Grid Connected PV Plant Jungfraujoch (3454m) in the Swiss Alps: Results of more than four Years of trouble-free Operation

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Abstract: The ***highest grid connected PV plant in the World*** at Jungfraujoch (3454 meters above sea level) was planned and realized by HTA 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. By now the plant has operated successfully with a 100% availability of energy production and monitoring data for more than 56 months. By means of some modifications energy production of the plant could even be increased compared to the first year of operation. Annual energy production varied between 1272kWh/kWp in 1994 and 1504kWh/kWp in 1997, winter energy fraction between 44.6% and 48%. In the record period between December 1996 and November 1997 (12 months), **annual final yield** was **1535kWh/kWp**, **winter energy fraction 46%** and mean **performance ratio** was **85.4%**. Such figures for a PV plant in central Europe are very good and would also be nice for plants in southern Europe.

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

1. Introduction

PV plant Jungfraujoch (3454 meters above sea level), was planned and realised by HTA Burgdorf during summer and fall 1993 and is probably still the highest grid connected PV plant in the World. It is not only connected to a small local grid, but 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.

Fig. 1: View of the grid connected PV plant (1.1kWp) at the research station at Jungfraujoch (3454m, about 46.5°N): One of the two arrays with irradiance sensor (pyranometer and reference cell).

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.

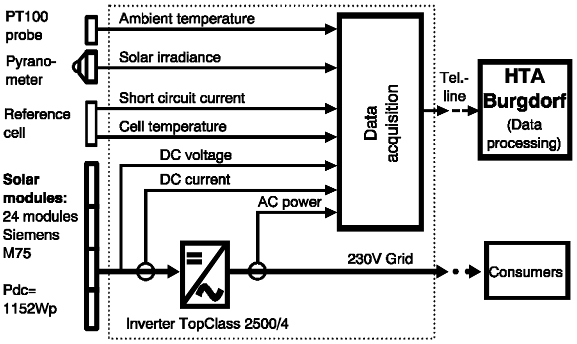

Fig. 2: Block Diagram of the grid connected PV Plant (1.152kWp nominal, 1.13kWp effective) of HTA Burgdorf at Jungfraujoch (3454m).

Every day, data are transmitted to HTA 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 reflexion 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.

No degradation of module performance was registered so far. 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.

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. Besides this, in February 1994 suddenly 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.

5. Annual energy production and performance ratio

5.1 Normalized EnergyYields

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: 1130Wp), 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 $1kW/m^2$ and performance ratio PR is Y_f / Y_r (details see [2]). Using *avarage daily values* eliminates the influence of different lengths of months.
In Fig. 3 to 6 show a normalized yearly analysis for 1994 to 1997 with monthly values of Y_f , Y_a and Y_r . All values are referred to effective PV generator power. Capture losses
$L_C = Y_r - Y_a$, system losses $L_S = Y_a - Y_f$ and performance ratio $PR = Y_f / Y_r$ (number on top of bar) are also indicated [2]. In fig. 3 to fig. 6 irradiance is measured with a *reference cell.*

5.2 Operating results in 1994

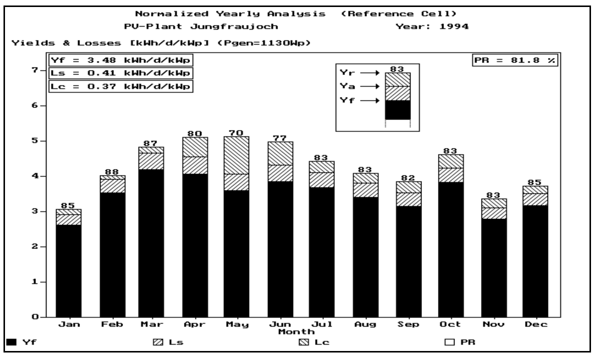

Fig. 3:
Normalized yearly analysis for **1994**. Partial snow covering of the solar generator in spring caused higher L_C and lower PR values. Monthly PR-values were between 70% and 88%, annual average was 81.8%.

