Degradation of photovoltaic systems based on long-term measurements and laboratory tests

Thomas Schott, Franziska Kuonen, Urs Muntwyler, Eva Schüpbach

Bern University of Applied Sciences BFH, Engineering and Information Technology, Photovoltaic Laboratory, Burgdorf, Switzerland

Abstract

Results of the analysis of long series of measurements of photovoltaic (PV) plants in Switzerland are presented. The tree PV systems, Jungfraujoch, 3'450 m a.s.l (Alps), Mont-Soleil, 1'270 m a.s.l. (Jura) and Tiergarten, 530 asl. (Swiss Basin) are part of the long-term measurement program of the Photovoltaic Laboratory (PV LAB) at the Bern University of Applied Sciences BFH in Burgdorf (Switzerland). The focus of the long-term measurement program is the question of the effective degradation of photovoltaic plants that have been in operation for more than 20 years, representing different climatic zones in Switzerland. The findings provide essential information about aging-related power losses of PV systems.

Keywords: Photovoltaic systems, long-term measurement, degradation, power losses, Jungfraujoch, Mont-Soleil

1. Introduction

In the 1990s, in the Swiss Alps (Jungfraujoch, 3'450 m a.s.l., Birg-Schilthorn, 2'677 m a.s.l.), in the Swiss Jura (Mont-Soleil, 1'270 m a.s.l.) and in the Swiss Midland (roof of the Bern University of Applied Sciences BFH in Burgdorf, 540 m a.s.l..) installed PV systems (Siemens modules) and measured since then (Mont-Soleil only since July 1st, 2001) by the Photovoltaic Laboratory (PV LAB) of the BFH (see e.g. Häberlin, 2010, Muntwyler et al., 2014, Schüpbach et al., 2014 and www.pvtest.ch). This long-term monitoring makes it possible to compare the solar technology used in four different climate zones in Switzerland. The processing of the measurement series is also done by BFH Bachelor students (see for example Breitinger and Moser, 2017).

This article presents the results of the evaluations for the photovoltaic systems Mont-Soleil (Figure 3), Jungfraujoch (Figure 4) and PV plant Tiergarten on the roff of the BFH in Burgdorf, which represent the climate zones Jura (Mont-Soleil), Alps (Jungfraujoch) and Swiss Midland (Tiergarten, Burgdorf).

2. Calculation of annual degradation

For the calculation and comparison of the PV systems, the normalized yields YA of the PV modules and the normalized reference yield YR of the pyranometer mounted next to the modules are used (Figure 1).

Symbol / Term	Meaning / Definition	Unit
Y_R = Reference Yield = theoretical yield measured by the pyranometer	Y_R is equal to the time that the sun has to shine with G_0 = 1kW/m² to irradiate the energy H_G onto the solar generator	$\left[\frac{kWh/m^2}{d \cdot 1kW/m^2}\right] = \left[\frac{h}{d}\right]$
Y_A = Array Yield = Generator (DC-) performance	Y_A is equal to the time that the P_V plant has to operate with its nominal power P_0 to generate array (DC-) energy E_A	$\left[\frac{kWh}{d \cdot 1kW}\right] = \left[\frac{h}{d}\right]$

Figure 1: Normalised representation (Häberlin, 2010).

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Since YR represents the actual trapped energy yield and YA represents generator yield converted by the plant, YA can be set in relation to YR and the quotient can be formed. This gives us an indicator for the degradation of a PV system (Figure 2).

