Highest Grid connected PV Plant in the World at Jungfraujoch (3454m): Excellent Performance in the first two Years of 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 ISB 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 components. PV components surviving in such a harsh environment should perform more reliably under normal operating conditions. Energy production (especially winter energy) reached record values for a plant in central Europe: Between September 1994 and August 1995 (12 months), **annual final yield** was **1370kWh/kWp** and mean **performance ratio** was **84.1%**.

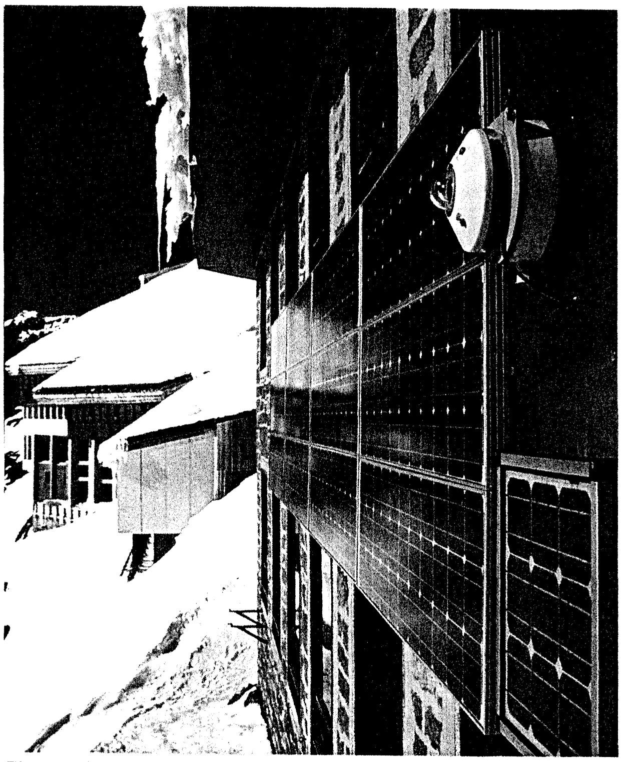

Fig. 1: View of ISB's grid connected 1.1kWp PV plant at the outer walls of the research station at Jungfraujoch (3454m): One of the two arrays with irradiance sensors (Pyranometer and reference cell).

1. Purpose and Goals of the project:

- **Test of PV components:** Operation in high altitudes is a very hard stress for all components due to **extremely high irradiance peaks** of more than 1.5kW/m², **heavy storms and thunderstorms**, and **large temperature differences**. PV components surviving in such a harsh environment should perform more reliably under normal operating conditions.
- **Experimental finding of the energy yield** of a high alpine grid connected PV plant.
- **Intensive analytical monitoring** with redundant sensors to ensure maximum reliability.
- **Maximum availability of energy production and monitoring data (AMD = 100%).**

2. Plant Layout

The solar generator consists of 24 modules Siemens M75, producing 1130Wp at STC (effective). 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). 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. 2 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.

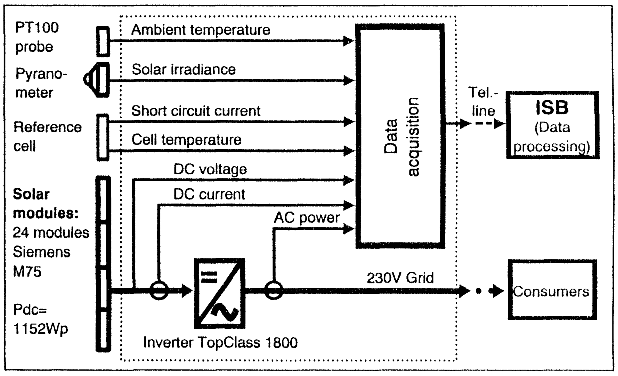

Fig. 2: Block Diagram of ISB's grid connected PV Plant (1.152kWp nominal, 1.13kWp effective) at Jungfraujoch (3454m).

3. Test of PV Components:

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.

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 1660W/m²: 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: 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. Sometimes energy production was also reduced by hoarfrost and partial shadowing by colossal icicles.

4. Data Acquisition System

The **data acquisition system** operated without mayor problems, too. Availability of monitoring data (AMD) so far was 100.0%.

Unfortunately the ventilation system of the pyranometers had not the same reliability like the rest of the system. As it did not meet the specifications of the manufacturer, 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.

