YIELD OF GRID CONNECTED PV SYSTEMS IN BURGDORF: CONSIDERABLY HIGHER THAN THE AVERAGE YIELD IN SWITZERLAND

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Abstract: Since 1991 energy produced by grid connected PV systems can be sold to the local utility in the town of Burgdorf at a special rate of CHF 1 per kWh (for 12 years). This rate based incentive is know as the „Burgdorf model" and has been adopted in similar form in several other towns, especially in Switzerland and Germany. As there were also some other subsidies available that were granted immediately after installation, 34 grid connected PV plants have been built in Burgdorf until spring 1997, pushing installed PV power to about 237 kWp or more than **15 Wp per capita**.
An interesting side effect of this high price paid for PV energy, specific energy yield of these PV installations in Burgdorf is considerably higher than in other parts of Switzerland, despite only average weather conditions. In a year with normal irradiation, annual energy yield of the plants with electronic inverters reaches **877kWh/kWp**. Some newer plants with advanced technology even pass the magic limit of **1000kWh/kWp**.
Keywords: Performance - 1: Grid Connected - 2: Yield - 3

1. Specifications of all grid connected PV systems evaluated in the project

Most PV systems in Burgdorf are owned by private persons or firms. A lot of them were mounted on roofs of schools, as there were additional subsidies for such PV plants granted in 1994 to 1996 by BEW. In order to make a clear identification of each plant possible without disclosing the name of the owner, several categories of plants are used. Plants of the category *firms* were erected on or at buildings of firms, those of the category *houses* on private houses. All other plants are on top of the roof of different schools indicated in the name of the plant. Plants *ISB* and *GIBBU* were erected by the schools themselves and plant *IBB* by the local utility, the remaining installations all by private persons.

Plant/ Location	Solar generator						Inverter	Con- struc- tion
	PV Modules	β	γ	P_{Gen} [kWp]	A_{Gen} [m²]	Mounting		
Firm 1	Siemens M55	25°	30° E	63.00	512.0	Tilted roof	Motor/Generator	1992
Firm 2	Siemens M55	60°	20° W	3.18	25.6	Façade	Solcon 3300	1991
Firm 3	Siemens M55	35°	5° W	2.97	23.9	Flat roof	TopClass 3000	1993
Firm 4	Kyocera K51	30°	0° (S)	3.06	26.3	Flat roof	Solcon 3400HE	1994
GIBBU	Solarex MSX64	30°/60°	0° (S)	3.07	26.7	Flat roof	Solcon 3400HE	1994
Gymnasium	Kyocera K51	30°	0° (S)	3.06	26.3	Flat roof	TopClass 2500/6 II	1994
House 1	Siemens M55	28°	10° E	3.18	25.6	Tilted roof	TopClass 3000	1992
House 2	Siemens M55	45°	45° W	3.18	25.6	Tilted roof	Solcon 3300	1991
House 3	Solarex MSX60	38°	30° E	1.44	13.4	Roof edge	PVWR 1500	1991
IBB/Gsteighof	Solarex MSX120	30°	20° E	16.00	151.1	Flat roof	Solarmax 15	1995
ISB/Tiergarten	Siemens M55HO	30°	29° W	59.66	450.6	Shed roof	div.	1994
Lindenfeld 1	Siemens M55	35°	0° (S)	3.30	25.6	Flat roof	Solarmax S	1995
Lindenfeld 2	Siemens M55	35°	0° (S)	3.30	25.6	Flat roof	Solarmax S	1995
Lindenfeld 3	Siemens M55	35°	0° (S)	3.30	25.6	Flat roof	Solarmax S	1995
Lindenfeld 4	Siemens M55	35°	0° (S)	3.30	25.6	Flat roof	Solarmax S	1995
Lindenfeld 5	Siemens M55	35°	0° (S)	3.30	25.6	Flat roof	Solarmax S	1995
Lindenfeld 6	Siemens M55	35°	0° (S)	3.30	25.6	Flat roof	Solarmax S	1995
Schlossmatt 1	Siemens M55	30°	7° E	3.18	25.6	Tilted roof	TopClass 4000/6 II	1994
Schlossmatt 2	Siemens M55	30°	7° E	3.18	25.6	Tilted roof	TopClass 4000/6 II	1994
Schlossmatt 3	Kyocera G102	30°	7° E	3.06	25.6	Tilted roof	TopClass 2500/6 II	1994
Schlossmatt 4	Kyocera G102	30°	7° E	3.06	25.6	Tilted roof	Solcon 3400HE	1994
Schlossmatt 5	Siemens M55	30°	7° E	3.18	25.6	Tilted roof	TopClass 4000/6 II	1994
Schlossmatt 6	Siemens M55	30°	7° E	3.18	25.6	Tilted roof	Solarmax S	1995
Schlossmatt 7	Siemens M55	30°	7° E	3.18	25.6	Tilted roof	Solarmax S	1995
Schlossmatt 8	Siemens M55	30°	7° E	3.18	25.6	Tilted roof	Solarmax S	1995
Schlossmatt 9	Kyocera G108	30°	7° E	3.24	25.6	Tilted roof	Solarmax S	1995

Table 1: Specifications of all grid connected PV systems in Burgdorf operational since Jan. 1996. β = tilt angle, γ = azimuth angle (deviation from south).

