Qualification of Fire Risks at PV Systems

Dipl.-Ing. F. Reil

E-Mail: florian.reil@de.tuv.com
Internet: www.tuv.com/solar
TÜV Rheinland Group Introduction
More than 140 Years of Innovation.

We are the engine for a modern society.
For your success. With certainty.
TÜV Rheinland Group Introduction  More than 140 Years of Innovation.

Service Scope:  Testing    Inspecting    Certifying    Consulting    Public Training

Global Network

GERMAN AT HEART – GLOBAL IN MIND.

Key facts

8  Regions
500  Locations
>200  Laboratories
20,000 people around the globe work for TÜV Rheinland
12,000 of them work outside Germany
2 Bill € Turnover in 2018

North America
Central and Eastern Europe
Western Europe
Germany
Greater China
Asia Pacific
India, Middle East, Africa
South America
Global Network for Photovoltaic Products
Testing, Certification and Advisory
Milestones in the Global Solar Business.

More than 35 years of experience in photovoltaic.
TÜV Rheinland – Solar Energy Worldwide

Quality, safety and reliability around the world

**OUR GLOBAL PV NETWORK**

No 1 in PV module and component testing worldwide

35 Years experience in PV product testing

27 Years experience in Power plant inspections

6 PV test laboratories + several outdoor test fields

> 250 PV Experts

> 20 GW Inspected PV projects
Content

- Introduction
- Solar Basics
- Principle of fire and solar module operation
- Arc situation with in-roof constructions
- Fire test method for PV modules on roofs during external fires
- Summary and outlook
Photovoltaics - Basics
PV Modules, Cells, Systems
Principle Set-up of Solar Cell

- Sunlight strikes a solar cell, an electron is freed by the photoelectric effect.
- The two dissimilar semiconductors possess a natural difference in electric potential (voltage), which causes the electrons to flow through the external circuit, supplying power to the load.
- The flow of electricity results from the characteristics of the semiconductors and is powered entirely by light striking the cell.
From a Solar Cell to a PV System


Source: First Solar
Setup of a PV Module

- Voltage from the PV module is determined by the number of solar cells and the current from the module depends primarily on the size of the solar cells.
- Parallel to the strings, bypass diodes are used, in order to prevent overheating of cells from partial shading.
PV module technology
Junction box

- The PV junction box is the **output interface** of the PV module, which is attached to the back side (TPT or glass) with silicone adhesive.

- For c-Si modules it usually includes electrical terminals, to which the 4 leads of the solar cell interconnection circuit, the bypass diodes and the module cables are connected.

- The junction box must provide sufficient protection against dust and low pressure water jets. This property is expressed in the IP (Ingress Protection) rating, which shall be minimum IP65.

- Most junction boxes have bypass diodes. Their function is to protect solar cells from hot-spot heating in the case of shading or cell breakage.
System Components

Source: www.usaid.gov/
Fire Incidents on PV
Statistics, Examples of Installation Errors
Fire risk on solar systems
Survey from 2011-2013 in Germany

More than 210 known cases where faults in the PV system caused a fire

- approximately 430 cases of fire or overheating in PV systems,
- about 220 cases thereof with external causes of fire
- about 210 cases with the cause of fire lying in the PV system

Breakdown of damage according to system type (based on 139 incidents of damage)

Number of causes of damage for more than 100 cases

Source: BMWi _ Project "Determination of fire risks in solar systems" (2011-2014) - http://www.pv-brandsicherheit.de
PV System Quality

Examples for PV system failures from fault installations

- Improper cable routing
- Missing edge protection
- Defective cable fastening
- Damaged cables
- Improper cable routing
- Cable corrosion
- Improper cable connection
- Improper cable connection
PV System Quality

Examples for PV system failures

- Improper cable routing
- Lightning protection neglected
- Improper cable fittings
- Wrong cable type used
- Bad connection / arc
- Damaged module back
- Water in connection box
- Water in connection box
PV System Quality

