TOPIC 5.3

28 YEARS OF OPERATIONAL DATA FOR A UTILITY SCALE 103 KWP PV PLANT (1989-2017)

ANALYSIS OF DEGRADATION OF PV MODULES, INVERTERS AND SYSTEM PERFORMANCE WITH TECHNICAL AND ECONOMICAL COMPARISON TO THE REPOWERED 260 KWP PV PLANT (2017-2019).

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SUMMARY: The PV plant on the noise barrier of the highway A13 at the time of its construction 1989 was the largest PV plant in Switzerland (104 kWp) and the first PV noise barrier plant worldwide, providing 28 years of field data for analysis. Degradation of PV modules, inverter efficiency and system performance are analyzed. A technological and economical comparison with the 260 kWp PV plant after repowering 2017 is performed.
Flasher measurements at STC of the 1989 PV modules after 28 years of operation show degradation of nominal power from 15…37%, corresponding to 0.55…1.32% per year. Inverter efficiency after 12 years of operation is 1.12% lower at 91.61%. Yield decrease started 2007, but was partially compensated by increasing solar irradiation. Analysis of performance ratio shows a linear decrease from 2006 to 2016. Performance decrease is far higher than can be explained with PV module and inverter efficiency degradation. It is therefore to large parts due to degradation in Balance of System (BoS) components such as array boxes, DC wiring, fuses, et. al. The repowered PV plant produces almost 3 times the energy of the original PV plant on the same length of noise barrier while system prices have dropped 95.1% from 1989 to 2017.

Keywords: Long-term field data, degradation of PV modules, inverter efficiency, performance ratio, ageing

1 PURPOSE AND AIM OF THE WORK

The **PV plant on the noise barrier** of the highway A13 at the time of its construction **1989** was the largest PV plant in Switzerland (104 kWp) and the first PV noise barrier plant worldwide. It remained operational with the original PV modules until 2017 and was considered to be a reference PV plant in terms of performance and grid-connected PV plants. In 2005 the inverters have been replaced together with some of the PV modules.

When the yield of the PV plant fell about 40% compared to the original yield around 2016, it was decided by the new owner, a utility, that the **PV system was to be repowered** with new PV modules and inverters in 2017 using the existing mounting structures.

To better understand the yield reduction of around 40%, different aspects are analysed. Is it the PV modules that have degraded to such an extent? Are the inverters breaking down? Is it the influence of other balance of system components leading to the yield reduction?

The results will help PV planners, installers, operators, utilities and investors to better understand the long-term behaviour of PV plants and how to optimize system performance and solar power yield.

2 APPROACH

A multilayered approach ensures the most comprehensive approach to understanding long-term behaviour of the PV plant and its components concerning yield, performance and degradation over time. It is based on the **combination** of data analysis and calculations from the **measurement campaign** with **simulation**- and calculation-models and the **lab-based measurements** and testing of components such as PV modules and inverters.

Overall, field-data for 28 years of operation of the original PV system is available. The PV plant A13 is particularly suitable for an in-depth analysis, as the detailed measurement campaign, carried out from 1989 to 2004, provides systematically recorded and evaluated measurement data in accordance to IEA performance analysis of PV plants. This is an almost **unique situation**, to have **operational data** for a utility scale PV plant available **over a period of 28 years**.

15 original **PV modules** from the PV plant 1989 as well as **one** of the two **inverters** were **measured on calibrated test equipment** of the University of Applied Sciences Burgdorf (BFH) for the inverter and a flasher of the Zurich University of Applied Sciences (ZHAW) in Winterthur. This allows for conclusions on the state of these core components after 28 years of operation in the field.

With the **repowering** of the PV plant at the same site using parts of the mounting structure, it is possible to **compare field data** from operation for two generations of PV plants **side by side**. This comparison is done for technical as well as economical aspects.

