Name of research institute or organization:

Berner Fachhochschule, Hochschule für Technik und Informatik (HTI)

Title of project:

Long-term energy yield and reliability of a high alpine PV (photovoltaic) plant at 3453 m

Project leader and team

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Project description:

Abstract: The ***highest grid connected PV plant in the World*** at Jungfraujoch (3454 meters above sea level) was planned and realised by HTI Burgdorf during summer and fall 1993. It has operated successfully with a 100% availability of energy production and monitoring data since Oct. 27, 1993. Operating in high altitudes is a very hard stress for all the components. Components surviving in such a harsh environment should perform more reliably under normal operating conditions. Until Dec. 2003, the plant has operated successfully with a 100% availability of energy production and monitoring data for more than 122 months. By means of some modifications energy production of the plant could even be increased compared to the first year of operation.

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	Average 1994-2003
Y_f (kWh/kWp/a)	1272	1404	1454	1504	1452	1330	1372	1325	1400	1467	**1398**
PR = Y_f/Y_r in %	81.8	84.1	84.7	85.3	87.0	84.8	84.6	78.6	85.2	84.9	**84.2**

Table 1: Annual energy production (referred to effective STC-power) and performance ratio from 1994 to 2003.

In 1999, 2000 and 2001, energy production was affected by the replacement of the windows of the research station. In spring 2001, energy production was relatively low due to a long snow coverage of half of the PV array. Winter energy fraction in all these years was between 44.6% and 50.7%. In the record period between March 1997 and February 1998 (12 months), **annual final yield** was **1541kWh/kWp**, **winter energy fraction 46.2%** and mean **performance ratio** was **85.2%**. Such figures for a PV plant in central Europe are very good and would also be nice for plants in southern Europe.

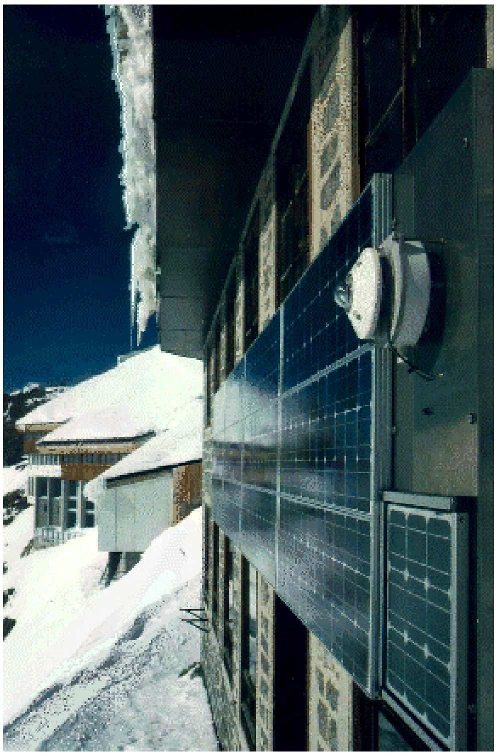

Fig. 1:

1. Introduction

PV plant Jungfraujoch (3454 meters above sea level), was planned and realised by HTI Burgdorf during summer and fall 1993 and is probably still the highest grid connected PV plant in the world. It is connected to the Swiss national grid and thus to the large grid in western Europe. It has operated successfully with a 100% availability of energy production and monitoring data since Oct. 27, 1993.

2. Plant layout

The solar generator consists of 24 modules Siemens M75 (48Wp) with a rated power of 1152 Wp. They are mounted vertically to the outer walls of the international research station at Jungfraujoch. Thus PV plant Jungfraujoch can be considered as a building integrated installation. At this location from time to time STC conditions occur, therefore it is possible to determine effective array power at STC from measured DC inverter input power at STC increased by calculated losses in array wiring and string diodes. Effective power of the array is 1130Wp at STC. The array 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). The first array has a west deviation of 12° from south, the second a west deviation of 27°.

Energy produced by the modules was injected into grid at first by an inverter Top Class 1800. After 32 months with very good operating results, plant performance could be increased further by elimination of the string diodes in the PV array and replacing the inverter by an improved model (Top Class 2500/4 Grid III).