Due to the large snow quantity in spring 1994, one of the two PV arrays was completely covered for a few days, causing a remarkable drop of energy production.

Referred to nominal PV generator power (1152Wp), energy production was 1247kWh/kWp, referred to effective power (1130Wp) even **1272 kWh/kWp**. Winter energy fraction (October - March) was **48.0%** . Mean value of performance ratio **PR** was **81.8%** , mean value of **energetic inverter efficiency** was **89.6%**.

5.3 Operating results in 1995

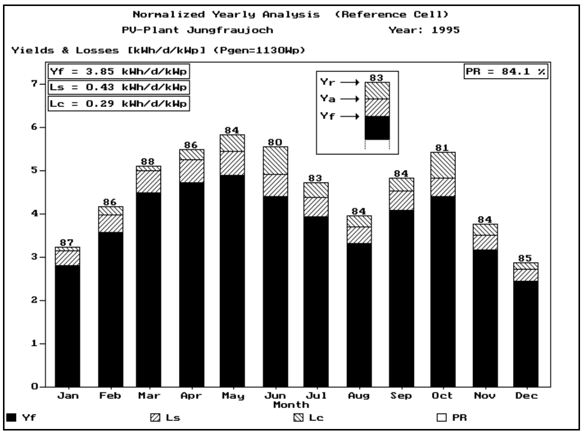

Fig. 4:
Normalized yearly analysis for **1995**. Monthly performance ratio PR was between 80% and 88%, annual average increased to 84.1%.

In **1995**, irradiation into the array plane increased and snow coverage in spring decreased considerably compared to 1994. Referred to nominal PV generator power (1152Wp), energy production was 1377 kWh/kWp, referred to effective power (1130Wp) even **1404 kWh/kWp**. Winter energy fraction was 45.0% . Mean value of performance ratio **PR** was **84.1%** , mean value of **energetic inverter efficiency** was **89.9%** .

5.4 Operating results in 1996

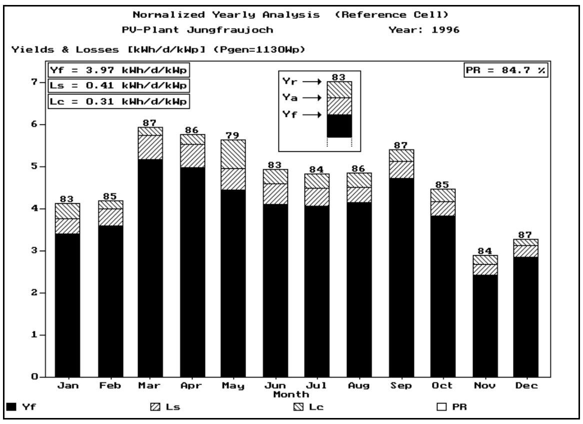

Fig. 5:
Normalized yearly analysis for **1996**. Monthly performance ratio was between 79% and 87%, annual average increased to 84.7%.

In **1996,** snow coverage in spring was again rather low and irradiation into the array plane increased again slightly compared to 1995. In July 1996 the **string diodes** in the array were **eliminated** and a **new inverter** with better efficiency was installed. Both measures caused an increase in performance ratio PR compared to the respective months in earlier years. Referred to nominal PV generator power (1152Wp), energy production increased to 1426 kWh/kWp, referred to effective power (1130Wp) even to **1454 kWh/kWp**. This is about 76 % more than the average energy production of grid connected PV systems in lower parts of Switzerland in the same year. Winter energy fraction (Oct. - Mar.) was 44.6% . Mean value of performance ratio **PR** was **84.7%**, mean value of **energetic inverter efficiency** was **90.6%** .

In a paper presented at the 13 th EU PV conference in Nice, based on the data of 1994 and the first 9 months of 1995, a possible energy production in a good year of 1450 kWh/kWp was predicted [1]. This value could be exceeded slightly already in 1996.