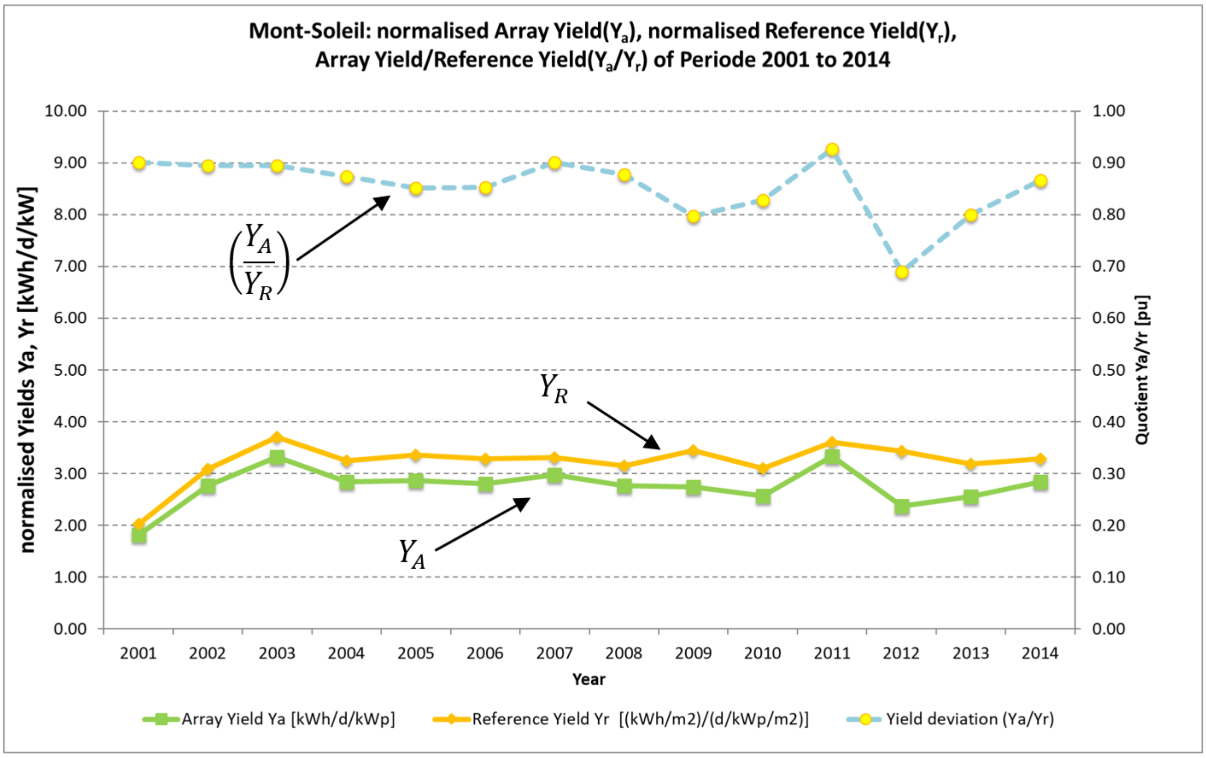

Figure 2: Use of the normalized representation for the determination of the degradation.

When applying a linear curve fit to the graph, the factor a in the function **y = ax + b** gives the gradient representing the average degradation of the PV modules per year. For the photovoltaic plant on Mont-Soleil, from which the period from 1 July 2001 to 31 December 2014 is available, this results in a degradation of 0.72% per year (Figure 5).

Snow that remains lying on the PV modules (Figure 3) and shutdowns of the inverter lead to an age-related reduction in DC yield YA. These failures cause a greater degradation of the plant in the calculation than it is effectively the case. Therefore, more attention is being paid to the Jungfraujoch PV plant, where a good data series from 1995 to 2014 is available. This is also because the system is mounted on the façade of the research building and barely covered by snow (Figure 4).

Figure 3: PV system Mont-Soleil with snow-covered modules in winter 2009.

Figure 4: General view of the Jungfraujoch PV system.

