Long-term Behaviour of Grid-Connected PV Systems

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Abstract: Besides tests of PV inverters started in 1989, since 1992 the PV laboratory of HTI in Burgdorf has also carried out several analytical monitoring projects without any interruptions with a continuously increasing number of plants and inverters. At present 42 grid-connected PV-plants with up to 55 inverters are monitored. Most of the plants are in the town of Burgdorf, but since 1993 also two high alpine plants at 3454m and 2670m are included in the project. In spring 2001, the PV laboratory has built a new and more reliable monitoring system for the (at present) largest PV plant in Switzerland (Mont Soleil). Since December 2001 also a PV pilot plant with three different thin-film technologies ($CuInSe_2$/CIS, a-Si tandem cells, a-Si triple cells) has been monitored (see separate contribution). The purpose of these long-term monitoring projects is to register all relevant influences on energy yield, degradation mechanisms, reliability, and life expectancy of grid-connected PV plants which can not be detected during relatively short initial monitoring campaigns of 1- 2 years, that are often performed after the erection of new PV plants, but stopped later in order to save costs. For some of the plants, very long monitoring periods (without interruptions or data losses) of 10 – 12 years will be available until the conference. Monitoring data of all these plants are also made available for IEA.

KEYWORDS: Grid-Connected - 1 : PV system - 2 : Performance - 3.

1. Inverter reliability and energy lost due to inverter defects

As for reliability, inverters are the most critical part of a grid-connected PV plant. During the monitoring projects mentioned above, valuable statistical data about inverter defects and reliability could be obtained. Between 1992 and 1994 the number of inverter defects per inverter operation year was in the range 0.7 to 1, dropped continuously in the following years and stabilised in the years 1997 to 2003 in the range 0.07 to 0.21.

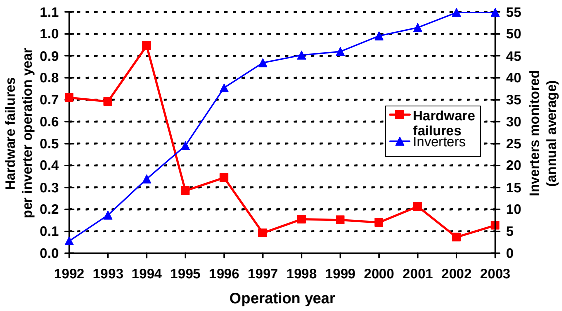

Fig. 1: Inverter defects per inverter operation year and average number of inverters monitored.

In 2001, a relative maximum was registered due to defects of mostly older inverters (especially after thunderstorms which were quite frequent in this year). In 2002, when no heavy thunderstorms were registered in Burgdorf, this number dropped again to 0.07.

Table 1 (on next page) shows the number of inverter defects registered for all inverter models from different manufacturers. It can be easily seen, that there are significant differences. Usually new inverter designs from manufacturers appearing on the market for the first time are less reliable due to lack of experience, whereas redesigns of inverter models from experienced manufacturers are more reliable in general.

Energy lost due to an inverter defect strongly depends on the moment when the defect occurs and on the time required to repair it (see fig. 2). In the years 1996 to 2003, annual energy lost owing to inverter defects varied between 2% and 0.2% with an average of 1.1% (see fig. 3).

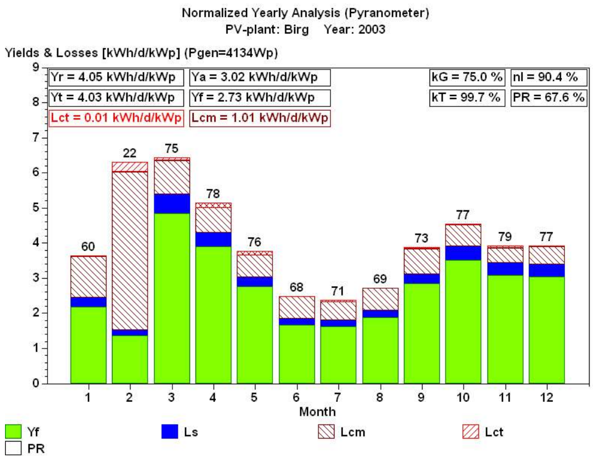

Fig. 2: Normalised yearly analysis for PV plant Birg (4.134kWp, 2670m) for 2003. Due to a severe inverter defect in January and February, which made a replacement necessary, about 10.5% of the possible annual production was lost!

