YIELD AND RELIABILITY OF GRID-CONNECTED PV-SYSTEMS AT DIFFERENT LOCATIONS IN THE CANTON OF BERNE (SWITZERLAND)

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ABSTRACT

In this project, some grid connected PV-systems in Switzerland are monitored. Global monitoring is performed for all installations in Burgdorf in order to get reliability data about the invertes used.
Analytical monitoring is performed for four grid-connected PV-plants at different locations in altitudes of 500m up to 3454m above sea level. These installations not only give reliability data, but also accurate yield and performance data. Among these is the **highest grid connected PV-system in the world at Jungfraujoch (3454m, see fig. 1)** operational since Oct. 1993 with sensational winter energy yields (2.5 to 6 times more than in lower parts of Switzerland).

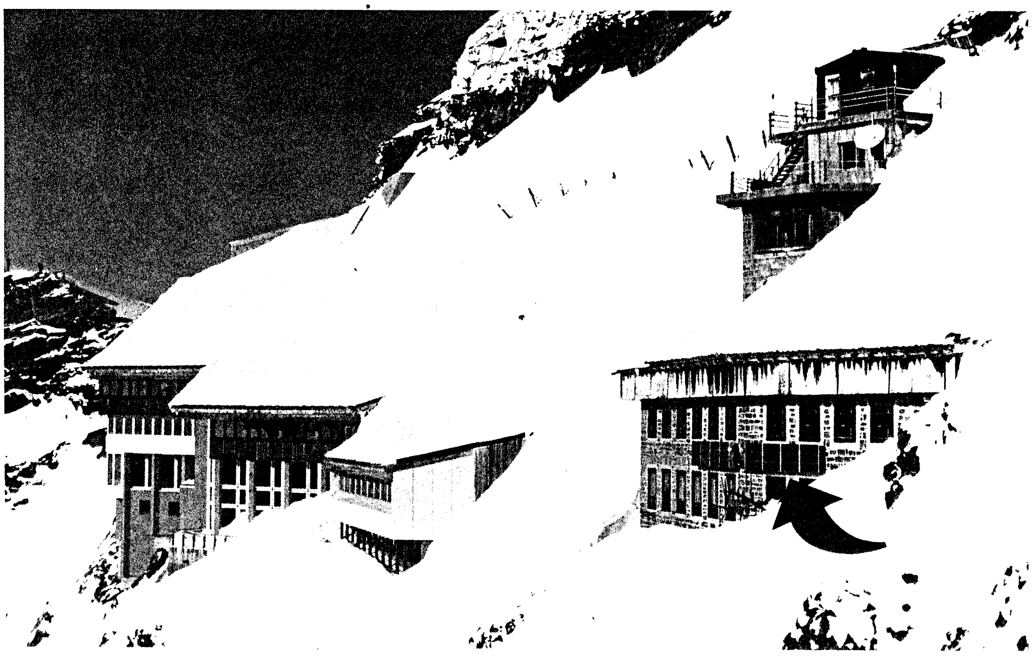

Fig. 1: Aerial view of the *highest grid-connected PV-plant in the world at Jungfraujoch (3454m)* at the outer walls of the research station. This PV-system with 1152Wp was planned and realized by ISB for this project. It has operated successfully with a 100% availability of energy production and monitoring data since Oct. 27, 1993. Referred to the size of the installation, winter energy production is sensational (by factors higher than in other parts of Switzerland).

Photo Siemens

1. Purpose and Goals of the Project

In the canton of Berne many grid-connected PV-systems have been realized in the last few years due to a favourable attitude of local authorities and utilities and (not to forget) substantial subsidies. Moreover, in some cities (e.g. Burgdorf), the local utility pays a substantial price for every kilowatt-hour (kWh) of PV energy injected into the grid (at present 1sFr./kWh). Only yearly energy production of these installations has been registered so far. As current research interests of ISB include the behaviour of grid-connected PV-inverters and systems, a project has been started to get a more detailed monitoring of some of these grid-connected PV-installations in this part of Switzerland. Results of this project will allow the improvement of simulation programs for energy production of grid-connected PV-systems and give data about long-term reliability and sporadic problems of the inverters used in the installations. This long-term reliability is still a problem with most PV-inverters.

