
01/08/2018 Glass breakage identified
15/08/2018 Module substituted (spare part)
Develop the PV4.0 hardware

Use of cloud based systems
Use of wireless sensor networks

Select diagnostic tool: thermal image
Select failure: hotspot
Develop models, algorithms and big-data back-end for PV4.0

20/08/2018 Warning, deviation detected component module XY

20/08/2018 Sent operator

CPN calculation O&M strategy optimiser

Warnings

Actions
Develop the PV4.0 software
Thank you!

“We ensure quality and sustainability in a PV driven energy transition”

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