Examples for PV system failures

- Delamination of backsheet
- Blistering after hot spot
- Improper under construction
- Installation specification not fulfilled
- Broken Connector
- Damaged frame (snow)
- Broken Module
- Broken Connector
PV System Quality

Examples for PV system failures

- Displaced Module
- Melted connector
- Corrosion at grounding point
- Erosion
- Cell breakage with Hot spot
- Burned cable/terminal
- Burned cable/terminal
- Loose Cables
PV System Quality

Examples for PV system failures

- Gunshot marks (grains of shot)
- Improper planning
- Shading
- Shading by vegetation
- Shading by vegetation
- Bad Foundation
- Corroded socket/plug
- Bad connection/Arc
PV Module Product Quality

Examples for PV module failures

- Different Connectors
- Solder joint failure
- Browning
- Backsheet cracks
- “Snail trails”
- Hot-Spots
- Connectors
- Backsheet “chalking”
External Fire or Electric Arcing
Preventive Fire Protection and Risk Reduction
Preventive fire protection

Installation, choice of materials & operation of the plant

- §14 of the MBO (Germany): Construction works are to be arranged, erected, modified and maintained in such a way that the occurrence of a fire and the spread of fire and smoke (spread of fire) is prevented and in the event of a fire the rescue of people and animals as well as effective extinguishing work are possible.

- The quantity of all fire prevention measures is composed of many requirements from the installation, material selection and operation of the system in general and with specific requirements:
  - Compliance with building and installation regulations, building regulations of the federal state
  - Obtaining advice from specialist authorities on fire protection issues
  - careful planning with qualified personnel
  - high-quality material and components
  - professional execution and acceptance Plant maintenance
Cause and effect of fires in PV systems

Electrical system as a trigger for fires

1) Triggering of a fire/fire by the PV system due to arcs at defective contact points in the module or system:

- cell connector
- cell connections
- connecting cables
- bypass diode
- plug connector
- Combiner box...

influence of the materials:
- Arc ignition
- Fire propagation during the arc
- Fire propagation after the arc has extinguished
Cause and effect of fires in PV systems

Mutual interference at defective contact points

- Increased contact resistance/heating of the contact point
- Heating and softening of the surrounding insulating material
- Reduction of air and creepage distances
- Interruption of contact points
- Inflammation of the surrounding materials
- Smoldering, flashing or electric arcing
- Possible flame preservation or stop after arc extinction on surrounding material
Reduction of Arcing Risk

Flammability of materials

2) External causes cause a fire in or at the building. As a component of the building, the PV system is "affected" by the fire. The development of the fire therefore also depends on the material properties of the PV system.

Aspects for materials in fire propagation:
- flying sparks
- Radiant heat
- Burn-through
- flame flashover
- Fire protection layer (prevention of forwarding)
- Burning dripping / falling off
- Glow/afterglow
- Smoldering
- Release of pyrolysis gases
Influencing Fires on Roofs

External Fires and Arcs
Electric Arcing
Preventive Fire Protection and Risk Reduction
Electric Arc Ignition

Current standard development on IEC level for arc detectors: IEC 63027
Fire Safety at BIPV

Influence on building materials

- Risk of ignition of materials by arcing: high temperatures
- Fire propagation risk due to ignited materials of the PV system (flame propagation, fire drip properties)
# Building Integrated Photovoltaics (BIPV)

## Roof structures and fire requirements

<table>
<thead>
<tr>
<th>Classification acc. to DIN EN 13501-1</th>
<th>Designation by Building Authorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Non-combustible (excluding shares in combustible building materials)</td>
</tr>
<tr>
<td>A2 s1 d0</td>
<td>Non-combustible (with proportions of combustible building materials)</td>
</tr>
<tr>
<td>A2 s3 d2</td>
<td>Low flame spread</td>
</tr>
<tr>
<td>B s3 d2</td>
<td>Low flame spread</td>
</tr>
<tr>
<td>C s3 d2</td>
<td>Low flame spread</td>
</tr>
<tr>
<td>D s3 d2</td>
<td>Normal inflammability</td>
</tr>
<tr>
<td>E d2</td>
<td>Normal inflammability</td>
</tr>
<tr>
<td>F</td>
<td>Easily flammable</td>
</tr>
</tbody>
</table>

s1, s2, s3 - Additional classification regarding smoke development

d0, d1, d2 - Additional classification regarding burning dripping / falling off
### Building Integrated Photovoltaics (BIPV)