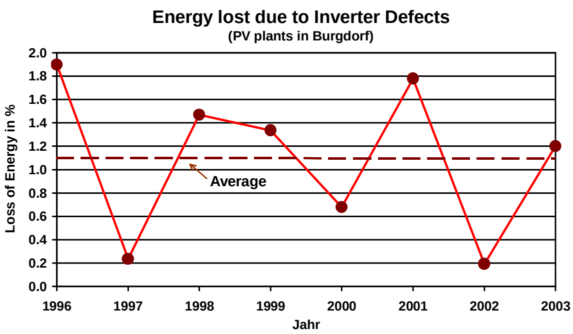

Fig. 3: Lost energy due to inverter defects at the plants monitored in Burgdorf. The average value is 1.1 % of the total energy production.

Registered inverter defects for different inverter types:

Inverter	Year of Start	Total months of oper.	Number of inverter Defects													Hardware-defects per inverter operation year												
			92	93	94	95	96	97	98	99	00	01	02	03	Total	92	93	94	95	96	97	98	99	00	01	02	03	Total
PVWR 1500	1992	112	0	0	0	0	0	0	0	0	0	1			1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1			**0.1**
PVWR 1800	1992	201	0	3	5	4	0								12	0.0	0.8	1.3	1.0	0.0								**0.7**
Solcon 3300	1991	189	0	0	0	0	1	0	0	2	0	0	0	0	3	0.0	0.0	0.0	0.0	0.5	0.0	0.0	1.0	0.0	0.0	0.0	0.0	**0.2**
Solcon 3400HE	1992	497	1	1	4	0	1	0	0	2	2	0	1	1	13	33.2	1.0	1.6	0.0	0.2	0.0	0.0	0.4	0.5	0.0	0.3	0.3	**0.3**
Solarmax S	1995	1539				0	5	0	4	1	2	8	2	3	25				0.0	0.4	0.0	0.3	0.1	0.1	0.5	0.1	0.2	**0.2**
TopClass 1800	1993	122		0	0	0	0	0	0	0	0	0	0	0	0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
TC 2500/4 Grid III	1996	90					0	0	0	0	0	0	0	0	0					0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
TC 2500/6 Grid II	1994	230			0	0	1	1	0	1	0	0	0	0	3			0.0	0.0	0.5	0.5	0.0	0.5	0.0	0.0	0.0	0.0	**0.2**
TC 2500/6 Grid III	1996	77					0	0	0	0	0	0	0	0	0					0.0	0.0	0.0		0.0	0.0	0.0	0.0	**0.0**
TopClass 3000	1992	184	1	2	1	1	1	0	0	0	0	1	0	0	7	1.9	1.3	0.5	0.5	0.5	0.0	0.0	0.0	0.0	1.0	0.0	0.0	**0.5**
TC 4000/6 Grid II	1994	370			0	2	0	0	1	0	0	0	0	0	3			0.0	0.5	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	**0.1**
TC 4000/6 Grid III	1996	553					1	0	0	1	1	0	1	0	4					0.7	0.0	0.0	0.2	0.2	0.0	0.1	0.0	**0.1**
Solarmax 15	1995	104				0	0	0	0	0	0	0	0	0	0				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
SolarMax20	1994	202			1	0	0	0	0	0	0	0	0	1	2			1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	**0.1**
SolarMaxDC30+	1998	60							0	0	0	0	0	0	0							0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
EcoPower20	1994	57			5	0	3	2	2						12			5.6	0.0	3.0	2.0	2.3						**2.5**
EdiSun 200	1996	86					0	1	0	0	0	0	0	0	1					0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.1**
Convert4000	1998	433							0	0	2	1	0	2	5							0.0	0.0	0.3	0.1	0.0	0.3	**0.1**
ABB	1992	31										0	0	0	0										0.0	0.0	0.0	**0.0**
Fronius Mini	2002	23											0	0	0											0.0	0.0	**0.0**
TopClass Spark	2001	73										0	0	0	0										0.0	0.0	0.0	**0.0**
Total		**5232**	**2**	**6**	**16**	**7**	**13**	**4**	**7**	**7**	**7**	**11**	**4**	**7**	**91**	**0.71**	**0.69**	**0.95**	**0.29**	**0.34**	**0.09**	**0.15**	**0.15**	**0.14**	**0.21**	**0.07**	**0.13**	**0.21**

Table 1: Registered inverter defects for different inverter types

2. Evolution of energy yield in course of time at the PV plants in Burgdorf

2.1 Normalised energy yields of PV plants in Burgdorf referred to standard year

In order to compare PV plants of different size, it is best to indicate energy yield in kWh/kWp. Thus the influence of the size if the plant is eliminated (see fig. 4).