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. Energy production and Performance Ratio

5.1 Operating Results in 1994

Referred to nominal PV generator power (1152Wp), energy production was 1247kWh/kWp, referred to effective power (1130Wp) even **1272 kWh/kWp**. Winter energy fraction (Oct. - Mar.) was **48.0%**, about as high as expected. **Referred to effective power** mean value of **performance ratio** was **81.8%.**

Mean value of **inverter efficiency** was **89.6%**, a very good value for a small device designed for much higher solar generator power. Despite of the harsh environment, the inverter had no defect so far.

Referred to a normal year, in 1994 irradiation was 7% too low. Converted to a year with **normal irradiation**, energy production should be about **1367kWh/kWp** (referred to effective solar generator power), when similar snow coverage like in spring 1994 is observed.

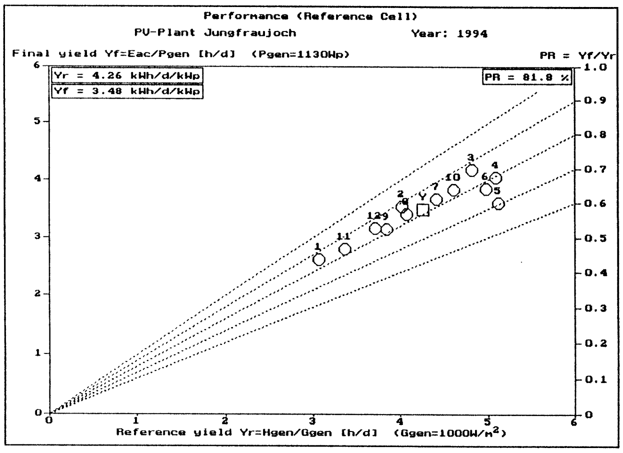

Fig. 3: Yearly analysis for 1994 with monthly values of performance ratio (Y_f/Y_r). Distribution of the data-points shows the regular energy production: Y_f is between 2.61 and 4.18kWh/kWp and no point is out of a PR-bandwidth of 70..90%.

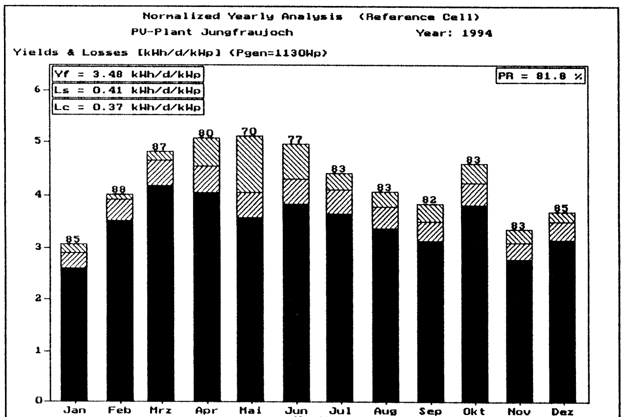

Fig. 4: More detailed normalized yearly analysis for 1994 with monthly values of Y_f, L_S, L_C and PR (referred to effective solar generator power). Irradiance is measured with a reference cell.
Partial snow covering of the solar generator in spring causes higher L_C and lower PR-values. Monthly performance ratio is between 70 and 88%, annual average is 81.8%.

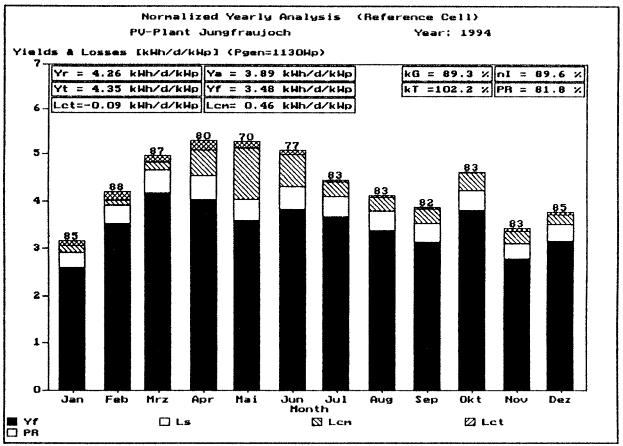

Fig. 5: Most detailed normalized yearly analysis for 1994. Capture losses are splitted into thermic capture losses L_{CT} and miscellaneous capture losses L_{CM} according to [2, 5]. Mean value of L_{CT} (<0) and temperature correction factor k_T (>100%) show, that there is an *energy gain* due to low temperatures.