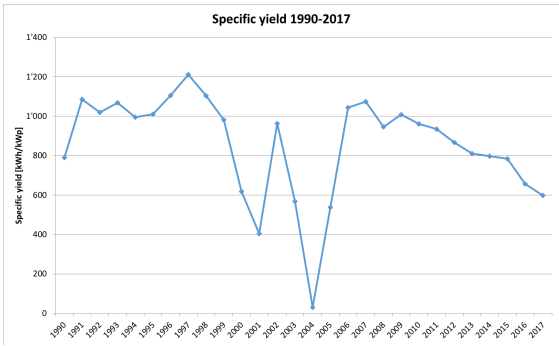
3 RESULTS

3.1 SYSTEM PERFORMANCE

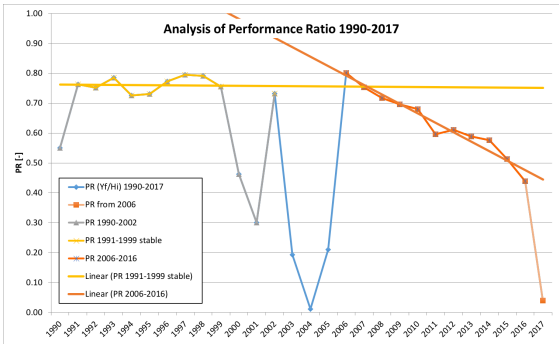
System performance is evaluated with different key indicators, such as specific yield and Performance Ratio. The original PV plant from 1989 was evaluated by the Joint Research Centre ISEI Institute in 1992 with the following conclusion:

"The plant performed well according to its design specifications. It reached the highest values of performance ratio, mean final yield and plant efficiency that we have found up to now."

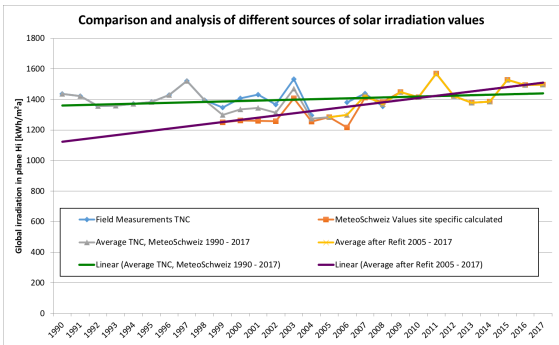
The **mean final yield** is evaluated over the full period of operation 1990-2016. Singular decreases in yield 1999-2005 are due to inverter failures and none-existing service structures for repair and maintenance of the prototype inverter. A **systematic decrease** of the final yield starts 2001 and continues approximately linear.



A more refined approach to analyze system performance is using the key indicator of **performance ratio PR**, since it takes into account the reference yield based on the available solar irradiation. During stable operation **1991-1999** PR was between **0.73 and 0.80**. The same value was reached in 2006 after the refit (replacement of inverter and some PV modules). During the period of **2006-2016** a **linear decrease** was observed with **-0.03/a**. This rate of change in PR is around a factor 100 higher than during the stable period 1991-1999.



For PR analysis, different available sources for **solar irradiation** in the module plane are compared and analyzed. Calibrated measurements are available from the measuring campaign TNC from 1990-2004 with. For the period of 1999-2017 solar irradiation is calculated by MeteoTest based on officially measured values from MeteoSchweiz weather monitoring stations in Switzerland. An average value is used for further processing and analysis.

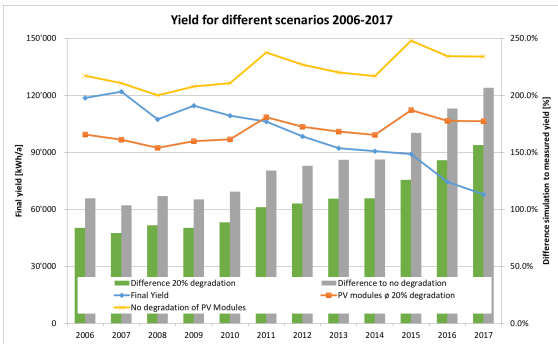


The linear fitted trend line for the period **1990-2016** shows a slight **increase of 2.95 kWh/m²a**, while the linear trend line after refit for **2005-2017** shows an **increase of 14.28 kWh/m²a**, which is considerably higher. This leads to higher decrease in PR for the period 2005-2017 as could be expected from specific yield.

3.2 PV MODULES

15 polycrystalline PV modules from the original PV plant have been measured at STC on a flasher after being operational for 28 years with no prior cleaning or preparation. The **Kyocera LA361J48 modules** with 48 Wp nominal power and an efficiency of 11% showed **degradation** in nominal power of **15% to 37%** with an average of 20%. This corresponds to an **annual** average reduction of **0.55 ... 1.32%** in nominal power.

I/V curves and EL recordings have been carried out for the test modules. EL pictures show cell cracks for some of the stronger degraded modules. I/V curves show higher serial resistance, which can have several reasons. An additional 8 PV modules were provided by TNC, which never have been mounted and no light-induced effects have taken place. These reference modules showed no degradation in nominal power in the flasher.