5.5 Operating results in 1997

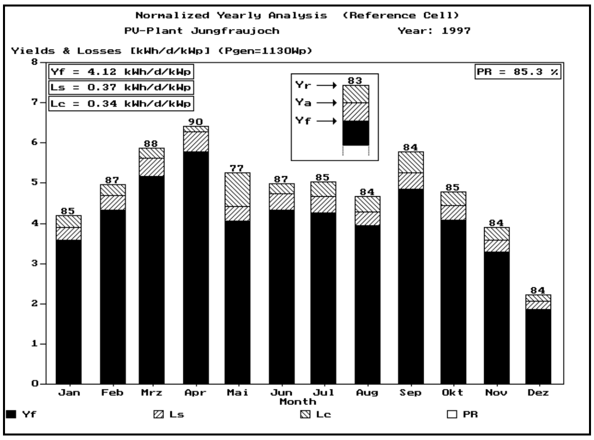

Fig. 6:
Normalized yearly analysis for **1997**. Monthly performance ratio was between 77% and 90%, annual average increased to 85.3%.

In **1997**, only in May a significant snow coverage was registered. Irradiation into the array plane increased again compared to 1997. Irradiation into the horizontal plane was 0.7% higher than the avarage value registered by the Swiss Meterological Office (SMA) at Jungfraujoch over many years. Referred to nominal PV generator power (1152Wp), energy production increased to the new record value of 1476 kWh/kWp, referred to effective power (1130Wp) even to **1504 kWh/kWp**. Winter energy fraction (Oct. - Mar.) was 44.9% . Mean value of performance ratio **PR** was **85.3%**, mean value of **energetic inverter efficiency** of the new device was **91.8%** or nearly 2% higher than in 1995.

6 Comparison with other Swiss PV plants

Fig. 7 shows normalized monthly energy production referred to peak array power in the years 1994 to 1997 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 48% .

7. Conclusion

In all four years, 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), **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 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 record values in the last four years. Experience obtained in this project will be very helpful for the realisation of other high alpine grid connected PV-plants.

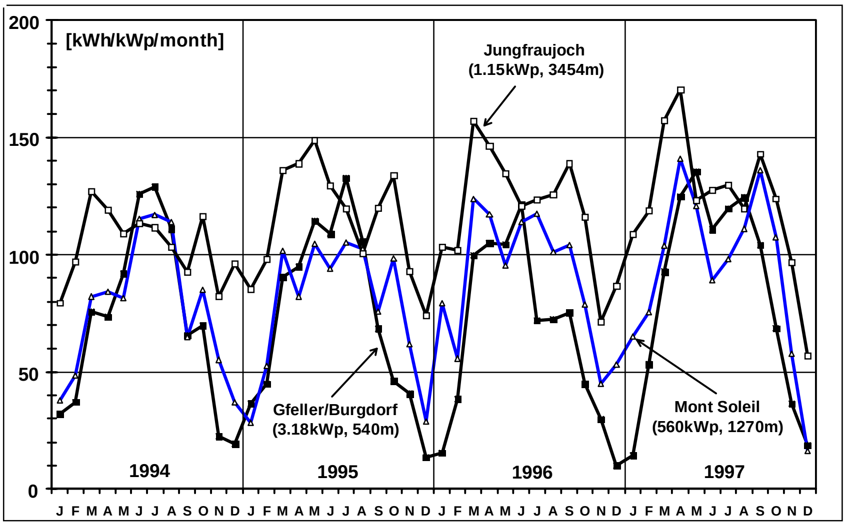

Fig. 7: Normalized monthly energy production (referred to nominal PV generator power) of PV plants Jungfraujoch (1.152kWp), Mont Soleil (560kWp) and Gfeller/Burgdorf (3.18kWp) in the years 1994 to 1997.

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