5.2 Operating Results in the last 12 Months (September 1994 to August 1995)

Winter 1994/95 brought a lot of snow in the Alps. However, the solar generator was covered by snow only on two days in November 1994 and a few days in spring 1995. Fortunately wind direction during the snowfalls was mainly from the north, preventing a deposition of lots of snow in front of the solar generator. Besides this, sometimes snow was removed from the generator by the staff of the research station. The weather, especially solar irradiation, was better than in 1994, too.

Table 1 shows the monthly values of yields and losses from September 1994 to August 1995. Capture losses L_C are splitted into thermic capture losses L_{CT} and miscellaneous losses L_{CM} (see also [2] or [5]):

	Y_r	Y_T	Y_A	Y_f	L_{CT}	L_{CM}	L_S	PR	H_{hor}	MN95	Diff.
	[kWh/d/kWp]							[%]	[kWh/m²]		[%]
Sep 94	3.84	3.89	3.52	3.15	-0.05	0.37	0.37	81.9	99.3	135	-26.4
Oct 94	4.61	4.59	4.24	3.82	0.02	0.35	0.41	82.9	90.6	92	-1.5
Nov 94	3.36	3.42	3.11	2.79	-0.06	0.31	0.32	83.1	51.4	58	-11.4
Dec 94	3.71	3.78	3.51	3.16	-0.07	0.26	0.35	85.3	48.0	48	0.0
Jan 95	3.24	3.37	3.13	2.80	-0.14	0.24	0.33	86.6	47.2	51	-7.5
Feb 95	4.16	4.25	3.97	3.57	-0.10	0.28	0.40	85.8	64.5	70	-7.9
Mar 95	5.11	5.31	4.99	4.48	-0.20	0.32	0.51	87.7	122.6	119	3.0
Apr 95	5.47	5.70	5.26	4.72	-0.22	0.44	0.54	86.2	146.3	156	-6.2
May 95	5.83	5.91	5.44	4.89	-0.08	0.47	0.55	83.9	194.9	187	4.2
Jun 95	5.54	5.59	4.91	4.40	-0.05	0.68	0.50	79.5	186.8	190	-1.7
Jul 95	4.72	4.72	4.37	3.93	0.00	0.35	0.44	83.3	187.1	199	-6.0
Aug 95	3.95	4.04	3.71	3.31	-0.10	0.34	0.40	83.9	141.4	174	-18.7
Total	4.46	4.55	4.18	3.75	-0.09	0.37	0.43	84.1	1380	1479	-6.7

Annual Final Yield:	**1370 kWh/kWp**		
Winter Energy Fraction:	**626 kWh/kWp**	⇒	**45.7%**
Summer Energy Fraction:	**744 kWh/kWp**	⇒	**54.3%**
Performance Ratio:	**84.1 %**		

Table 1: Monthly yields and losses from September 1994 to August 1995. On the right side of the table, monthly values (H_{Hor}) and ten-year-average values (MN95 [6]) of global horizontal irradiation are listed.

During these 12 months, energy production (referred to effective solar generator power) was sensationally **1370kWh/kWp**! Mean value of **performance ratio** was **84.1%** (referred to reference cell measurements). **Winter energy fraction** (October 94 - March 95) was **626 kWh/kWp** or **45.7%**. While absolute winter energy production increased compared to the year 1994, relative winter energy percentage decreased due to an even stronger increase in spring energy production, as snow coverage could be avoided in 1995 most of the time. Compared to the **Swiss mean value** of annual final yield of grid connected PV systems (840kWh/kWp), the PV plant at Jungfraujoch produced an **additional yield** of more than **63%.**

Referred to the ten-year average value of irradiation H_{Hor}, the yearly value during these 12 months was 6.7% too low. In a year with normal irradiation and moderate snowfalls energy production could easily exceed 1400kWh/kWp.

