Grid Connected PV Plant Jungfraujoch (3454m) in the Swiss Alps: Results of more than six 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. Until Dec. 2000, the plant has operated successfully with a 100% availability of energy production and monitoring data for more than 73 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, 1404kWh/kWp in 1995, 1454kWh/kWp in 1996, 1504kWh/kWp in 1997, 1452kWh/kWp in 1998, and 1330kWh/kWp in 1999. In 1999 and 2000, energy production was affected slightly by the replacement of the windows of the research station. The winter energy fraction in all these years was between 44.6% and 48%. 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.

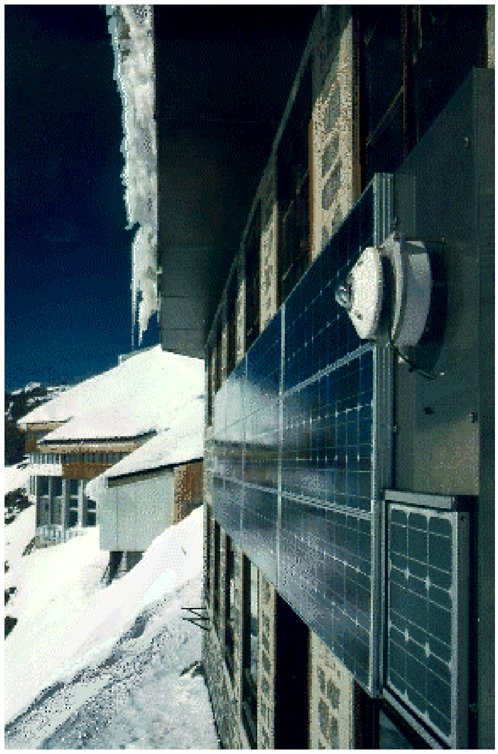

Fig. 1: *View of the grid connected PV plant (1.1kWp) at the research station at Jungfraujoch (3454m, about 46.5°N): One of the two arrays with irradiance sensor (pyranometer and reference cell).*

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.

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.

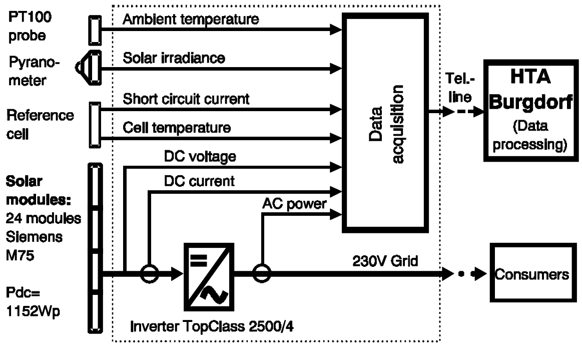

Fig. 2: *Block Diagram of the grid connected PV Plant (1.152kWp nominal, 1.13kWp effective) of HTA Burgdorf at Jungfraujoch (3454m).*

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 of PV plant Jungfraujoch compared to other Swiss PV plants

Fig. 3 shows normalized monthly energy production referred to peak array power in the years 1994 to 1998 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% .

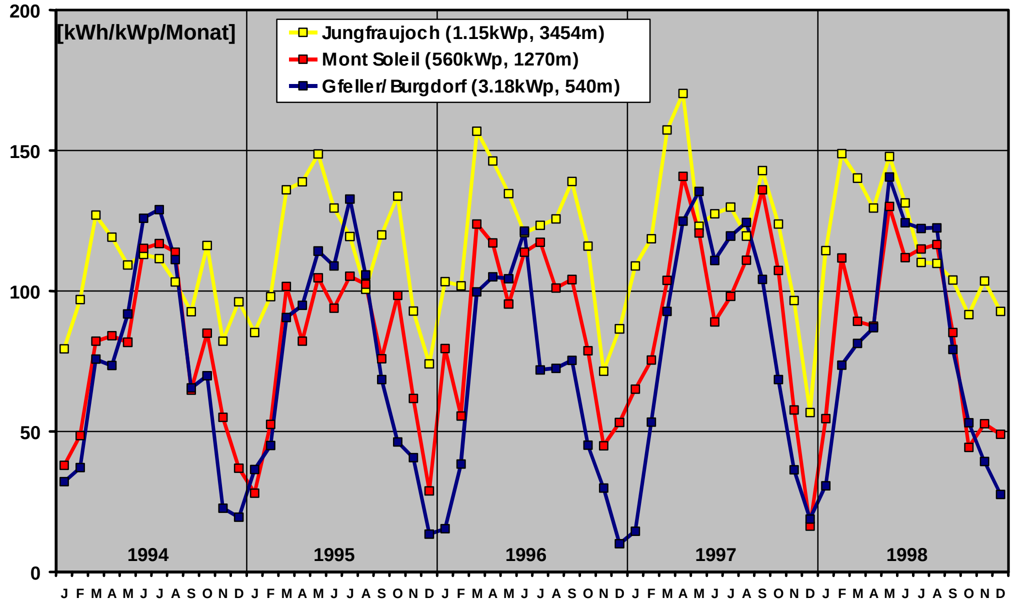

Fig. 3: *Normalized monthly energy production (referred to nominal PV generator power) of PV plants Jungfraujoch (1.15kWp), Mont Soleil (560kWp) and Gfeller/Burgdorf (3.18kWp) in the years 1994 to*

6. Conclusion

In more than six years of successfull operation, owing to the tilt angle of 90° 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. 3), **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°. 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° 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 six years. Experience obtained in this project will be very helpful for the realisation of other high alpine grid connected PV-plants.

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