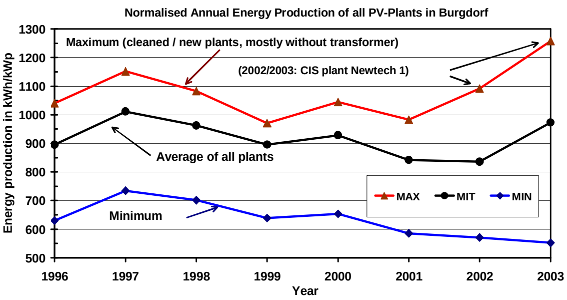

Fig. 4: Normalised annual energy production of all PV plants in Burgdorf from 1996 to 2003.

It is astonishing that the difference between the energy yield of good plants and poor plants increases considerably in course of time despite the high payback rate for PV power (CHF 1 per kWh) paid by the local utility (Localnet AG). It seems that some owners (especially after a change of ownership of the building on which the plant is built) gradually loose their interest in their PV plant.

As far as irradiation is concerned, 2003 was by far the best year between 1996 and 2003. However, the average energy yield of all PV plants in Burgdorf was only the second best and slightly below the values registered in 1997, the year with the second highest irradiation. As most PV plants in Burgdorf were erected between 1994 and 1996, increasing pollution of the arrays and some aging effects seem to be responsible for this phenomenon.

In order to eliminate the influence of the irradiation changes between different years, measured data have to be converted to a standard year with average irradiance conditions. Fig. 5 shows the resulting normalised energy yields. Besides the average value of all plants also the average value of all inverters without transformers, the maximum value (from cleaned plants without transformers) and the minimum value (mostly from a façade plant with tilt angle β = 60° and a west deviation γ = 20° from south that is partially shaded by parts of the building) are indicated. Nearly all PV plants in Burgdorf have modules with frames.

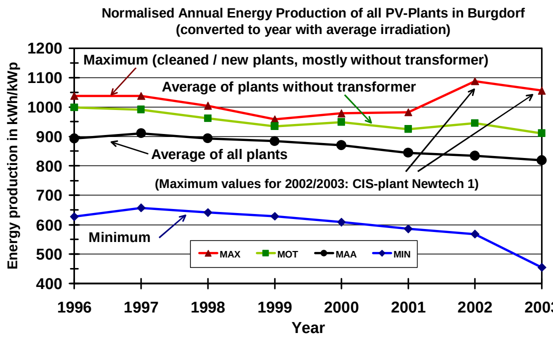

Fig. 5: Normalised annual energy production of all PV plants in Burgdorf (converted to year with average irradiance conditions with H = 1163 kWh/m²).

In fig. 5 almost all curves have a slightly falling tendency. Moreover the differences between plants with good maintenance and neglected plants increase with time. The significant decrease of the average value for all plants in the years 2000 to 2003 is mainly caused by a relatively new large plant commissioned in 1999 that seems to have problems with inverters as well as the PV generator with roof-integrated PV shingles with a low tilt angle β (not monitored in detail in this project).

2.2 Normalised energy yields of older PV plants in Burgdorf (energy losses due to inverter defects eliminated)

In order to examine the long-term behaviour of the PV generator only, besides the conversion to a standard year with average irradiance conditions also the influence of inverter defects must be eliminated and only older plants must be considered.

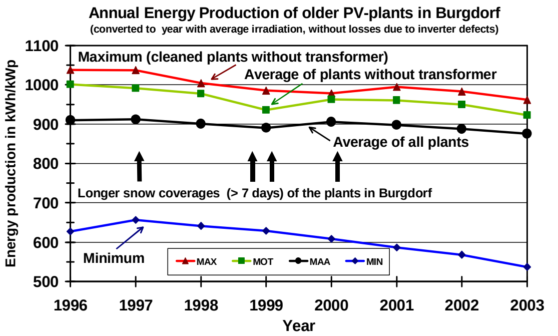

Fig. 6: Normalised annual energy production of all PV plants in Burgdorf built before 1998 (converted to year with average irradiance conditions) corrected for energy losses due to inverter defects.

In fig. 6, for all plants with inverter defects, the energy lost due to the defect was added to the measured energy. Therefore the normalised energy yields in fig. 6 mainly show the effect of PV array problems (pollution, aging, degradation, string defects {at some plants only, e.g. problems with string diodes, fuses, connectors}, snow covering, in part also increasing shadowing due to growing trees). Most curves have a slight tendency to decrease in course of time. In 1998 and especially 1999 there was a slight dip, but in 2000 and 2001 there was again an increase in the curves for PV plants without transformer (nearly all these plants with Siemens M55 with metal frames and long side parallel to the horizontal plane). From 1996 to 2003 the average value, but also the maximum value coming from plants with occasional cleaning has decreased about 8%. Sensitivity to pollution strongly depends on the location of the plant and the module type. Framed modules, especially those with relatively small distance between the cell and the frame (e.g. Siemens M55) have a strong tendency for pollution. It seems that there is also some aging with these modules. However, it is astonishing that the average value of all plants decreases less than the maximum value (only about 4% from 1996 to 2003). It must be noted that in this average value also many plants with other modules and the large plant of HTI are included, that are cleaned from time to time.