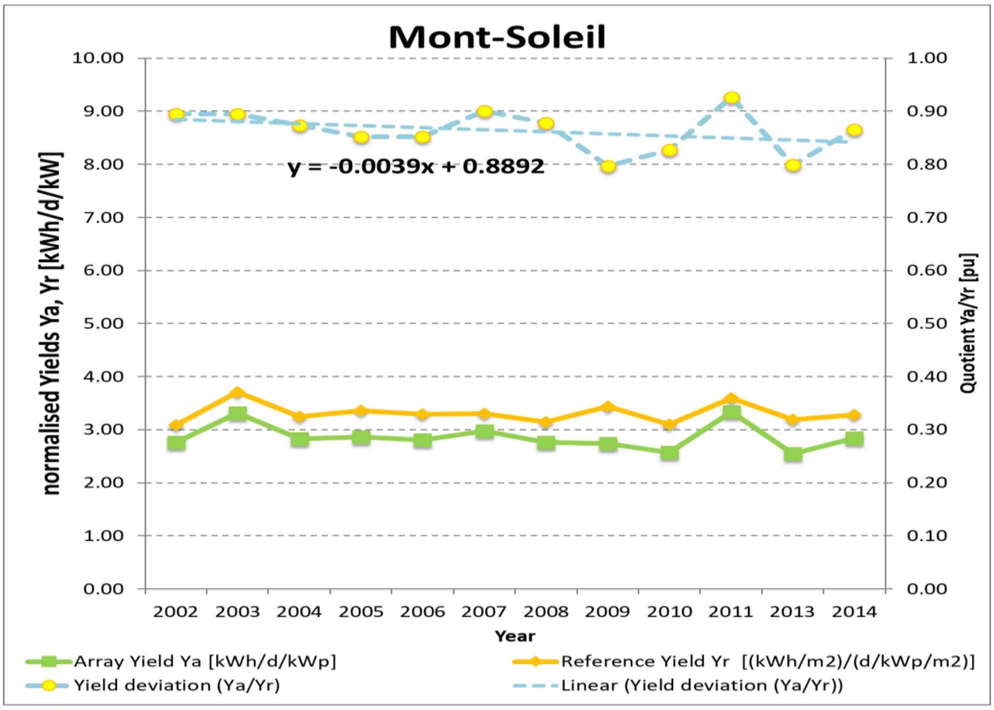

Figure 5: Degradation of 0.39% per year of the Mont-Soleil PV plant (July 2001 - December 2014). The relatively low value in 2012 (yield deviation) is due to failures due to snow and inverter failures and is excluded in the calculation.

$$\frac{Degradation}{year} = y' = -0.0039 \qquad \text{(eq. 1)}$$

$$\frac{Degradation}{year}[\%] = -0.0039 \cdot 100 = 0.39[\%] \qquad \text{(eq. 2)}$$

As Figure 6 shows, the photovoltaic system on the Jungfraujoch from the data series from 1995 to 2014 results in a reduction of the effective yield (degradation) of only 0.11 % per year.

$$\frac{Degradation}{year} = y' = -0.0011 \qquad \text{(eq. 3)}$$

$$\frac{Degradation}{year}[\%] = -0.0011 \cdot 100 = 0.11[\%] \qquad \text{(eq. 4)}$$