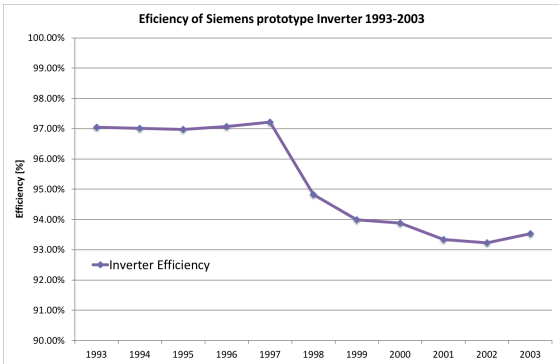


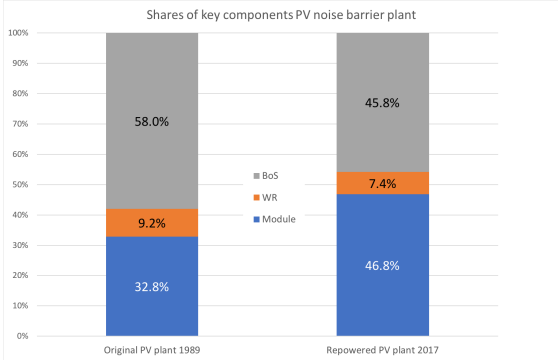
To calculate the **expected target yield** for the PV plant, a **simulation** was run based on a model of the PV plant. Different scenarios were tested, one of them taking into account the average degradation of 20% of the nominal power of the PV modules. These calculations were compared to the measured final yield, showing that **Balance of System (BoS)** components must contribute greatly to the **overall system performance degradation**. These BoS components include array boxes, DC wiring, fuses, etc. which at the time of construction were all not standardized.

3.3 INVERTERS

The inverters as the second core component have been analyzed separately. The **efficiency** of the **Siemens** prototype inverter (1989-2004) was calculated using measured DC input and AC output from field measurements. After a stable efficiency of around **97%** from 1993-1997 there was a decline to 93…94% efficiency for 1998-2003.

With the refit 2005 the Siemens inverter was replaced by two **Sputnik SolarMax 60** inverters. Efficiency was calculated accordingly to the Siemens inverter to be at **92.64%** for the first years of operation. In 2018 one of the two SolarMax 60SE inverters was **measured** according to EN 50530 at the University of Applied Science in Burgdorf after being operational from 2005-2017. The European Efficiency was measured at **91.61%**, which is a **degradation of -1.12%**. These results were also included in the model to calculate the expected yield.





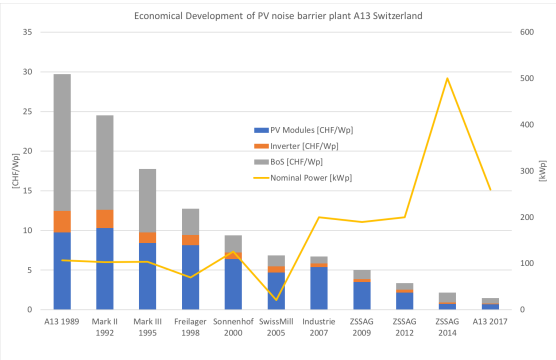
3.3 COMPARISON TO REPOWERED PV PLANT

In 2017 the PV plant on the noise-barrier was repowered. Parts of the mounting construction were reused, PV modules, inverters and cables were replaced.

The new plant uses **state of the art PV modules** from LG (LG 335N1C-A5), which have a **+597% nominal power** at 335 Wp, a **+78.2% module efficiency** at 19.6% and result in a nominal power of the plant of 260 kWp on the same length of noise barrier (+150%). The two Sputnik inverters were replaced with 5 **ABB TRIO 50 inverters**, which have an European efficiency of **98%** according to datasheets.

Flasher Reports have been analyzed in order to determine the distribution of nominal power of the PV modules and examine the influence on all other calculations. State of the art modules have a positive tolerance on nominal power, leading to deviations in specific yield and performance ratio of 0.5…1.1%.

In the first full year of operation 2018, there have been problems with the inverters. This leads to a performance ratio of only 0.76. For the second **year of operation 2019**, **PR** reached **0.80**. Specific yield is at 1'294 kWh/kWp and therefore a little higher than longtime average of the original PV plant. Solar irradiation is only from limited sources available, which leads to higher uncertainties in performance analysis for the repowered PV plant.



The original **PV noise barrier plant 1989** was built at around **30'000 CHF/kWp**, while the repowered PV plant **2017** was built at around **1'463 CHF/kWp**. This corresponds to a **reduction of system prices of 95.1%**! Cost shares for the key components PV modules, inverters and BoS for the original PV plant 1989 and the repowered PV plant 2017 are similar.