2.3 Reduction of energy yield and measured STC-power of the PV plant of the PV laboratory of HTI

Since spring 1994, the PV laboratory has operated a PV test plant of 60 kWp on the roof of its building. In course of time, a permanent pollution strip has developed gradually at the lower edge of the (framed) PV modules with a tilt angle β = 30°. Owing to the analytical monitoring, detailed data are available since then. Since 1996 it is also possible to measure I-V-curves and convert them to STC with a special device developed especially for this purpose.

For a first overview over energy production and possible operational problems at PV plants, normalised monthly statistics are very useful. For this purpose normalised quantities Y_r (reference yield into array plane in (kWh/m^2/d)/(1kW/m^2)), Y_T (temperature corrected reference yield into array plane in (kWh/m^2/d)/(1kW/m^2)), Y_a (array yield on the DC side in kWh/kWp/d) and Y_f (final yield on the AC-side in kWh/kWp/d) and in addition performance ratio PR = Y_f / Y_r are indicated as average daily values for each month [1].

For an assessment of the energy yield of an array with a relatively low tilt angle it makes sense to examine the generator correction factor k_G = Y_a / Y_T in the months April to September that are not affected by snow covering, unless unusual events (e.g. inverter defects, cleanings) occurred in these months. As the influence of temperature is already contained in Y_T , k_G should be close to 1 in an ideal case. Fig. 7 shows k_G for 1994 to 2003 for the part of HTI's PV plant that has been monitored for the longest time.

Fig. 7 shows that k_G and thus energy yield of the PV generator decreased at first slowly, then faster and faster due to increasing pollution at the lower edges of the frames. Longer snow coverings seem to alleviate this decrease. From 1994 till the first cleaning in summer 1998, the generator correction factor k_G in the summer months dropped about 9%, from 1998 till the second cleaning in summer 2002 about 11%.

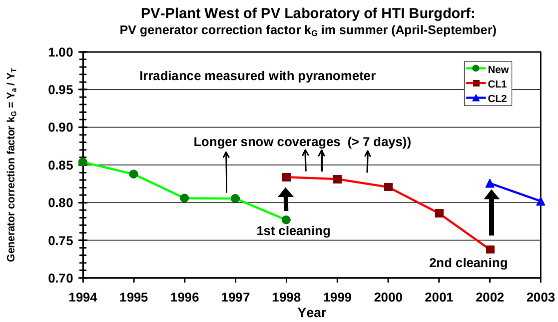

Fig. 7: Measured generator correction factor k_G of sub-plant west of the PV test plant of HTI Burgdorf with modules Siemens M55 with frames (long sides horizontal) and tilt angle β = 30°. See also [2].

During these measurements a defective module was discovered and replaced, which was responsible for about 1% of this reduction. After cleaning k_G increased about 7% in 1998 and 9% in 2002. However, part of this reduction of k_G and thus also of the energy yield seems to be irreversible. Since 1994 a permanent loss of about 3.3% has been encountered until 2002. As a relatively short time after the cleaning again a beginning pollution at the lower edges could be observed, some degradation of the glass surface at those locations seems to have occurred. It is also possible that some internal degradation (cells, foils) has occurred in the modules.

Fig. 8 shows the I-V-curves of an array that is part of the PV generator of the plant before and after cleaning in 2002. The reduction of measured STC power matches very well with the reduction of k_G according to fig. 7 observed between 1998 and 2002. Similar reductions of STC power were also measured at PV arrays with modules without frames and low tilt angle (β < 5°).

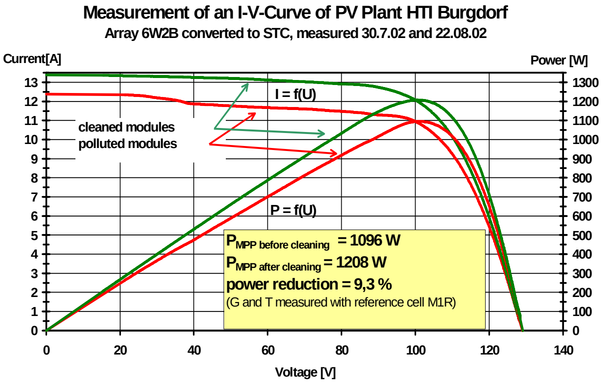

Fig. 8: Measured I-V and P-V curves (converted to STC) of an array of HTI's PV plant with a rated power of 1310W (24 modules M55 with 55W minus about 10W diode losses) before and after cleaning.