5.3 Best and weakest Month

Energy production in **May 1995** reached a new record value: **4.89kWh/d/kWp** resp. **151.6kWh/month/kWp.** Figure 6 shows the standardized monthly analysis for May 1995 with record values of reference yield and final yield:

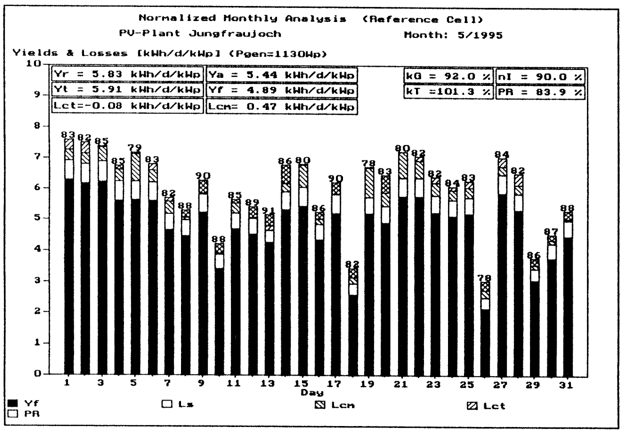

Fig. 6: Normalized monthly analysis for May 1995: Highest monthly production so far (Y_f = 4.89kWh/d/kWp or 151.6kWh/month/kWp!). Monthly value of PR is 83.9%. Due to low temperatures, monthly mean value of thermic capture losses is negative (L_{CT}=-0.08kWh/kWp, this means there is an energy gain due to the low temperature). On very cold days, PR reaches values of up to 91%.

The lowest energy production observed so far was in December 1993 (see fig. 7) due to a very long period of bad weather. Final yield in this month was by far the lowest since the start of operation of the plant (see also fig. 9).

In Switzerland during the winter months irradiation can vary considerably between the same month of the year, whereas during the summer months variations of irradiation values of a certain month are much lower. This can be seen clearly in fig. 9, especially by comparing November 1993 with November 1994 and December 1993 with December 1994. Owing to the high altitude of the plant Jungfraujoch, the ratio of monthly final yield between the best month (May 1995) and the worst month (December 1993) is only 2.43, by factors less than in lower parts of Switzerland, where this ratio can easily be greater than 6. In winter there is often foggy weather in these lower regions, while the weather is very fine in the mountains (see also chapter 6).

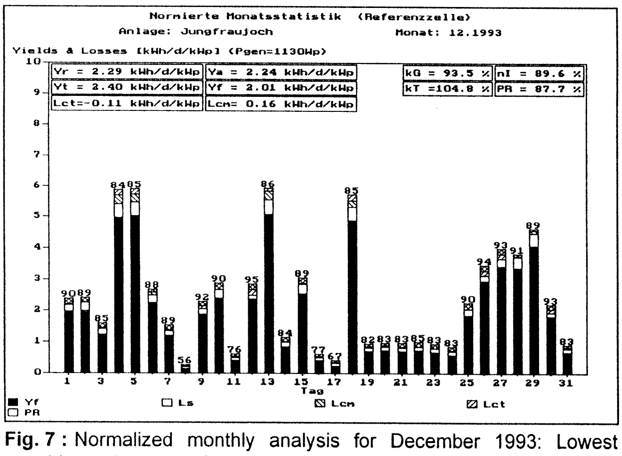

Fig. 7 : Normalized monthly analysis for December 1993: Lowest monthly production so far (Y_f = 2.01kWh/d/kWp).

Despite the lowest irradiation ever recorded so far, December 1993 had the **second highest value of performance ratio (PR = 87,7%)** due to the low module temperatures encountered during this month. This PR value is only 0,2% lower than the absolute monthly record value (PR = 87.9%) registered in February 1994.

5.4 Day with high Energy Production and very high Performance Ratio

On very cold, but sunny spring days with strong winds, energy production and performance ratio can reach peak values. Fig. 8 shows such a day with high Y_f (7.05kWh/d/kWp) and high PR (92.1%).