1.1 Global Monitoring of all PV-systems in Burgdorf

To get a maximum of **reliability data** at a very low cost, a central meteo data monitoring station on ISB's main building was installed and every grid-connected PV-system in Burgdorf was equipped with at least a simple recording device. This device records energy production in intervals of fifteen minutes. Thus severe problems and especially hardware defects of the inverters used can be detected. Currently five installations in Burgdorf are monitored. Inverters used are two TOP CLASS 3000, a PV-WR 1500, a SOLCON 3300 and a rotating motor-generator-group. Installed peak solar generator power varies from 1.5kWp to 65kWp.

1.2 Analytical Monitoring of some PV-Systems in the Canton of Berne

In some locations in different parts of the canton and at different altitudes a more detailed monitoring is performed, giving not only **reliability data** but also precise **yield data.** Irradiance in the array plane (at some locations also in the horizontal plane), ambient temperature, cell temperature, DC voltage and DC current, AC power and at some locations also AC line-voltage are measured every second and recorded in intervals of five minutes. Currently four plants are monitored. They are located in Burgdorf and in Interlaken at about 500m above sea level and at Birg/Schilthorn in the Alps at an altitude of about 2600m.

The highlight of this project is **the highest grid connected PV-plant in the world** (1152Wp) at the research station **on Jungfraujoch at 3454m** above sea level, operational since Oct. 27, 1993. This installation has worked so far with a 100% availability of both the power generating and the data acquisition system and has given **sensational winter energy yields** compared to nearby installations in lower parts of Switzerland. A great deal of this paper will be dedicated to this very interesting plant on Jungfraujoch.

Operation in high altitudes is a very hard stress for the inverters due to extremely high irradiance peaks of more than 1.5kW/m² (highest value measured so far on Feb. 15, 1994: 1660W/m²) and heavy line voltage fluctuations and transients in such remote areas. PV-inverters surviving in such a harsh environment should perform more reliably under normal operating conditions.

Peak solar generator power of the plants is between 1.1kWp and 8.9kWp. Inverters used are a TOP CLASS 3000, a TOP CLASS 1800, four PV-WR 1800 in master-slave configuration and a SOLCON 3400.

2. Reliability of the inverters

Location	Inverter	Months of operation	Hardware failures per inverter operation year
Lohe/Burgdorf	PVWR 1500	19	0.0
IBI/Interlaken	4 x PVWR 1800	18	0.5
Lugeon/Burgdorf	Solcon 3300	21	0.0
Birg/Schilthorn	Solcon 3400	14	1.7
Jungfraujoch	TopClass 1800	4	0.0
Aebi/Burgdorf	TopClass 3000	8	0.0
Gfeller/Burgdorf	TopClass 3000	20	1.8

Table 1: Reliability of the inverters monitored in the project.

Table 1 gives the reliability data of the different installations. At IBI's plant at Interlaken, 3 inverters had hardware defects in spring 1993. At the plant Gfeller/Burgdorf, there were also 3 hardware defects. At Birg/Schilthorn, operational since Dec. 1992, 2 hardware defects in the SOLCON 3400 (prototype version) were registered. Such hardware defects occurred most frequently with prototype versions or models with low serial numbers. After modifications and improvements by the manufacturer the situation usually improved. More informations about some hardware defects can be found in [1].

Besides these defects, sporadic errors without hardware defects but with losses of energy production could be registered. Due to the limited number of sensors, the exact reason for these problems could not exactly be determined.

Fig. 2 shows such a sporadic problem at the plant at Birg/Schilthorn. We suppose that fast line voltage fluctuations or transients caused by on/off switching of the big AC motors of the Schilthorn cableway together with some problems in the driving circuits of the power stage (according to the manufacturer) caused these problems. At the beginning of 1994 this driver circuit was modified. Performance of the inverter is now much better. Regular voltage transients following the time table of the cableway still cause inverter stops, but normal inverter operation is resumed after a very short time without major influence on energy production (see fig. 3).