Fig. 2 shows a block diagram of the plant. The following parameters are measured:

- Irradiance into array plane 1 and 2 (two sensors per array: A heated pyranometer 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.

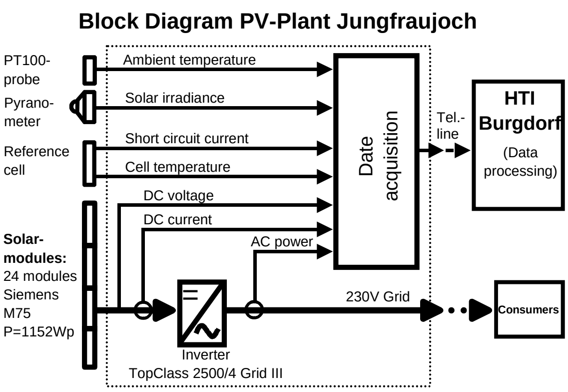

Fig. 2: Block Diagram of the grid connected PV Plant (1.152kWp nominal, 1.13kWp effective) of HTI Burgdorf at Jungfraujoch (3454m).

Every day, data are transmitted to HTI Burgdorf early in the morning via a telephone line and a modem for further analysis and storage.

To get a maximum reliability, appropriate mechanical and electrical design is essential. Wind loads encountered at this location are extremely high, and due to the quite frequent thunderstorms lightning and overvoltage protection is a very important issue.

3. Plant operation experience and reliability

Since the start of operation in October 1993, the plant survived the following high alpine stress factors *without any damages*:

- **Heavy storms** with wind speeds above 200km/h: This is a very hard test for the mechanical components and construction.
- **Thunderstorms** with heavy lightning strokes causing damages in other experiments that were not appropriately protected at the research station.
- **Irradiance peaks** with values up to 1720W/m²: Such peaks (higher than the solar constant!) may occur at this location during cloud enhancement situations, because the irradiance from the sky is increased considerably by diffuse reflection from the glacier in front of the array. Due to the proportionality of irradiance and DC-power, these peaks are a hard stress for the inverter.
- **Large temperature differences**: On a cold winter day, drop of solar cell temperature after sunset can exceed 40 degrees (centigrade) within 30 minutes. Total range of measured solar cell temperature so far was -29°C to +66°C.
- **Snow and ice covering** of the solar generator: In spring, snow heights of more than 3 m are possible. The resulting snow height depends not only from the amount of snow coming down, but also from the wind speed and wind direction during and after the snowfall. Sometimes energy production is also reduced by hoarfrost and partial shadowing by colossal icicles.

In Summer 1999, 2000 and 2001 the windows at the façade of the research station had to be replaced. For this purpose a scaffold had to be erected, which caused partial shadowing in August, September and October of these years. During the work carried out in 2001, a module of the PV array was mechanically damaged.
When this module was replaced, it was discovered that at another module delaminations were developing at the lower edge of the PV array of the west generator. During a visual check two years ago nothing was noticed, therefore this delamination seemed to have appeared quite rapidly.
This delamination was probably caused by moisture entering the module through the lower module edge causing electrolytic degradation of the neighbouring cells. No measurable power loss of the whole PV array was noted so far, but as a measure of precaution this delaminated module was also replaced in autumn 2001.

Thus it can be noted that in more than 10 years of operation under extreme climatic conditions only one module out of 24 showed visual signs of degradation that were caused by natural influences. However, no degradation of electrical module performance was registered before it was replaced. The only operational problem is the large snow quantity encountered in spring, which may cause a covering of one of the two PV generators and thus a loss of energy for a few days up to a few weeks per year.

4. Data acquisition system

The **data acquisition system** with a data logger CR10 operated without major problems, too. Availability of monitoring data (AMD) so far was 100%.