#### Roof structures and fire requirements

#### Insulating materials

<table>
<thead>
<tr>
<th>Material</th>
<th>building material classes</th>
<th>flammability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass wool, rock wool</td>
<td></td>
<td>A1, A2</td>
</tr>
<tr>
<td>Flax, hemp, coconut fibres</td>
<td></td>
<td>B1, B2</td>
</tr>
<tr>
<td>Wood fibres, wood wool</td>
<td></td>
<td>B1, B2</td>
</tr>
<tr>
<td>Cellulose</td>
<td></td>
<td>B2, E (with boric salt)</td>
</tr>
<tr>
<td>Sheep’s wool</td>
<td></td>
<td>B2 (with boric salt)</td>
</tr>
<tr>
<td>Polyurethan</td>
<td></td>
<td>B1, B2</td>
</tr>
<tr>
<td>Polystyrol</td>
<td></td>
<td>B1, B2</td>
</tr>
</tbody>
</table>

#### Vapor barrier

<table>
<thead>
<tr>
<th>Material</th>
<th>building material classes</th>
<th>flammability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene foil</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Polypropylene foil</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Polyester fleece</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Vapour control board</td>
<td></td>
<td>B2</td>
</tr>
</tbody>
</table>

#### Sarking membranes

<table>
<thead>
<tr>
<th>Material</th>
<th>building material classes</th>
<th>flammability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyelofine</td>
<td></td>
<td>E</td>
</tr>
<tr>
<td>Polystere fleece</td>
<td></td>
<td>B1, E</td>
</tr>
<tr>
<td>Polypropylene-spunbonded fabric</td>
<td></td>
<td>E</td>
</tr>
</tbody>
</table>
Fire Safety at BIPV

Influence on building materials

- Measurements on isolated and ventilated systems in comparison have shown temperature differences of $\Delta T=8...20\,\text{K}$.

- Rear ventilation lower compared to roof-parallel systems: consideration of the interaction with temperature rise in junction box.

![Image of a cable with a green light near an arc ignition spot](image-url)

**Temperatures close arc ignition spot**

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>74.48</td>
</tr>
<tr>
<td>1.0</td>
<td>77.13</td>
</tr>
<tr>
<td>2.0</td>
<td>77.77</td>
</tr>
<tr>
<td>3.0</td>
<td>85.48</td>
</tr>
<tr>
<td>4.0</td>
<td>85.48</td>
</tr>
<tr>
<td>5.0</td>
<td>85.48</td>
</tr>
<tr>
<td>6.5</td>
<td>85.48</td>
</tr>
</tbody>
</table>

T. Sample, A. Virtuani: 24th EUPVSEC, Hamburg, 2010
Burning Behavior of Backsheets

Normative State of the Art

- FSI 100 through ASTM E 162 is used as pre-evaluation method for backsheets
- Determination of flame spread and propagation, evaluation of burning velocity and exhaust gas temperatures
- Standard characterizes only the single product

- RnD test series:
  - Comparison of different international standards
  - More detailed characterization of backsheets (also from both sides)
  - Derivation of end-product oriented test method
Burning Behavior of Backsheets

Set-up of test series

- Use of different foils: ETFE, TPT, PPE etc.
- Comparison with building components (sarking membrane (PA)), class B2 → European E (EN 13501-1)
- Backing materials (clamped) with CaSi-plate at ASTM E 162 and ISO 11925-2
- Comparison to European construction product classification with ISO 11925-2 on module level
- Also, testing of inner side of the backsheets foils (resulting from experiences of UL 790 tests)