2. Energy production in 1996

To make possible a simple and fair comparison between PV plants of different size, *energy production is given only* in *kilowatthours per kilowatt peak (kWh/kWp)* in this paper.

For the following analysis only the 26 plants which were installed until the end of 1995 were used. Energy production of the other plants which were installed in 1996 and 1997 is not included.

Average annual energy production of these 26 plants in 1996 was 856 kWh/kWp, considerably higher than the Swiss average of 825 kWh/kWp in the same year [4]. Considering only the 25 plants with electronic inverters, annual energy yield is even 894 kWh/kWp. *Some new PV plants with advanced inverters even passed the magic limit of 1000 kWh/kWp*. The best plant produced 1040 kWh/kWp.

3. Irradiation in Burgdorf compared to irradiation in other parts of northern Switzerland

In Meteonorm 95 [5], a new publication about irradiation in all parts of Switzerland, average values of monthly and annual irradiation can be found, which are based on measurements in the last ten years and thus represent the most recent data available. It can be easily demonstrated, that as far as irradiation is concerned, **Burgdorf is an average location** in the lower part of northern Switzerland (see fig. 1). There are locations that have irradiation values a few percent higher (e.g. Bern Liebefeld, Neuchâtel and St. Gallen), but there are also locations whose values are a few percent lower (e.g. Schaffhausen, Wynau and Lucerne). Therefore Burgdorf is by no means preferred in comparison with other places.

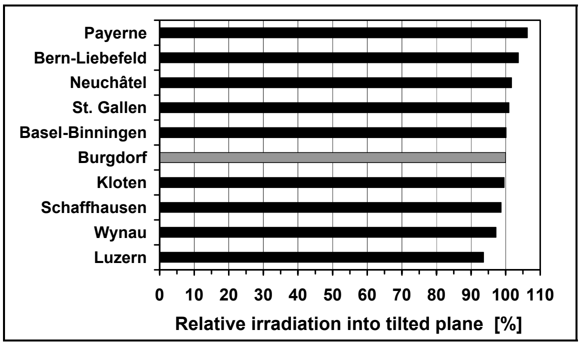

Fig. 1: Comparison of average annual irradiation into a tilted plane ($\beta = 30^o$) facing due south at different lower places in northern part of Switzerland (according to Meteonorm 95).

4. Irradiation in Burgdorf during 1996 compared to annual average

In 1996, global irradiation measured on ISB's main building in Burgdorf into a horizontal plane was 1165 kWh/m^2 . This value has to be compared to existing long term average values known for Burgdorf. From ISB's direct measurements in Burgdorf there were only data for the last 5 years, which is a relatively short period. From Meteonorm 85 there was an old average value and from Meteonorm 95 a new, slightly different average value available, both of which were extrapolated from irradiation measurements at locations about 20 km away. To get a maximum accuracy under the given circumstances, the average value of these 3 average values was chosen. Referred to this value, irradiation measured in the reference period used was 1.9 % higher than in a reference year with average irradiation.

5. Energy production in a reference year with average irradiation

For a fair comparison with energy yield data from other years, *measured energy production must be converted to a reference year with average irradiation*. For all grid connected PV plants in Switzerland, in 1996 the average energy production in such a reference year was 815kWh/kWp [4]. Table 2 shows the values obtained for the PV plants in Burgdorf described in Table 1 for such a reference year (calculated using data from 1996).

Average energy yield is 839 kWh/kWp, still considerably higher than the Swiss average. Considering only the plants with electronic inverters, this value is even 877 kWh/kWp. This value is 7.6% higher than the Swiss average. Two plants exceeded 1000 kWh/kWp even in such a reference year. Winter energy fraction is between 26.5% and 33.5% .