3. Evolution of energy yield at high alpine PV plants in course of time

The same analytical monitoring was performed also at the two high alpine PV plants Jungfraujoch (3454m) and Birg (2670m). As the plants are vertically mounted with $\beta = 90°$, only k_G-values during the winter months can be used and they must be corrected for snow coverings and inverter defects. No measurable effect of pollution was registered there. Fig. 9 shows the evolution of the generator correction factor k_G in the winter months in the years 1993 to 2003 for the two high alpine plants Birg (2670m) and Jungfraujoch (3454m). Due to sporadic inverter problems in 1993 and 1994, at PV plant Birg only values from 1995 on can be used.

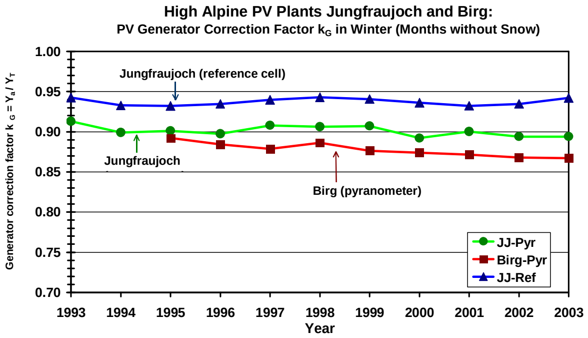

Fig. 9: Measured values of k_G for PV plants Jungfraujoch (3454m) and Birg (2670m) with $\beta = 90°$.

Fig. 9 shows, that considering the measurement accuracy at PV plant Jungfraujoch, k_G is about constant. Also at PV plant Birg only a reduction of about 2.5% in eight years was registered. At these locations air pollution and biological activity, which contribute considerably to the registered module pollution [2], are significantly reduced or not present at those altitudes. Due to the vertical mounting also no pollution at the lower edges can develop. Especially at plant Jungfraujoch several times a year snow coverings by air transported snow occur, that do not last very long, but have certainly a good cleaning effect. The low humidity of the air at those altitudes may also slow down possible internal degradation mechanisms in the modules.

4. Conclusions

At the plants monitored in Burgdorf, between 1996 and 2003 about 1.1% of energy was lost due to inverter defects. In lower parts of the country, especially at PV plants with framed modules and low distance between frame and cells, in course of time a significant reduction of energy yield may occur (up to 10 % after a few years). An important part of this reduction is due to the pollution developing gradually despite the cleaning by rain, a smaller part is caused by irreversible internal degradation of the modules. The same permanent pollution usually also develops with modules without frames, if they are mounted with low tilt angles. At high alpine plants these effects are significantly smaller.

At PV plants that are designed and maintained properly and that have been operated between 5 and 11 years, in the years 1996 to 2003 the energy yield converted to a standard year with average irradiance conditions was remarkably stable, the loss of normalised energy production in this period was only close to 4%. Depending on plant location, tilt angle and module type, a periodical cleaning of the modules may make sense to prevent a decrease in energy yield. Based on the data registered so far, a life expectancy of PV plants of 20 to 30 years is reasonable. However, especially for small plants a replacement of the inverter every 10 – 15 years seems to be necessary.

Most inverters already have an internal power monitoring and are controlled by microprocessors. By adding of a built-in input channel for a sensor for irradiance (and if possible for module temperature) by the manufacturer, it would be easy to integrate continuous monitoring of the performance ratio [1]. This would allow an early detection and analysis of plant malfunctions based on real measurements.

Acknowledgements

Thanks go to all the institutions that gave financial support for these projects. The work described in this paper was funded by Swiss Federal Office of Energy (BFE), the office of water and energy (WEA) in Bern, PSEL (Projekt- und Studienfonds der Elektrizitätswirtschaft), GMS, c/o BKW, Bern and Localnet AG.

My special thanks go to Mr. Ch. Beutler and Mr. Ch. Renken, who were assistants in charge of the projects in 1992-1997 and 1997 to 2004 respectively. The long-term monitoring projects will be continued also in the next years and the new assistant in charge will be Mr. Ch. Geissbuehler.

References

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Further informations about the research activities of HTI Burgdorf's PV laboratory and many monitoring data of 10 different PV plants : http://www.pvtest.ch