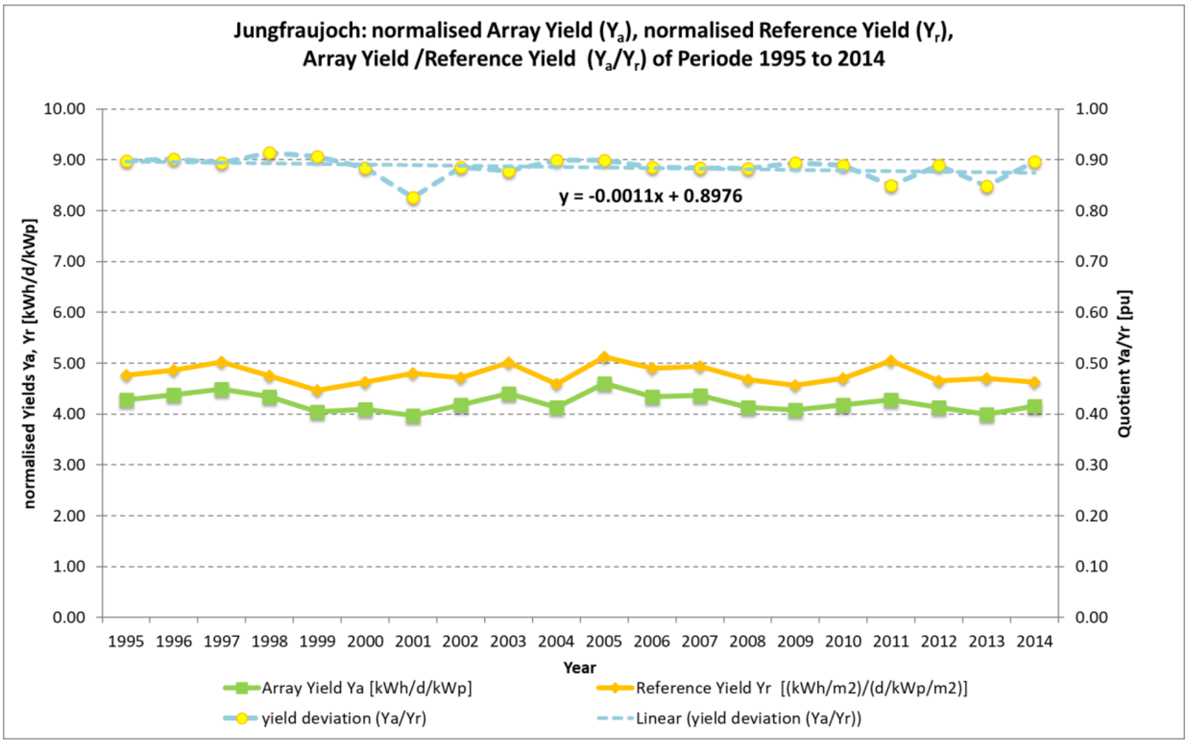

Figure 6: Degradation of 0.11% per year of the Jungfraujoch PV plant (January 1995 - December 2014).