Plant / Location	P_{Gen} [kWp]	β	Winter-energy	Final yield [kWh/kWp]
Schlossmatt 8	3.18	30°	29.6%	1020
Schlossmatt 7	3.18	30°	28.8%	1013
Schlossmatt 6	3.18	30°	27.4%	994
Lindenfeld 6	3.30	35°	30.1%	978
Lindenfeld 1	3.30	35°	30.0%	975
Lindenfeld 3	3.30	35°	30.0%	974
Lindenfeld 5	3.30	35°	30.0%	971
Lindenfeld 2	3.30	35°	29.8%	968
Schlossmatt 9	3.24	30°	29.4%	961
Lindenfeld 4	3.30	35°	29.9%	958
Firm 4	3.06	30°	29.4%	955
Schlossmatt 1	3.18	30°	29.8%	937
Schlossmatt 2	3.18	30°	29.5%	922
Schlossmatt 5	3.18	30°	29.6%	914
GIBBU	3.07	30°/60°	31.5%	904
Schlossmatt 3	3.06	30°	28.3%	898
IBB/Gsteighof	16.00	30°	27.9%	890
Schlossmatt 4	3.06	30°	30.4%	866
ISB	59.66	30°	27.9%	837
Firm 3	2.97	35°	29.8%	833
House 2	3.18	45°	30.2%	804
Gymnasium	3.06	30°	28.8%	787
House 3	1.44	38°	27.7%	768
Firm 1	63.00	25°	26.5%	748
House 1	3.18	28°	29.4%	734
Firm 2	3.18	60°	33.5%	617
Mean value of all plants:			**28.2%**	**839**
Mean value of plants with electronic inverter:			**28.8%**	**877**

Table 2: Energy production of the PV plants in Burgdorf in a reference year (irradiation equal to long term annual average).

Having a look at the distribution of the energy yield of the different PV systems, you can see that **most plants** are in the interval between **900 and 1000 kWh/kWp**. Only four older plants are in classes below 800 kWh/kWp, but 17 plants are in classes of 900kWh/kWp and more.

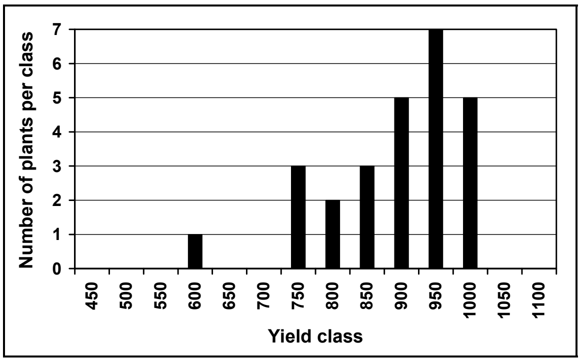

Fig. 2: Distribution of normalized energy production in kWh/kWp of the PV systems in Burgdorf in a reference year.

Fig. 3 shows the average monthly and yearly energy yield of the grid connected PV systems in Burgdorf with electronic inverters in a reference year.

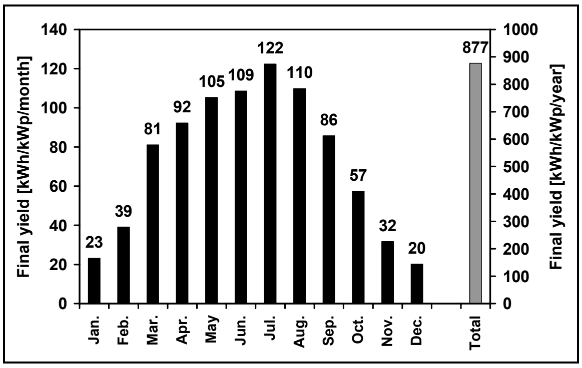

Fig. 3: Average energy production of the grid connected PV systems in Burgdorf using electronic inverters in a reference year with irradiation equal to the long term average value (Calculated using data from 1996).

6. Reasons for the differences in energy production

6.1 Monitoring setup to examine the reasons for these differences

From an earlier monitoring project carried out by ISB's PV laboratory for BEW (Bundesamt für Energiewirtschaft), WEA (Wasser- und Energiewirtschaftsamt des Kantons Bern) and IBB (Industrielle Betriebe Burgdorf), some of the older PV systems were already equipped with monitoring devices (simple data loggers for energy production and a central irradiation monitoring station).

To have a closer look at this additional energy yield, a new project was started and all newer plants were also equipped with these monitoring devices in January 1996. In this new project funded by PSEL (Projekt- und Studienfonds der Elektrizitätswirtschaft), BEW and IBB, energy production of all PV plants in Burgdorf will be monitored for at least three years. With this equipment it is also possible to detect not only inverter hardware defects but also more subtle system problems (e.g. sporadic malfunctions of the inverter) affecting energy production.

6.2 PV systems with high energy production

The highest production comes from new PV systems erected in 1995 with modules Siemens Solar M55 and inverters Solarmax S (with no transformer). Owing to the high MPP voltage (between 400 V to 600 V) on the DC side, wiring losses can be reduced considerably already at power levels of around 3 kWp. Moreover DC to AC conversion losses of these inverters are also relatively small [3]. However, electrical stress for modules and cable insulation is considerably higher with this approach than in conventional low voltage systems (MPP-voltages around 60 V to 100 V). The lack of a galvanic separation (no transformer) is certainly not enhancing security, too. Another reason for the additional energy production of these new plants is that module manufacturers can supply now modules that are much closer to rated power (not -10% to -15% as often observed in the past). Possibly effective MPP power values of new modules also have less distribution around the rated power value, which reduces mismatch losses.