At IBI's PV-plant at Interlaken, in June 93 two inverters failed with hardware defects. For a few weeks, the plant had to operate with only two remaining inverters, limiting the power injected into grid to 4kW and after some time to about 3.5kW due to warming up of the inverters (see fig. 4).

At Gfeller/Burgdorf, in spring 93 sporadic inverter malfunctions were registered. On March 28th, after 11:10 the inverter had maximum power tracking problems at high irradiance peaks, causing a drop in DC efficiency of the whole PV-plant and also of some inverter efficiency (see fig. 5). After a few days, the inverter failed completely with a hardware defect (April 11th, see [1]).

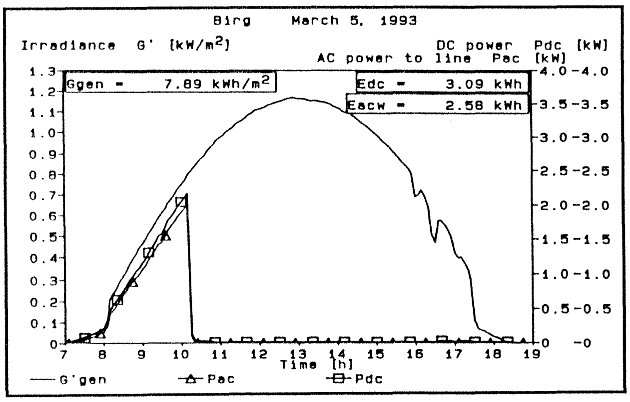

Fig. 2: Sporadic shutdown of prototype version of new inverter SOLCON 3400 at Birg/Schilthorn at 2600m during 1993. No hardware defect, automatic restart next morning.

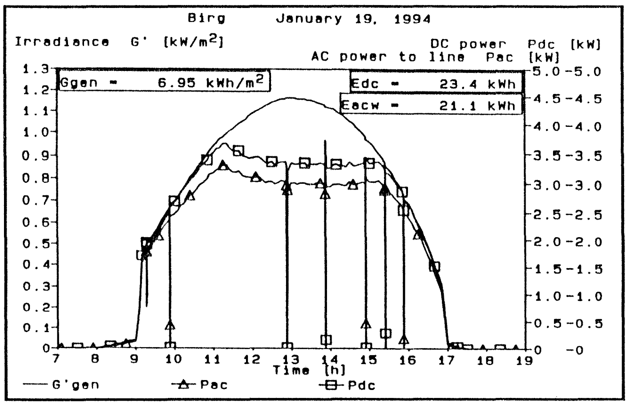

Fig. 3: Situation at Birg/Schilthorn after modification of SOLCON 3400 by manufacturer: Still short dropouts probably caused by voltage transients (following time-table of cableway). Energy production not longer affected seriously by these short inverter stops.

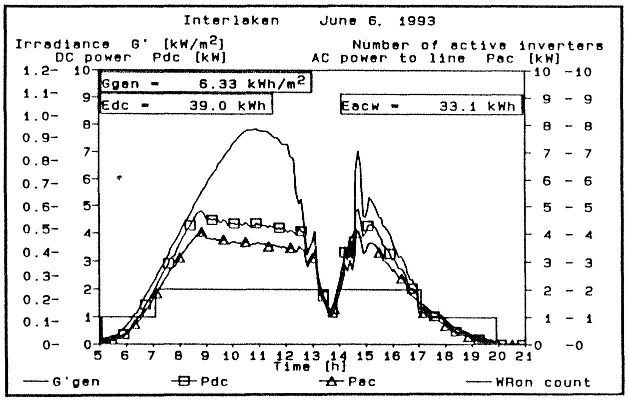

Fig. 4: Irradiance G', Pdc, Pac and number of active inverters at PV-plant IBI Interlaken(8.9kWp) when the plant is operating with only two instead of four active inverters after 2 hardware defects in June 93. From 9:00 to 15:00 the power injected into the grid is limited to 3.6 ... 4.0kW