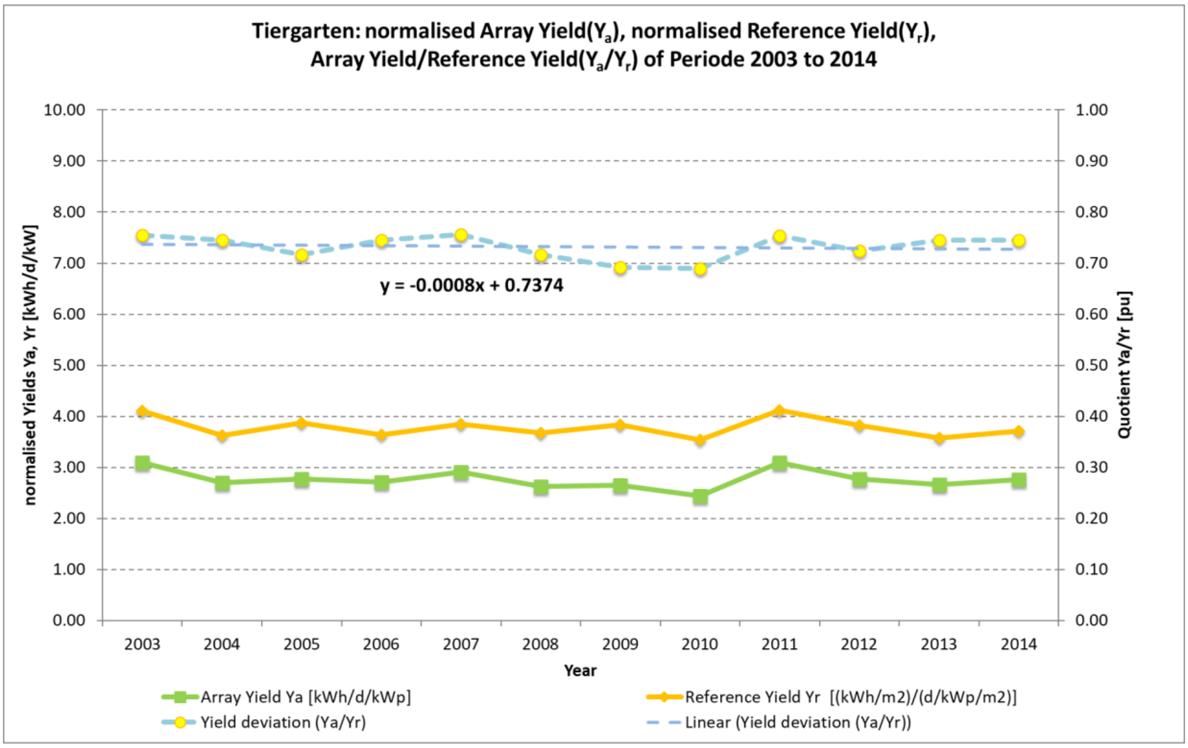

Figure 7: Degradation of 0.08% per year on the roof of the BFH in Burgdorf (January 2003 - December 2014).

$$\frac{Degradation}{year}[\%] = -0.0008 \cdot 100 = 0.08[\%] \qquad \text{(eq. 5)}$$

3. Plausibility test by measuring Jungfraujoch PV modules in the Laboratory

3.1. Proceeding

In a next step, the plausibility of the annual degradation of the Jungfraujoch PV system calculated based on the long-term measurements was evaluated. Since the PV modules, installed on the Jungfraujoch in 1993 (Siemens modules M75) with a power of 48 Wp, were not measured before installation, there is thus no reference value for the time of commencement of the measurement. However, since we know the bandwidth in which the photovoltaic modules installed on Jungfraujoch had been delivered, we can use the calculated degradation values to find the initial value at the beginning of the measurement and determine whether this is within the known bandwidth. Thus, although we have no exact reference, but a good guide to the plausibility estimate.

According to the data sheet, the production tolerance is ± 10 %. This results in a power bandwidth of a maximum of 52.8 Wp to a minimum of 43.2 Wp. From discussions between the founder of the PV LAB (Prof. Dr. Heinrich Häberlin) and the then module supplier, we know that the effective performance of the 1990s supplied modules for the PV system Jungfraujoch was below the nominal 48 Wp. The effective power of the individual modules must therefore have been between the minimum (43.2 Wp) and the nominal (48 Wp) value in the 1990s (i.e., when new).

3.2. Laboratory measurements

In June 2017, two Siemens Modules M75 (48 Wp) were removed from the PV plant on the Jungfraujoch, which had been in operation since 1993, and taken to the PV LAB of the BFH in Burgdorf for measurement. In the PV LAB of the BFH in Burgdorf, Breitinger and Moser (2017) analysed the performance of the modules with the flasher and recorded the state of the individual cells by means of electroluminescence. It was shown (Table 1) that one of the photovoltaic modules of the Jungfraujoch plant measured in the PV LAB was slightly below 43.2 Wp and the other PV module slightly above this value. On average, both flashed PV modules are just above the minimum of the production tolerance specified in 3.1.

Table. 1: Results of the flasher measurements of the two PV modules of the Jungfraujoch plant (Breitinger and Moser, 2017)

Modul	SN 670898	SN 670897	Median	Mean value
SN 670897	41.565 Wp	41.635 Wp	41.600 Wp	41.600 Wp
SN 670898	44.800 Wp	44.827 Wp	44.814 Wp	44.814 Wp
Median / Mittelwert			43.218 Wp	43.207 Wp

Figure 8 shows the current-voltage curve of the PV module SN 670898 removed from the Jungfraujoch plant and examined in the PV LAB of the BFH (see section 3.2).