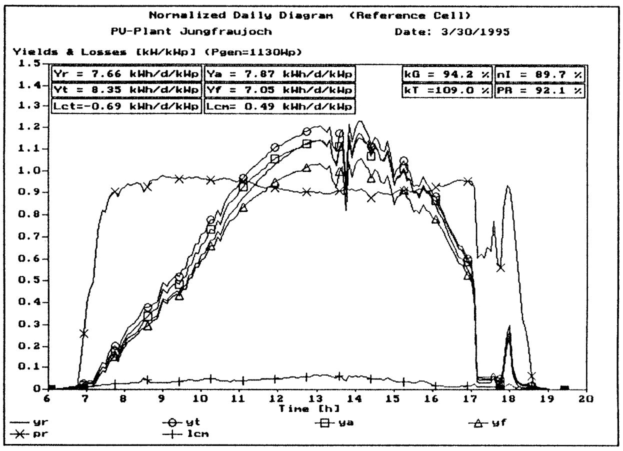

Fig. 8: Normalized daily diagram for March 30th, 1995: Very cold and sunny winter day. Due to the very low ambient temperature and strong winds, thermic capture losses are negative during the whole day. Therefore both instantaneous and mean value of performance ratio are very high, too. Between 17:00 and 18:00 the sun is behind a mountain peak. For more details about this kind of diagram see [2 ,5].

6. Comparison of 3 different PV plants in the Canton of Berne

In 1994 PV plant Jungfraujoch produced an **additional yield of 46% referred to a plant in the lower part of Switzerland in Burgdorf** (3.18kWp/540m)! Referred to the plant at Mont Soleil (560kWp/1270m), the additional yield was 35%. Comparing energy distribution of the different plants is interesting, too: While the plants in Burgdorf and at Mont Soleil produce a maximum of energy during summer, production of Jungfraujoch is relatively constant.

Table 2 shows the most important statistical data of the three different plants for energy production in 1994:

Yf [kWh/kWp]	Gfeller (3.18kWp, 540m.)	Mont Soleil (560kWp, 1270m.)	Jungfraujoch (1.152kWp, 3454m.)
Jan. 94	32.1	37.9	79.5
Feb. 94	37.2	48.6	97.0
Mar. 94	75.8	82.1	127.0
Apr. 94	73.5	84.1	119.2
May 94	91.8	81.8	109.2
Jun. 94	125.9	115.1	113.1
Jul. 94	129.0	117.0	111.5
Aug. 94	111.2	113.8	103.3
Sep. 94	65.5	64.8	92.6
Oct. 94	69.8	85.0	116.2
Nov. 94	22.7	55.0	82.2
Dec. 94	19.5	36.9	96.2
Total	854.1	922.1	1247.0
Summer	596.9	576.5	649.0
	69.9%	62.5%	52.0%
Winter	257.1	345.6	598.1
	30.1%	37.5%	48.0%
Max. Value	129.0	117.0	127.0
Min. Value	19.5	36.9	79.5
Mean Value	71.2	76.8	103.9
Std. deviation	36.7	27.6	14.1

Table 2: Final yields, statistical data and calculations for the PV plants Gfeller (3.18kWp, 540m above sea level), Mont Soleil (560kWp, 1270m) and Jungfraujoch (1.15kWp, 3454m) for energy production during 1994. Yields are referred to *nominal* solar generator power.