A quite good performance can also be registered at plant firm 4, a well designed and maintained low voltage system. Here an optimal location (tilt 30°, facing due south, no shadowing at all, on readily accessible flat roof), a inverter with high efficiency and a good maintenance (immediate removal of snow in winter!) combined give a high energy yield.

6.3 PV systems with low energy production

PV plant Gymnasium is partially shaded in winter months by trees. Although they have no leaves during this season, shading by the wood alone reduces energy production considerably. In addition there was an inverter malfunction (power limitation at too low level), reducing energy production.

Another large PV system (firm 1) uses a DC motor driving a induction generator to convert DC power to AC. Especially partial load efficiency of such a mechanical energy conversion is very low, giving a low performance ratio of the system especially in winter. This solution was chosen in 1992 to save a great part of the very expensive inverter costs of a 60 kW inverter in those days.

Also a low performer is plant house 3: An older inverter with low partial load efficiency is fed by a solar generator smaller than the inverter's rated DC power.

Plant house 1 had a long inverter failure during holidays of the owner in summer (worst case!). Beside this failure, the inverter often shows sporadic malfunction, causing significant energy production losses, too.

The lowest production comes from a PV installation in a façade. Several groups of panels with a tilt angle of 60° are stacked vertically. In summer a nearby wall of the building as well as higher panels partially shade the array until the beginning of the afternoon, causing a low performance ratio also in summer.

6.4 PV systems with medium energy production

Annual energy yields of 850 to 950 kWh/kWp are quite nice for older installations. However, some PV plants should perfom better, e. g. Schlossmatt 4, whose production is relatively low compared to production of other plants at exactly the same location. Further measurements finally showed, that there was a broken cable in one string (of ten strings). This means that the energy production of this plant would be 11% higher if all ten strings were operational.

Additional energy production losses also arise in two plants, that are not only used for energy production, but also for education (GIBBU) or education and research (ISB).

6.5 Defects at inverters and other components affecting energy production

From time to time, system defects or malfunctions may occur. Most of them are inverter hardware defects. However, in the last few years, reliability has increased very much [3,6]. A few years ago several defects per year were not unusual.

Depending on the season, the prevailing weather conditions during the system outage and the reaction time to the defect, annual energy production can be affected considerably by such an event.

An example was a serious inverter malfunction at plant Schlossmatt 6 in the end of February 1996. The inverter operated far from MPP and therefore used only a small fraction of the DC power available. This problem was detected quickly and the inverter was repaired within a few days, but in 9 days 97 kWh or about 3% of the annual production was lost.

A similar defect at PV plant house 1 in summer caused a production loss of 8.6% in 19 days! Unfortunately this defect happened in a period of fine weather when the owner of the plant was on vacation.

6.6 Summary of energy losses of the PV systems in Burgdorf with electronic inverters in 1996

Analysis of the energy losses shows the good performance of the PV systems in Burgdorf: Inverter defects caused an energy loss of 0.6%. Inverter malfunctions reduced the energy production by 0.4%. Our own tests with the 60kWp test system reduced the energy production by 0.3%. Finally there was an energy loss of 1% of the annual energy production because of a snow coverage of the solar generator of most systems for some winter days (see fig. 5).

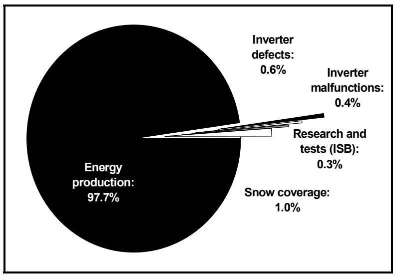

Fig. 5: Comparison of energy production and losses due to different reasons.

7. Conclusion

Owing to the additional subsidies from BEW for installations on roof of schools, a lot of PV systems were built only in 1995 to 1996. Thus newer modules, whose effective power is closer to rated power, and inverters of the newest technology with higher DC to AC conversion efficiencies were used in these plants. Owners probably care very much about design, orientation and operation of their installations which results in a higher availability.

Monitoring over several years during this project backed with some field measurements will show if these assumptions are correct.

Already now it seems quite clear, that besides a moderate initial subsidy **a high payback rate for PV energy from the local utility is the most efficient way to promote PV system technology** and gives better operational results than simply giving large initial subsidies for the erection of such PV plants and forgetting the performance of the plants afterwards.

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