<table>
<thead>
<tr>
<th>Prüfung</th>
<th>Maße</th>
<th>Dicke</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL 94</td>
<td>0,43</td>
<td>APA</td>
<td>APA</td>
</tr>
<tr>
<td>ISO 11925-2</td>
<td>0,43</td>
<td>APA</td>
<td>APA</td>
</tr>
<tr>
<td>ISO 5658-2</td>
<td>0,43</td>
<td>APA</td>
<td>APA</td>
</tr>
<tr>
<td>950/8 EG</td>
<td>0,43</td>
<td>APA</td>
<td>APA</td>
</tr>
<tr>
<td>ASTM E 162</td>
<td>0,1</td>
<td>ETFE-frontsheet-F1</td>
<td></td>
</tr>
<tr>
<td>ISO 11925-2</td>
<td>0,1</td>
<td>ETFE-frontsheet-F1</td>
<td></td>
</tr>
<tr>
<td>ISO 5658-2</td>
<td>0,1</td>
<td>ETFE-frontsheet-F1</td>
<td></td>
</tr>
<tr>
<td>950/8 EG</td>
<td>0,1</td>
<td>ETFE-frontsheet-F1</td>
<td></td>
</tr>
<tr>
<td>ASTM E 162</td>
<td>0,28</td>
<td>TPT</td>
<td>TPT</td>
</tr>
<tr>
<td>ISO 11925-2</td>
<td>0,28</td>
<td>TPT</td>
<td>TPT</td>
</tr>
<tr>
<td>ISO 5658-2</td>
<td>0,28</td>
<td>TPT</td>
<td>TPT</td>
</tr>
<tr>
<td>950/8 EG</td>
<td>0,28</td>
<td>TPT</td>
<td>TPT</td>
</tr>
<tr>
<td>ASTM E 162</td>
<td>0,35</td>
<td>PPF</td>
<td>PPF</td>
</tr>
<tr>
<td>ISO 11925-2</td>
<td>0,35</td>
<td>PPF</td>
<td>PPF</td>
</tr>
<tr>
<td>ISO 5658-2</td>
<td>0,35</td>
<td>PPF</td>
<td>PPF</td>
</tr>
<tr>
<td>950/8 EG</td>
<td>0,35</td>
<td>PPF</td>
<td>PPF</td>
</tr>
<tr>
<td>ASTM E 162</td>
<td>0,06</td>
<td>PA (Dampfsperre)</td>
<td></td>
</tr>
<tr>
<td>ISO 11925-2</td>
<td>0,06</td>
<td>PA (Dampfsperre)</td>
<td></td>
</tr>
<tr>
<td>ISO 5658-2</td>
<td>0,06</td>
<td>PA (Dampfsperre)</td>
<td></td>
</tr>
<tr>
<td>950/8 EG</td>
<td>0,06</td>
<td>PA (Dampfsperre)</td>
<td></td>
</tr>
<tr>
<td>UL 94</td>
<td>0,06</td>
<td>PA (Dampfsperre)</td>
<td></td>
</tr>
</tbody>
</table>

ASTM E 162, ISO 11925-2, ISO 5658-2, UL 94
Burning Behavior of Backsheets

Results, Derivation of Measures

- Quality and burning behavior can be determined well through all methods: quality of each foil type can be seen with same results in all methods.
- Foil types always react equally good or bad throughout the tests.
- Strong deviations: with and without backing materials of CaSi
- Best results: Single foils (frontsheet of ETFE)
- Thin foils: material abstracts from the flame. Critical in end-product: encapsulant is exposed quicker.
- All tests are suitable for pre-selection, but not for end-product-based conclusions.