Unfortunately the ventilation system of the pyranometers had not the same reliability like the rest of the system. As its power supply was undersized, it failed after only one month of operation. Thus between December 93 and June 94 the pyranometers were covered by snow or ice on some days for some hours. This deficiency could be cured by replacement of the power supply by a stronger unit. In February 1994 a measuring error of 2% occurred in a AC-power measuring device. This error could be detected and corrected with the redundant measuring system. The defective device was replaced by a new one as soon as possible. In Feb. 2003, a DC-DC converter feeding some of the sensors failed and had to be replaced. Fortunately the missing data could be reconstructed by means of the remaining data that were not affected by the event.

5. Average annual energy production and performance ratio from 1994 - 2003

To compare performance of PV plants of different size and at different locations, normalized quantities are very useful. By dividing energy production in a given period (month, year) by peak PV generator power (at Jungfraujoch: 1.13kWp), array yield Y_a (DC) and final Yield Y_f (AC) is obtained. Reference yield Y_r is calculated by dividing irradiation in the same period by 1kW/m^2. If array temperature is measured, the temperature corrected reference yield Y_T can be calculated from Y_r taking into account the temperature dependent reduction of PV conversion efficiency (details see [1]). Using *average daily values* eliminates the influence of different lengths of months.

In Fig. 3 a normalized yearly analysis for the average year for the time period between 1993 and 2003 with monthly values of Y_f , Y_a , temperature corrected reference yield Y_T and reference yield Y_r is shown. All values are referred to effective PV generator power. Thermal capture losses $L_{CT} = Y_r – Y_T$, miscellaneous capture losses

$L_{CM} = Y_T – Y_a$, system losses $L_S = Y_a - Y_f$ and performance ratio $PR = Y_f /Y_r$ (number on top of bar) are also indicated [1].

In fig. 4 to 6 normalized yearly analysis for the year with lowest energy yield, the year with the highest energy yield, and 2003, the year with the second highest energy yield and the highest average module temperatures, are shown. In all these figures (fig. 3 - 6) irradiance was measured with a *reference cell.*

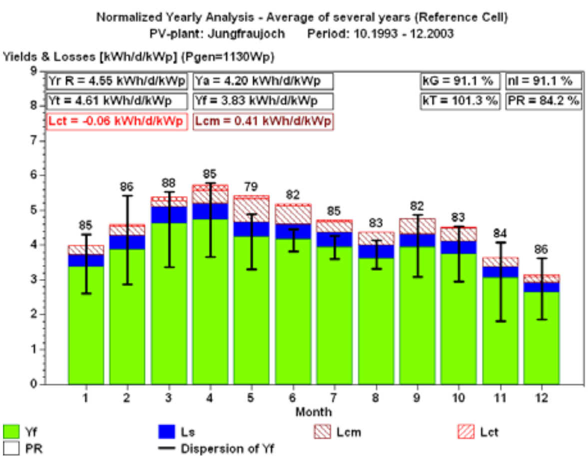

Fig. 3: Normalized monthly energy production for the average year between Nov. 1993 and Dec. 2003 for PV plant Jungfraujoch (irradiance measured with a reference cell). Partial snow covering of the solar generator in spring causes higher L_C and lower PR values especially in the month of May and June. Production in August till October is also somewhat reduced due to the partial shadowing of the PV array by the replacement of the windows in 1999-2001. Monthly PR-values are between 79% and 88%, annual average is 84.2%.
Note: If the values would be referred to the rated power of 1.152kWp, Y_f and PR would be about 2% lower.

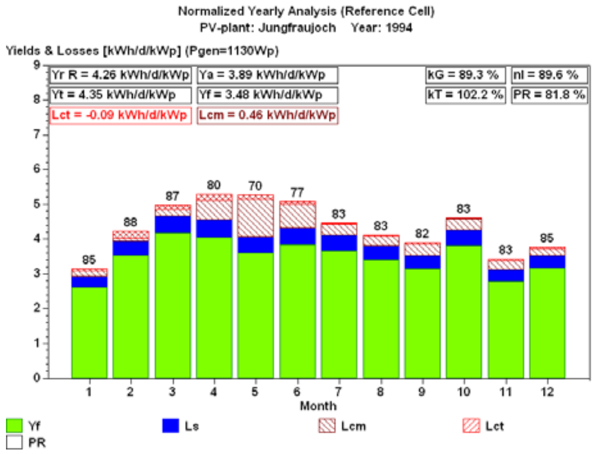

Fig. 4: Normalized monthly energy production for 1994 (year with lowest annual energy production in 10 years). In April to June, energy production is reduced by snow.