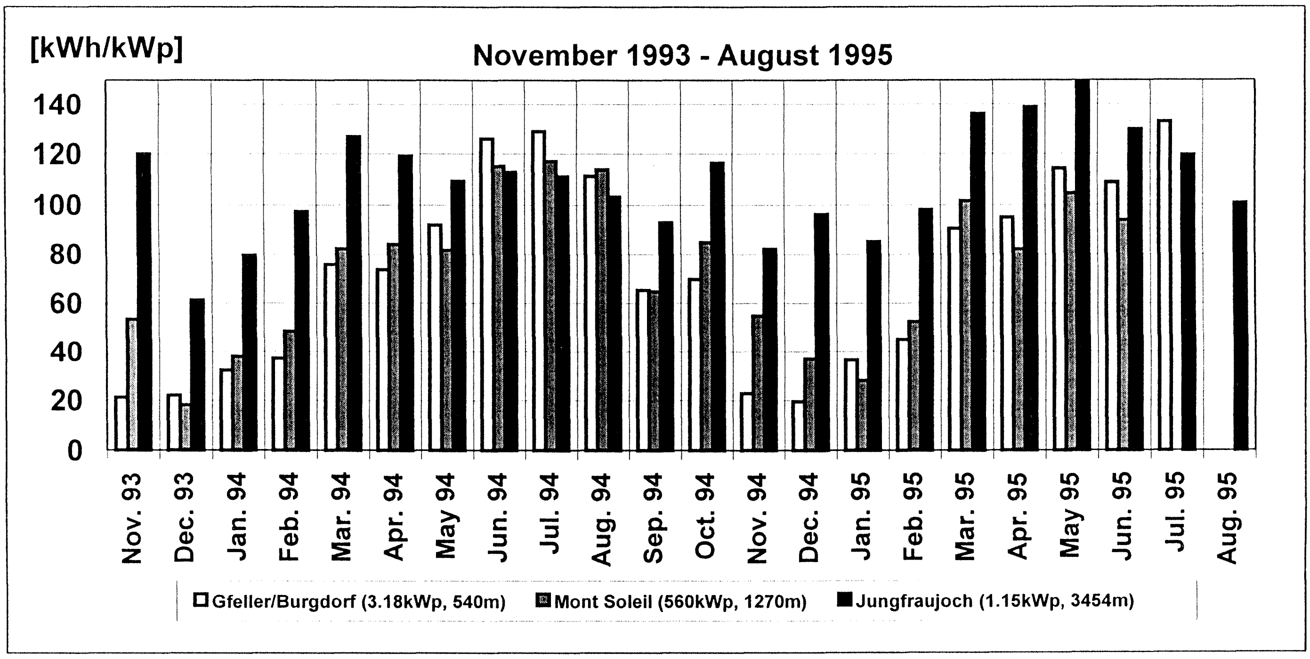

Fig. 9: Monthly energy production from November 1993 to August 1995 referred to nominal PV generator size for a PV-plant in Burgdorf (540m, 3.18kWp), at Mont Soleil (1270m, 560kWp) and Jungfraujoch (3454m, 1.152kWp).

Comparison of the statistical data for 1994 gives very interesting results: One of the largest difference is observed at the **minimal monthly value**. While this value amounts only 19.5kWh/kWp at PV plant Gfeller and 36.9kWh/kWp at Mont Soleil, at Jungfraujoch it is **79.5kWh/kWp**, thus considerably higher. PV plant Gfeller reached the highest maximal monthly value observed in 1994: 129kWh/kWp. This value was reached in summer, due to long days and the low inclination of the solar generator (30°). Jungfraujoch reached nearly the same value in Winter (March 1994: 127kWh/kWp). Standard deviation is very high at Gfeller and still quite high at Mont Soleil. The much lower value for Jungfraujoch reflects the more continuous energy production at this location.

The very high **winter energy production** of 598kWh/kWp (referred to effective power even **611kWh/kWp**) at Jungfraujoch is very useful. It is much higher than winter energy production of PV plants in lower altitudes in central parts of Europe and **matches the European peak electricity demand** usually occurring in winter much better.

Despite of the vertical position of the solar generator, summer energy production at Jungfraujoch is higher than in lower altitudes, too. The most important factor for the high summer energy production is the **albedo effect**, caused by the glacier in front of the solar generator. Without reflections from the glacier, summer energy production would be considerably lower!

Fig. 9 shows normalized monthly energy production of all three PV-plants since the start of operation of PV plant Jungfraujoch. The more continuous monthly energy production of PV-plant Jungfraujoch is obvious. It is quite interesting that **monthly energy production** of this plant has **two relative maximums per year**, one occuring in spring and one in fall, instead of the usual summer maximum.

Acknowledgements:

Our special thanks go to all the institutions that gave us financial support. The work described in this paper was funded by the Swiss Federal Office of Energy (BEW), Berne and the Office for Water and Energy (WEA) of the canton of Berne.

Construction of our PV-plant at Jungfraujoch was sponsored by BEW, VSE (Verband Schweizerischer Elektrizitätswerke), Siemens Solar (modules), Fabrimex Solar (inverter) and the Railways of Jungfrau Region. Our thanks go also to the International Foundation Scientific Stations Jungfraujoch and Gornergrat, the owner of the research station at Jungfraujoch, who permitted the use of its building for this project. Electrowatt Engineering Services (EWI) kindly supplied us the data of their PV-plant on Mont Soleil for comparison purposes.

Our PV-activities in general are also supported by IBB, Burgdorf, BKW Energy AG, Berne, and EWB, Berne.

Conclusion:

Energy production and performance ratio of the high alpine PV plant at Jungfraujoch reached record values in the last two years. Hopefully this challenging project can be continued for many more years and will establish new records for energy production and performance ratio. Experience obtained in this project will be very helpful for the realisation of other high alpine grid connected PV-plants.

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