Test method on ISO 11925-2 was integrated in latest IEC 61730-2 standard (safety standard) for PV modules
Risk Determination of Cell Connectors and Cells

Derivation of Stress Tests for Modules

- Test series with 30 modules:
  - Damaged modules from the field (failures at cell connectors, hot-spots were generated), technique: 2 bus bars.
  - Faultless modules, 2&3 bus bars.
- Determination and application of appropriate stress test method for reproduction of field failures. Intentionally induced stress on cell connectors under the influence of electrical, thermal and mechanical loads.

- Bypass-diodes were not dismounted → Risk minimization on product level.

Initial Measurement
Pre-conditioning: TC 400
Intermediate Measurement
Dynamic loads with forward bias
Final Measurement

08.03.2013
Fire Seminar 2019, 8 OCT, VNAB
Risk Determination of Cell Connectors and Cells Example:

worst-case-scenario (double failure)

- Example: Intentionally induced contact failures, meanderwise cutting of cell connectors. Directed current flow through the cells.
- Result after forward bias and dynamic loads: fire damage along the microcrack.
Fire Safety at Roof-Integrated BIPV

Test series – Provoked Ignition of Electric Arcs

- Miniature of regular rafter roof, wood as construction material
- Damp barrier and sarking membrane with classification of E acc. To EN 13501-1
- Insulation materials have classification ‘A’ acc. To EN 13501-1 (‘hardly flammable’)
- Provoked ignition of electric arcs at several contact spots, such as j-box and bus-bars
  - Burning dripping of housing materials
  - Undercarriage was ignited and burned.
  - Flame spread quickly via the underlayment
  - Flame propagation due to induced arcing stronger than in standard tests
  - Thermal insulation has not been ignited
  - Electric arcs have generated high pressure inside the AS box, "bursting" the lid
  - Largest risk with cable connections
### Enhanced Fire Safety at BIPV

**Derivation of Construction and Installation Measures**

<table>
<thead>
<tr>
<th>Fehlerfall</th>
<th>Auswirkung</th>
<th>Betrachtung von Gegenmaßnahmen (elektrotechnisch, baulich, konstruktiv)</th>
</tr>
</thead>
</table>
| Arc at cable or plug                                                      | ignition of the roof foil           | - Professional installation  
- Additional protection tubes  
- Suitable choice of roofing materials/constructions  
- ... |
| Hotspot on cell connectors or cells with arc ignition                      | Possible ignition of rafters         | - Use of protective tubs and mats  
- Use of protective varnishes  
- ... |
| Arc at cable clamp with open cover and burning dripping material          | Ignition of the roof foil, fire     | - Constructive: Consideration of the behaviour of j-box when igniting an arc, prevention of oxygen supply to an arc  
- Improvement of the inflammation properties of the plastic parts, strain relief  
- ... |
| Defective or detached bypass diode (possibly with arc ignition)           | Heating of the affected cell string possible in case of shading | - Ensuring sufficient heat dissipation (distance control, rear ventilation)  
- Reduction of fire hazard due to diodes (electronics, "smart j-box")?  
- ... |
| Arc at cable clamp with open cover and hot dripping material              | defective module, holes in the roof foil, leakage | - Suitable choice of substructure materials (consider building material classes: consult roofer.), use of protective varnishes for wood to question...  
- ... |

...
Fire test acc. to ANSI/UL 1703 with UL 790 (also formerly IEC 61730-2)

- Spread of Flame (gas flame) and Burning Brand
- Test method of UL 790 Standard – Fire test for roofs.
- Three classes to be tested:
  - **Class A/B:**
    - Burner class 369 kW - 387 kW
    - Flame duration 10 min
    - Brand A: 2000 g, B: 500 g
  - **Class C:**
    - Burner class 316 kW - 334 kW
    - Flame duration 4 min
    - Brand C: 10 g

Fire test mandatory, but following UL 790 non-compulsory →
reference to locally existing test codes, also EN/TS 1187...
Fire Testing for Roofs / Roof Applications in Europe

Test methods for ENV 1187 with classification of EN 13501-5

- The test sequences differentiate: source of ignition, inclination and general application (test duration, radiant sources, wind velocities)
Common Technical Challenges for BIPV

Influences of temperatures

- Various measurements on the backsides of the modules lead to the following temperatures from CEN/TS 1187-1:
  - Glass/Backsheet: 200 °C
  - ETFE/Backsheet: 125 °C
  - Glass/Glass: 500 °C
  - Glass/Backsheet: 160 °C
  - Glass/Backsheet (laminate): 160 °C

Further test methods in Europe with CEN/TS 1187-2, -3 and -4: No harmonization yet!