4 CONCLUSIONS

- The key components of PV plants hold up very well over 28 years of operation. Module degradation was at average 20% nominal power reduction, inverter efficiency degradation is at 1.12%.
- Balance of System (BoS) components such as array boxes, DC wiring, fuses, et. al. are key to maintaining high performance and high yield PV plants and have to be monitored and researched accordingly. Their influence is shown to be as high as any degradation of PV Modules and inverters.
- Monitoring and measurements on site are essential to detect potential failures and performance drops fast. Reliable measurements are needed, otherwise all evaluations are futile. Know-How and experience in these areas sometimes lack with plant owners and operators.
- Yield monitoring is not sufficient for detecting failures in PV plants, since decrease in performance can be partially or fully compensated in final yield if solar irradiation rises (reference yield rises).
- Technical and economical development of PV components and systems is very impressive. One generation of PV (28 years) was found to have led to 95.1% cost reduction for system prices.
- Field measurements of large-scale PV plants as well as testing of components at end of lifetime are essential to better understand performance and yield development of PV plants. Lab-measurements are not sufficient.

5 REFERENCES

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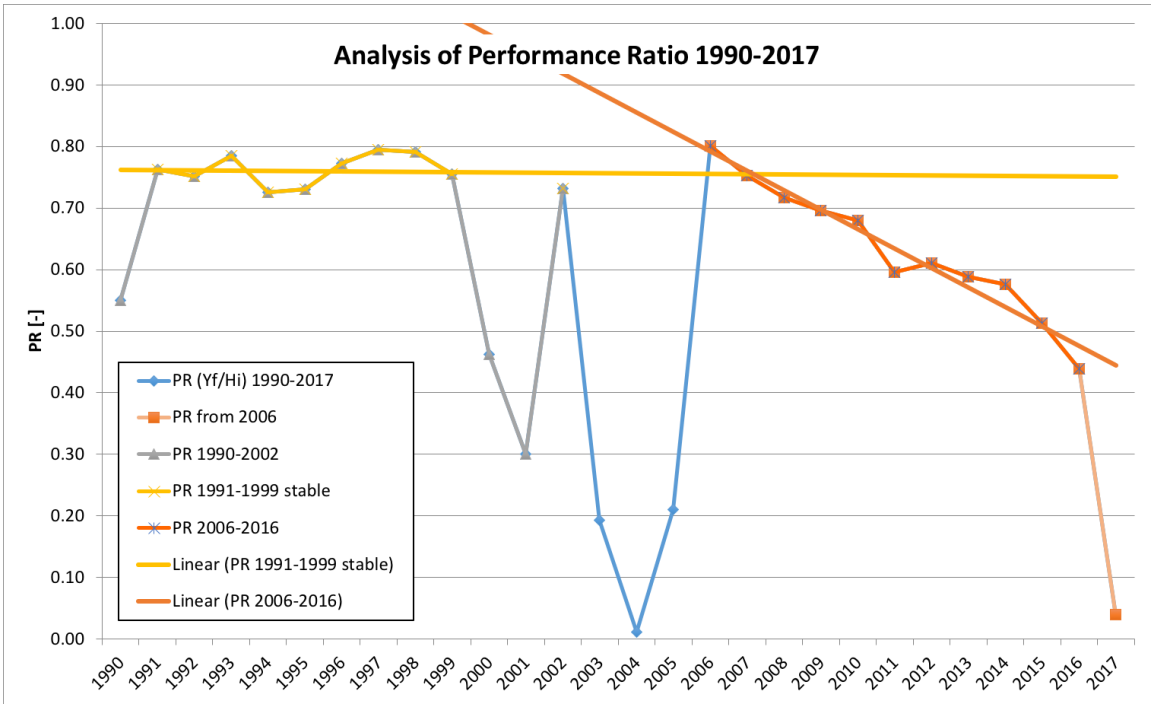
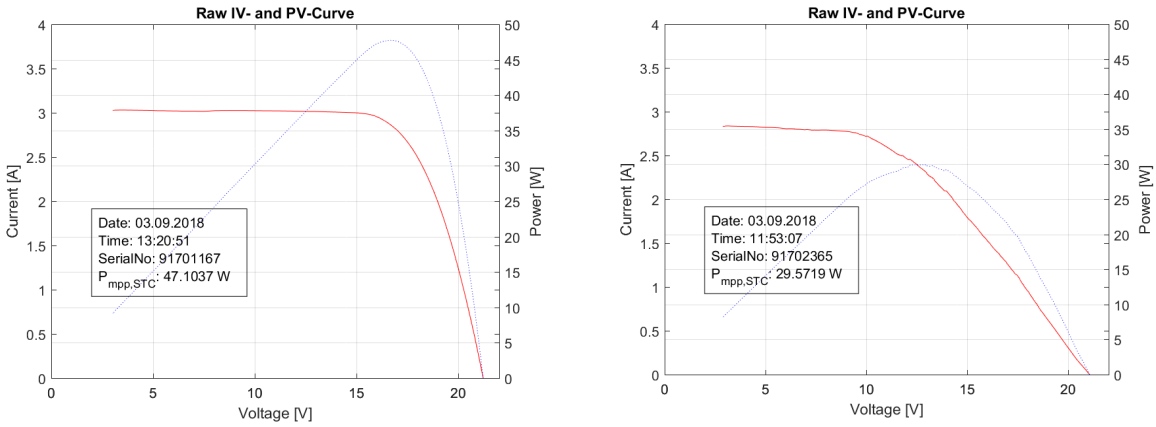