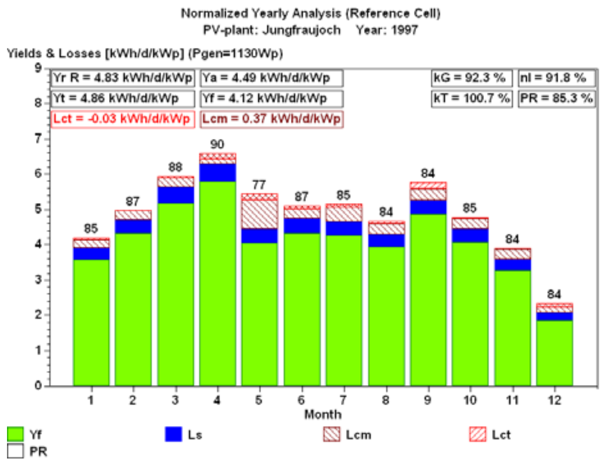

Fig. 5: Normalized monthly energy production for 1997 (year with highest annual energy production in 10 years).

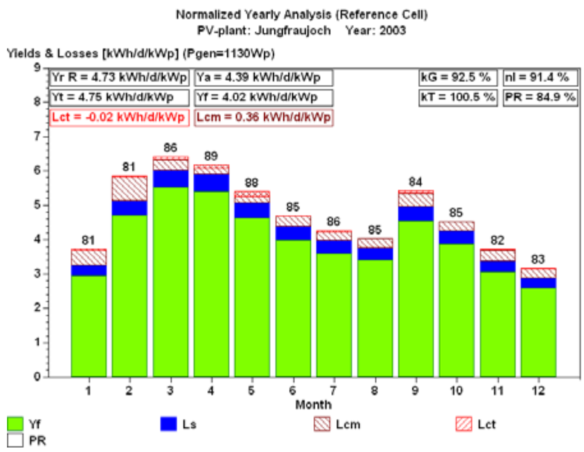

Fig. 6: Normalized monthly energy production for 2003, the year with the second highest energy production and the highest module temperatures in 10 years.

In 1997, irradiation and energy yield was highest in the reporting period of 10 years between 1994 and 2003. In 2003, in lower regions of Switzerland record values of solar irradiation and summer temperature were reached. However, at Jungfraujoch, measured irradiation in the array plane and energy production was only the second highest in the reporting period, whereas irradiance-weighted module temperatures were highest in the reporting period (slightly higher than in the record year 1997).

Thus from a PV point of view, 2003 was by far the best year for PV-plants in lower parts of Switzerland, but on Jungfraujoch only the second best!

6. Annual energy production of PV plant Jungfraujoch compared to other Swiss PV plants

Fig. 7 shows normalized monthly energy production referred to peak array power in the years 1994 to 2003 of a PV plant in Burgdorf on the roof of a house (3.18kWp, 540m), of the large PV plant Mont Soleil (560kWp, 1270m) and of PV plant Jungfraujoch (1.15kWp, 3454m).

In summer 1996 energy production of the plant in Burgdorf was affected considerably by a inverter defect that occurred during the vacation of the owner and was discovered only when he came back.

At PV plants in the lower parts of the country, where it is often foggy or overcast in autumn and winter, energy production varies very much between a high maximum value in summer and a deep minimum in winter. Winter energy fraction at such locations is below 30%. At the plant in Burgdorf at 540m, the ratio between summer maximum and winter minimum is around 10:1.

At PV plant Mont Soleil at 1270m, the ratio between summer maximum and winter minimum is already considerably lower, energy production is more continuous and winter energy fraction is higher. In some years there is a summer maximum like in the lower regions of the country, but in some years there are two maximums in spring and autumn like at PV plant Jungfraujoch.