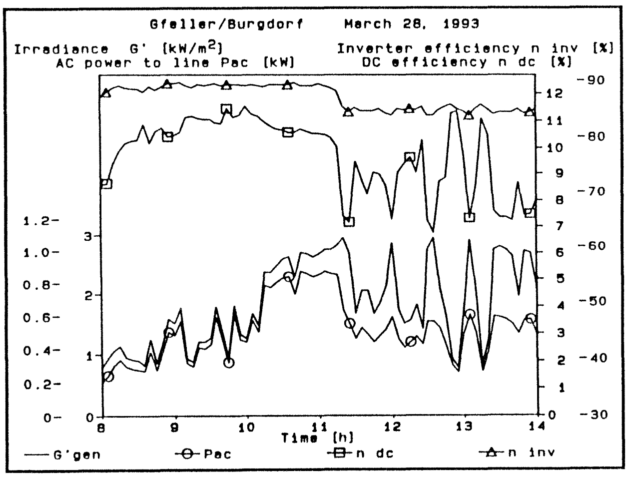

Fig. 5: Irradiance G', AC power Pac, DC efficiency n dc and inverter efficiency n inv at PV-plant Gfeller/Burgdorf on March 28th 1993.
After 11:10 the inverter had sporadic maximum power tracking problems at high irradiance peaks. As a result of these problems, DC efficiency n dc and inverter efficiency n inv were reduced considerably.
A few days later a hardware defect occurred.

3. ISB's Grid connected PV-Plant at Jungfraujoch

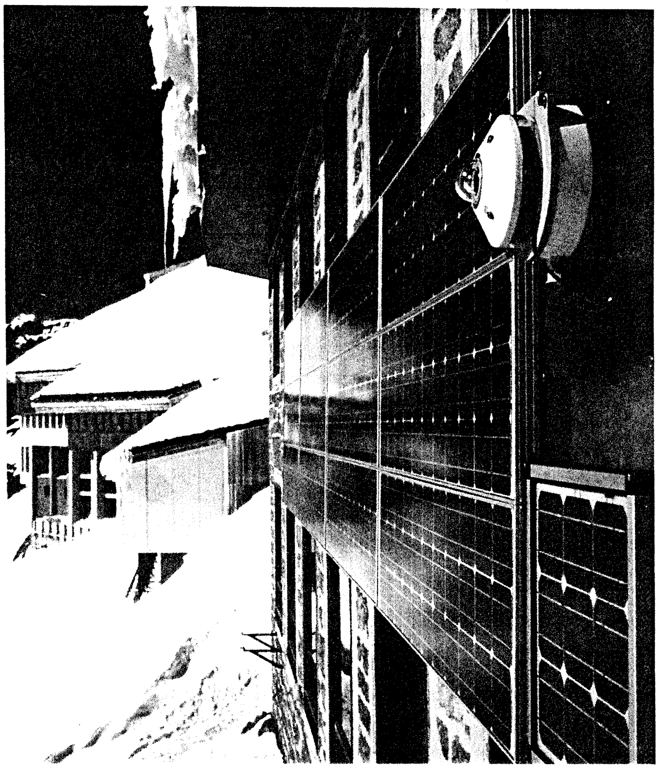

Fig. 6: PV-generator and irradiance sensors of ISB's PV-plant (1152Wp) at Jungfraujoch (3454m)

3.1 Plant Layout

The solar generator consists of 24 modules Siemens M75, producing 1152Wp at STC. It is divided into two arrays of 12 modules that are mounted in vertical position at the outer walls of the research station at Jungfraujoch (see fig. 1 and 6). The first array has a west deviation of 12° from south, the second a west deviation of 27°. DC power produced is converted to AC by means of an inverter TOP CLASS 1800. Fig. 7 shows a block diagram of the plant. The following parameters are measured:

- Irradiance into array plane 1 and 2 (For each array two sensors: A pyranometer with heating and a reference cell)
- Module temperature of array 1 and 2
- Ambient temperature
- DC current produced by each array
- DC voltage at inverter input
- AC voltage at inverter output
- AC power injected into utility grid

These values are sampled every two seconds. Data are stored temporarily in a data logger Campbell CR10. Under normal conditions, every 5 minutes average values are calculated and stored from these values. However, in case of an error, the original data are stored as an error file, allowing detailed analysis of such an error. Every day, data are transmitted to ISB early in the morning via a telephone line and a modem for further analysis and storage.

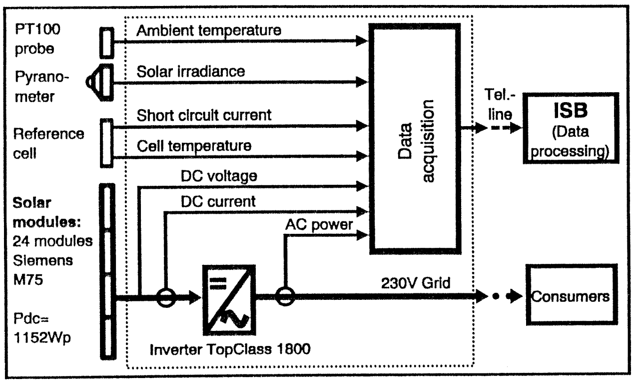

Fig. 7: Block diagram of ISB's grid-connected PV-plant (1152Wp) at Jungfraujoch (3454m).

3.2 Energy Production

Energy produced so far was even higher than expected. Fig. 8 shows irradiance, DC- and AC-power and module temperature during a very fine and sunny day, Feb. 19, 1994. Irradiance is peaking at 1.3kW/m² around 13:40, much higher than in lower parts of Switzerland in summer. One reason is that the athmosphere has only about 2/3 of its usual thickness in lower regions, another the very strong diffuse irradiance of the snow on the glaciers just below the arrays. Owing to the very high irradiance, solar cell temperature reaches 27°C in early afternoon despite very low ambient temperatures.

Fig. 9 shows global irradiation, DC- and AC-energy production of the plant Jungfraujoch in winter 93/94 (November until February). It survived several heavy snow storms with wind speeds up to 200km/h without any damage. Referred to the size of the installation, it has produced much more (by factors!) than a PV-plant in Burgdorf (3180Wp, 540m) or Mont Soleil (560kWp, 1270m), see fig. 10.

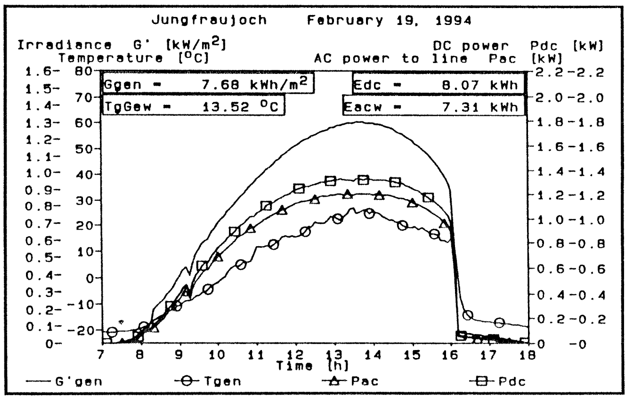

Fig. 8: Irradiance G' into array plane, DC power Pdc, AC power Pac and module temperature Tgen on a sunny, but very cold winter day (Feb. 19, 1994).