Performance decrease after Refit of inverter in 2005. BoS components contribute heavily to the PR decrease.

Serial Number	Voc Raw [V]	Isc Raw [A]	Vmpp Raw [V]	Impp Raw [A]	Pmpp Raw [W]	Voc STC [V]	Isc STC [A]	Pmpp STC [W]	I/V curve commentaries	Pmpp nameplate [W]	Difference Pmpp to nameplate	Difference Pmpp to Flasher manufacturer
91621048	21.26	2.96	15.08	2.50	37.69	21.02	2.97	37.18	Rs	46.80	-21%	-21%
91620357	21.25	2.90	14.84	2.41	35.72	21.02	2.91	35.25	Rs	46.80	-25%	-25%
91613393	21.27	2.95	15.64	2.57	40.26	21.04	2.95	39.73	Semi Rs	46.80	-15%	-15%
91621017	21.25	2.70	14.40	2.34	33.72	21.02	2.70	33.28	Rs, Isc	46.80	-29%	-29%
91702360	21.21	2.92	14.82	2.53	37.44	20.97	2.93	36.91	Rs	46.80	-21%	-21%
91701156	21.12	2.91	15.18	2.64	40.04	20.90	2.91	39.52	Ok	46.80	-16%	-15%
91701144	21.08	2.90	14.26	2.59	36.99	20.79	2.90	36.37	Rs	46.80	-22%	-22%
91701160	21.14	2.90	14.05	2.57	36.07	20.92	2.90	35.60	Rs	46.80	-24%	-25%
91702075	21.13	2.89	14.29	2.57	36.68	20.91	2.89	36.21	Rs	46.80	-23%	-24%
91701145	21.07	2.88	15.24	2.50	38.14	20.85	2.88	37.66	Rs	46.80	-20%	-18%
91621015	21.19	2.93	15.12	2.61	39.53	20.96	2.94	39.00	Semi Rs	46.80	-17%	-18%
91702076	21.05	2.89	13.48	2.53	34.09	20.83	2.89	33.66	Rs	46.80	-28%	-29%
91702365	21.05	2.83	12.45	2.41	29.95	20.83	2.84	29.57	Extreme Rs	46.80	-37%	-37%
91703124	21.02	2.89	13.30	2.36	31.34	20.80	2.90	30.94	Extreme Rs	46.80	-34%	-34%
91621049	21.15	2.94	15.27	2.33	35.57	20.93	2.95	35.10	Rs, Bypass	46.80	-25%	-26%
89903051	21.15	3.10	16.18	2.84	45.97	20.94	3.10	45.40	Ok	48.00	-5%	-
89Y23101	21.28	3.13	16.75	2.84	47.56	21.06	3.13	46.95	Ok	48.00	-2%	-
89903052	21.07	3.07	16.66	2.79	46.52	20.86	3.07	45.95	Ok	48.00	-4%	-
91701167	21.22	3.02	16.72	2.85	47.73	20.99	3.03	47.10	Ok	46.80	1%	0%
91704002	21.32	3.10	16.89	2.90	48.90	21.11	3.11	48.32	Ok	46.80	3%	3%
91703055	21.37	3.15	16.67	2.94	49.00	21.16	3.16	48.42	Ok	46.80	3%	2%
91209257	21.33	3.05	16.96	2.88	48.81	21.11	3.05	48.21	Ok	46.80	3%	3%
91209250	21.37	3.07	16.95	2.91	49.33	21.17	3.08	48.75	Ok	46.80	4%	3%



Results from the Flasher used to measure the original Kyocera PV modules from 1989 after 28 years of operation.