At PV plant Jungfraujoch, the situation is even better. Annual energy production is much higher than at the other locations and monthly energy production is distributed much better over the whole year and thus relatively constant. The ratio between maximum and minimum is usually only slightly over 2 (exception in 1997: about 3) and winter energy fraction is between 44.6% and 50.7%

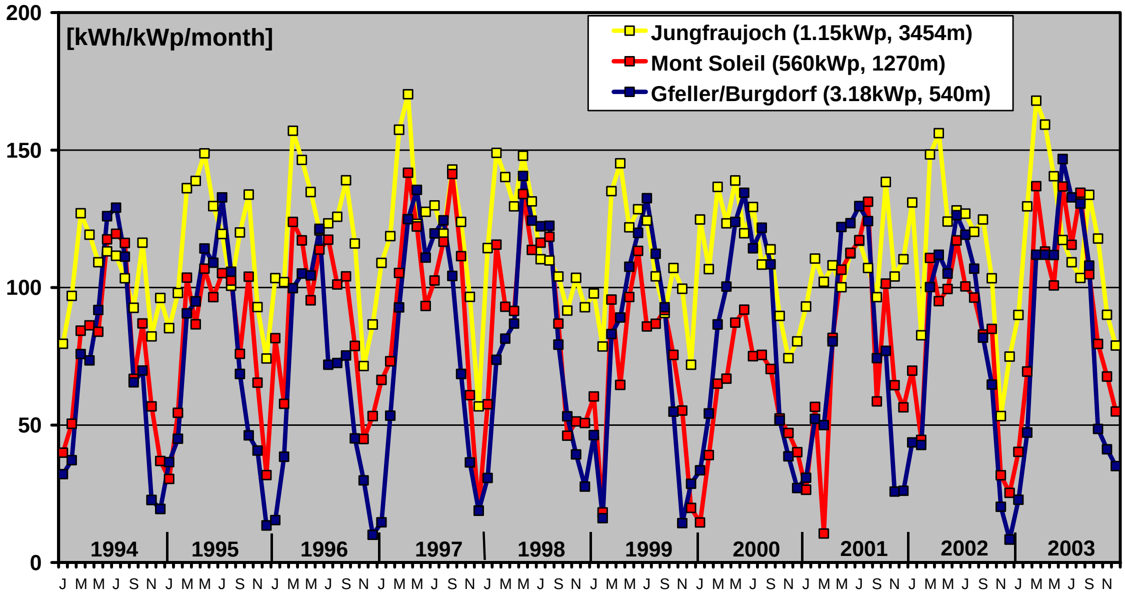

Fig. 7: Normalized monthly energy production (referred to rated PV generator power) of PV plants Jungfraujoch (1.15kWp), Mont Soleil (560kWp) and Gfeller/Burgdorf (3.18kWp) in the years 1994 to 2003.

7. Conclusion

In more than ten years of successful operation, owing to the tilt angle of 90^{o} and the high amount of sunshine in winter, **energy production of PV plant Jungfraujoch was relatively constant over the whole year**. Instead of the usual summer maximum and winter minimum (which can vary by a factor of ten in lower parts of Switzerland, see PV plant at Burgdorf in fig. 7), usually two maximums per year (a higher one in spring (March, April or May) and a lower one in autumn (September or October)) are observed. In summer, due to high albedo of the glacier in front of the PV array, a lot of irradiation is reflected onto the array despite the high tilt angle of 90^{o} . Therefore summer energy production is also remarkably high.

The only major operational problem encountered was a temporary snow coverage occurring often in spring. However, due to the tilt angle of 90^{o} this problem was not very serious. With a greater array height above ground (e.g. 5m to 7m instead of only 3m), this problem could probably be completely eliminated.

Energy production and performance ratio of the high alpine PV plant at Jungfraujoch reached very high values in the last ten years. Thus it has been demonstrated that reliable operation of a grid-connected PV plant and high energy yields are possible under such extreme climatic conditions. Experience obtained in this project will be very helpful for the realisation of other high alpine grid connected PV-plants.

Acknowledgements

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References

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