Fire exposure tests here are all done from the top surface.
Main Challenges for European Standard/TR for PV Modules

Main challenges:

- Positioning of sub construction and source of ignition
- Time duration
- Slope (acc. to slopes from EN 13501-5 with the used materials of the sub construction)
- Classification criteria for roof (EN 13501-5) → Harmonization to existing standards?
**Standard Situation on PV Modules**

with regards to fire from external sources

- IEC 61730-: Fire resistance requirements for a PV module intended for building applications are defined in local or national building codes → Annex B of standard enables various test set-ups and standards
- EN 61730-2 states ‘fire test under discussion’
- Standard situation on roof tests in Europe harmonized, but still range of different test methods (CEN/TS 1187-1…-4)

- BIPV is replacement of roof → CEN/TS 1187

- Roof-added and mutual reaction of PV modules to roof with source of ignition: undefined

- ABCSolar project in the US has experimented with set-ups also placing the source of ignition between modules and roof (roof-added)
CLC/TR 50670

Set-up of Gas Burner

Gas Burner of CLC/TR 50670 in comparison to EN 1187-1 wired basket
Results from Testing of Roof-Parallel PV Installation
Results from Testing of Roof-Parallel PV Installation

- No roof inflammations or critical fire transmissions at the module
- Classification of the roof remained unchanged
- Damaged area was approx. 20cm
Results from Testing of Roof-Added PV Installation (PVC+Stone Wool) / Flat-Roof
Results from Testing of Roof-Added PV Installation (PVC+Stone Wool) / Flat-Roof

- For wood wool baskets, the roof structure remained BROOF (t1), for gas burners FROOF (t1)
- For gas burners: lateral flame propagation reached the edge of the measuring zone
- Both attempts: No burn-through, no significant spread of fire
Results from Testing of Roof-Added PV Installation (2 layers Bitumen+PIR)
Results from Testing of Roof-Added PV Installation (2 layers Bitumen+PIR)

- Exceeding the measuring marks (upwards and downwards)
- For gas burners and wood wool baskets it led to a class FROOF (t1).
- Impairment of PIR was low
Teilergebnisse Aufgeständert (Bitumen+PIR, zweilagig)

- Exceeding the measuring marks (upwards and downwards)
- For gas burners and wood wool baskets it led to a class FROOF (t1).
- Early cancellation/ termination, ignition after 10min
Placement of the burner between module and roof position

Placement of the burner between module and roof position (flat roof)
Conclusions

- Work presents single test series out of German research project: ‘Determination of Arcing Risks at PV Systems and Minimization Measures’ and ‘Development of Fire Test Procedure for BIPV and BAPV Systems’
- Evaluation of ignitability of different materials/components and derivation of additional requirements
- Transfer of results to potential adaptions of (inter-)national standards (e.g., test inclination, focal spots for ignition, stress procedures etc.) for further risk minimization and fire safety enhancements
- Observation of mutual properties to building materials in case of fire and electric arc
- Presentation of European TR 50670 for PV Modules for Risk Evaluation of different roofing constructions with PV

- The most important key: AWARENESS!

Credits

Icons used:
- https://thenounproject.com/search/?q=fire%20prevention&i=325463
- https://thenounproject.com/search/?q=solar%20module&i=1660689
- https://thenounproject.com/search/?q=house%20fire&i=7386
Thanks for your Attention