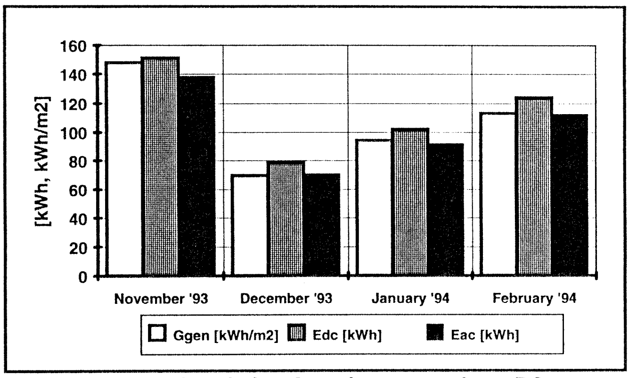

Fig. 9: Monthly irradiation Ggen into array plane, DC energy Edc and AC energy Eac of PV-plant Jungfraujoch from November 93 to February 94.

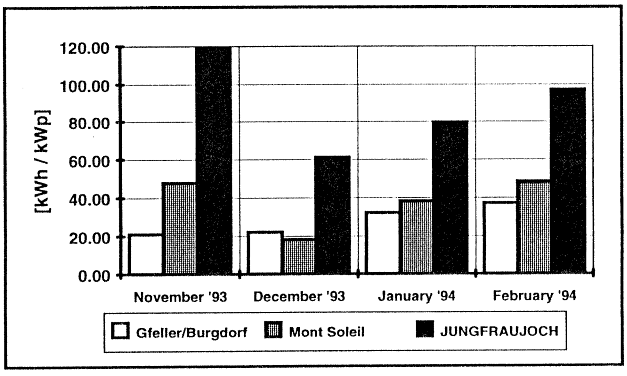

Fig. 10: Monthly energy production referred to PV-generator size for a PV-plant in Burgdorf (540m), Mont Soleil (1270m) and Jungfraujoch (3454m).

4. Comparison of Energy Production of PV-Plants of different Size and at different Locations

In order to compare energy production of grid-connected PV-plants of different size and at different locations, the following values are useful:

Final Yield Y_f : $$Y_f = \frac{Eac}{Pgen} \quad [h/d]$$

Operating time with peak solar generator power in order to produce the same AC energy (hours per day)

Reference Yield Y_r : $$Y_r = \frac{Ggen}{1000\ W/m^2} \quad [h/d]$$

Time needed with standard irradiance of 1000W/m² to get same irradiation in array plane (hours per day).

Performance Ratio PR = Y_f / Y_r

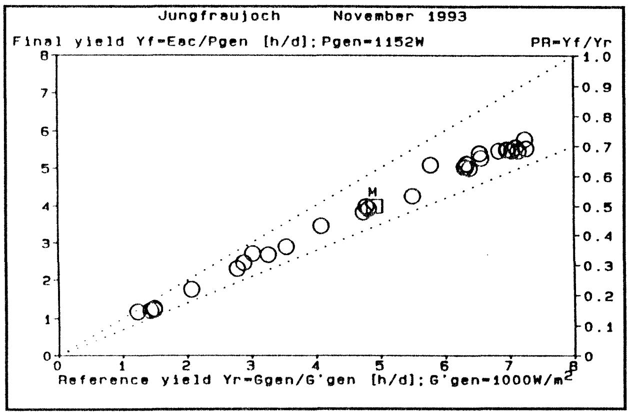

Fig. 11: Y_f , Y_r and performance ratio PR in November 93 for PV-plant Jungfraujoch (3454m).

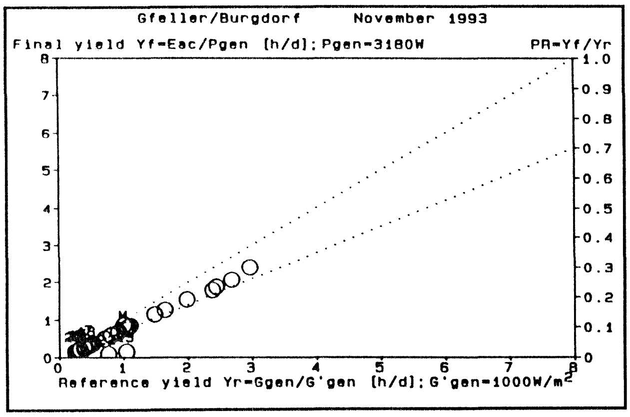

Fig. 12: Y_f , Y_r and performance ratio PR in November 93 for a PV-plant in Burgdorf (540m).