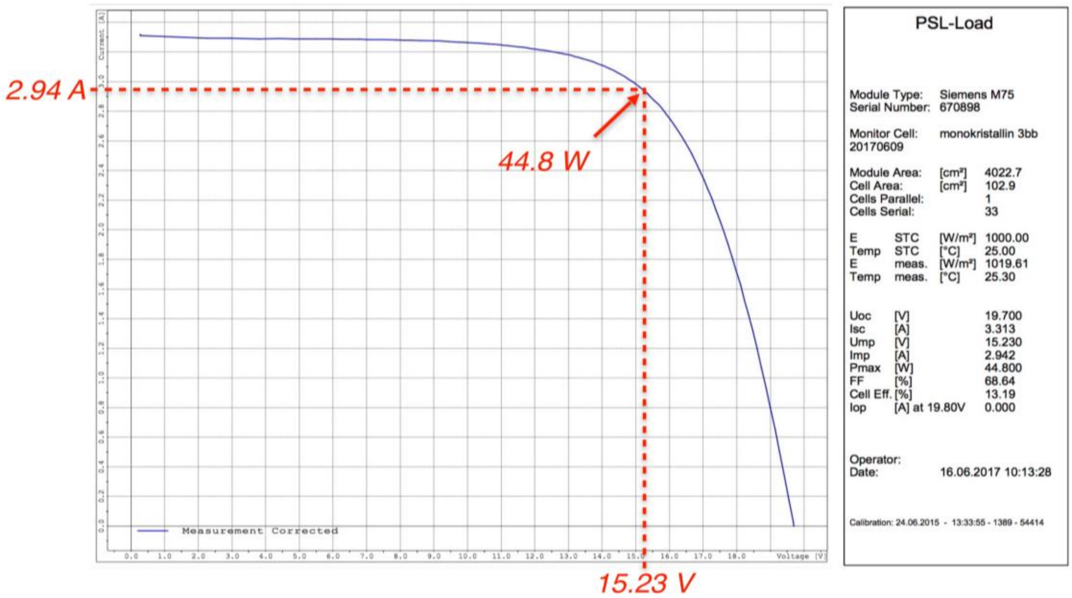

Figure 8 Flasher power of the SN 670898 module of the Jungfraujoch PV system.

It can be seen that the performance of the (in the 1990s new) PV modules is pretty much in the middle of the restricted tolerance band between P_{min} = 43.2 Wp and $P_{nominal}$ = 48 Wp (48 Wp + 0 % / - 10 %).

4. Recalculation to new condition

For the recalculation to the new condition, the period for the calculation of the annual degradation of the Jungfraujoch PV modules - using the methodology in item (2) - back to the beginning of the measurement (1995) was used (see Figure 6).

The recalculated initial value is 45.8 Wp at an annual degradation of 0.11 % on the Jungfraujoch (Figure 9). This confirms that our degradation of 0.11 % per year calculated based on long-term measurements at the Jungfraujoch PV plant is plausible.