Fig. 11 shows the very high values Y_f and Y_r in November 1993 for ISB's PV-plant at Jungfraujoch, whereas fig. 12 displays the same values for a grid-connected PV-installation in Burgdorf. In fig. 13 the monthly values for Y_f and Y_r for three different PV-plants in Burgdorf, Mont Soleil and Jungfraujoch are indicated for the time between November 93 and February 1994. Table 2 shows performance ratio PR for the same PV-plants in the same time. Owing to reflections at the surface of the glass of the reference cells (especially at low angles) and due to differences between the standard spectrum and the spectrum at Jungfraujoch, there are differences in performance if Y_r is measured with a pyranometer or a reference cell (especially in November 93). Between December 93 and February 94 there were a few hours of snow coverage on the pyranometers after heavy snow storms due to a defect in the heating, resulting in a smaller difference than in November. However, as there are differences in irradiance measurements with pyranometers and solar cells, the type of sensor used should always be indicated when a PR-value is given.

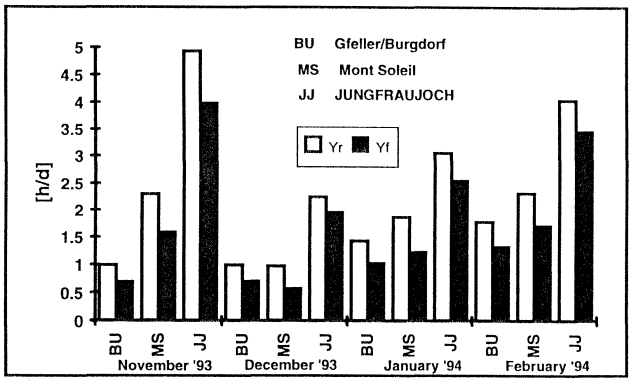

Fig. 13: Monthly average values of Y_f and Y_r from November 93 to February 94 for a grid connected PV-plant in Burgdorf (540m), Mont Soleil (1270m) and Jungfraujoch (3454m).

Performance Ratio PR=Y_f/Y_r	Nov 93	Dec 93	Jan 94	Feb 94
Gfeller/Burgdorf	0.71	0.72	0.72	0.75
Mont Soleil	0.69	0.60	0.66	0.74
Jungfraujoch (Pyranometer)	0.81	0.88	0.84	0.86
Jungfraujoch (Ref.-module)	0.84	0.86	0.84	0.87

Table 2: Monthly performance ratio PR for three grid-connected PV-plants in Burgdorf, at Mont-Soleil and Jungfraujoch (two values given, one for pyranometer monitoring, one for reference cell monitoring) from November 93 to February 94.

Acknowledgements

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Conclusion

The members of ISB's PV-laboratory hope, that the alpine PV-plants in this project and especially the plant at Jungfraujoch will survive the storms throughout the year and the thunderstorms and lightnings in summer and that their yield data will be so interesting as in the past. Winter production of grid-connected PV-installations in lower parts of Switzerland is mostly between 20% and 35% of the annual production. However, winter production of PV-plants mounted at the walls of high alpine buildings should be between 45% and 50% , matching much better to the annual load profile in Switzerland (peak electricity demand in winter). Hopefully, this prediction can be confirmed by actual yield data of the PV-plants in this project.

References:

[1] H. Häberlin, F. Käser and S. Oberli: "New PV-Inverters from 2kW to 20kW for Grid-Connection: Results of extended Tests with single- and three-phase-Units". Proc. 12th EU-PV-Conf., Amsterdam, 1994.

[2] H. Häberlin and H.R. Röthlisberger: "PV-Inverters from 1kW to 3kW for Grid-Connection: Results of Extended Tests". Proc. 11th EC-PV-Conference, Montreux, 1992.