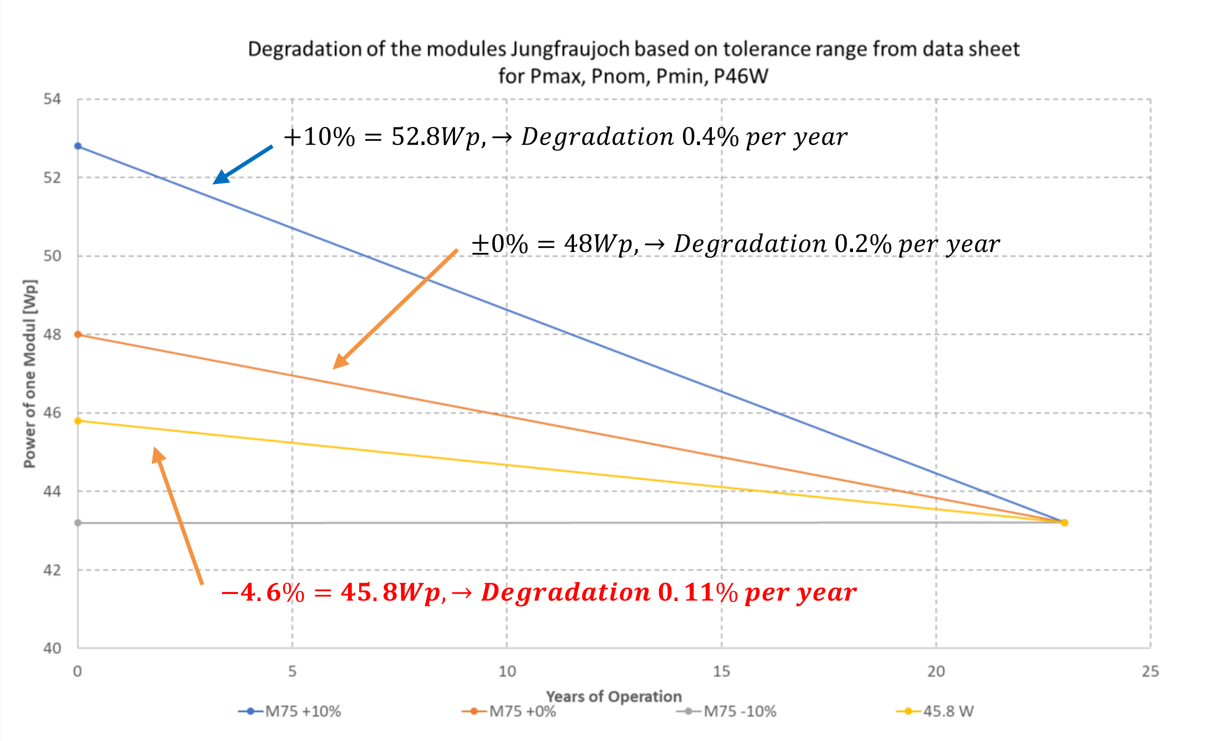

Figure 9: calculation of the average module output of the Jungfraujoch PV plant at 0.11% annual degradation back to the beginning (Figure 6).

5. Conclusions

The PV LAB of the BFH in Burgdorf (Switzerland) has been measuring numerous PV systems since the 1990s. Based on these long-term measurements, the power losses of the Mont-Soleil, Jungfraujoch PV plants and the plant on the roof of the BFH in Burgdorf were analyzed. For the period 2001-2014, the calculated annual degradation was 0.39 % for the Mont-Soleil PV plant (1'270 m a s l. in the Jura). Further investigations must be made on this system i to exclude influences such as snow and inverter shutdowns, which disturb the calculation of the degradation. The degradation of the plant on the roof of the BFH in Burgdorf was 0.08%.

With the relatively long data series from 1995 to 2014 of the PV plant Jungfraujoch (3'450 m a.s.l. in the Alps) an annual degradation of 0.11 % could be found. This value was confirmed with a plausibility test based on flasher measurements and electroluminescence in the laboratory.

From our analyses we conclude:

- That the modules used by the BFH from the 1990s aged much less than the modules from a study of the HTW Berlin in 1999 (Quaschning et al., 1999), and that the mechanical structure of PV modules is therefore not insignificant.
- It seems that the solar radiation has a very small influence on the aging of the PV cells, because with only 0.11% power loss per year on the Jungfraujoch, where the solar radiation is 1.45 times higher than on the Mont-Soleil, the power loss would have to be greater be.
- That other influences than the intensity of solar radiation are important for the aging of the PV modules, such as the
  - Operating temperature
  - Moisture (if the PV cells get moist -> "Packaging" of the cells)
  - Material properties of the modules (glass, plastics, adhesives, etc.).
- Looking at the degradation of the three plants (25 years of operation), it is noticeable that they are below the 0.8% reported in the literature for all three plants (ca. factor 8 smaller). This means that these plants produce more than specified after the 25 years. For the Mont-Soleil plant, the year 2012 was omitted due to inverter failure from the evaluation. Nevertheless, the highest degradation can be found here. This comes from snow damage. The modules were mounted without frame and therefore are no longer in the warranty conditions.

6. Outlook

In a next step, the PV system Birg-Schilthorn (2'677 mü.M.) is examined. The aim is to compare the long-term degradation of PV systems in four different climate zones in Switzerland.

7. References

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