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Titel	**ALBEDO MEASUREMENTS AND SYSTEM PERFORMANCE OF A GRID-CONNECTED PHOTOVOLTAIC PLANT IN THE SWISS ALPS***	Ersetzt —
Autor / en	W. Durisch, M. Brack, W. Bulgheroni, E. Gähwiler	Erstellt 15. Nov. 1989/DW51

Abstract

The primary goal of this investigation *is* to obtain a reliable data base as required for optimum planning, design, realization and operation of future photovoltaic plants in alpine regions, in particular with respect to snow-reflected solar radiation. For this purpose a 2.5 kW_p photovoltaic plant was kindly made available by the companies FABRIMEX, Cableways Titlis and Alpha Real. The plant was installed in summer 1988 at a height of 2450 m a.s.l. and consists of three generator rows mounted on a vertical wall of a building facing south-west. Each row can be tilted individually. The electricity produced is fed directly into the local grid. For this purpose, an inverter, synchronized by the grid, is used as interface. Due to the high altitude, the plant is exposed to relatively low ambient temperatures, as well as to much snow-reflected solar radiation (continuous snow-cover for almost seven months per year). To investigate the impact of these particular conditions on the plant's behaviour and on the electricity production, the plant has been equipped with special measuring instruments developed at PSI. These include a new type of an albedometer consisting of a shadowed pyranometer absorbing ground- and snow-reflected radiation only. Also included is a pyranometer which receives all radiation except ground- and snow-reflected radiation. For the investigation of the system performance (component and plant efficiencies), power/electricity meters developed at PSI are applied on the DC side and conventional equipment on the AC side. Furthermore, cell temperature, ambient temperature and global irradiation in all generator rows are also measured. First albedo measurements in April 1989, at vertical generator position, resulted in albedo coefficients of snow-covered ground of up to 44 %, at a monthly mean value of 35 %. Solar generator efficiencies in the range of 11.5 to 14.2 % (based on active cell area) and inverter efficiencies between 80 und 90 % were measured, leading to a plant overall-efficiency of 11 % (monthly mean for April 89). Up to now no detrimental environmental influences on the photovoltaic generators were observed.

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ALBEDO MEASUREMENTS AND SYSTEM PERFORMANCE OF A GRID-CONNECTED PHOTOVOLTAIC PLANT IN THE SWISS ALPS

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ABSTRACT

The primary goal of this investigation is to obtain a reliable data base as required for optimum planning, design, realization and operation of future photovoltaic plants in alpine regions, in particular with respect to snow-reflected solar radiation. For this purpose a 2.5 kW_p photovoltaic plant was kindly made available by the companies FABRIMEX, Cableways Titlis and Alpha Real. The plant was installed in summer 1988 at a height of 2450 m a.s.l. and consists of three generator rows mounted on a vertical wall of a building facing south-west. Each row can be tilted individually. The electricity produced is fed directly into the local grid. For this purpose, an inverter, synchronized by the grid, is used as interface. Due to the high altitude, the plant is exposed to relatively low ambient temperatures, as well as to much snow-reflected solar radiation (continuous snow-cover for almost seven months per year). To investigate the impact of these particular conditions on the plant's behaviour and on the electricity production, the plant has been equipped with special measuring instruments developed at PSI. These include a new type of an albedometer consisting of a shadowed pyranometer absorbing ground- and snow-reflected radiation only. Also included is a pyranometer which receives all radiation except ground- and snow-reflected radiation. For the investigation of the system performance (component and plant efficiencies), power/electricity meters developed at PSI are applied on the DC side and conventional equipment on the AC side. Furthermore, cell temperature, ambient temperature and global irradiation in all generator rows are also measured. First albedo measurements in April 1989, at vertical generator position, resulted in albedo coefficients of snow-covered ground of up to 44 %, at a monthly mean value of 35 %. Solar generator efficiencies in the range of 11.5 to 14.2 % (based on active cell area) and inverter efficiencies between 80 und 90 % were measured, leading to a plant overall-efficiency of 11 % (monthly mean for April 89). Up to now no detrimental environmental influences on the photovoltaic generators were observed.

KEYWORDS

Photovoltaic electricity; cell efficiency; inverter efficiency; plant efficiency; grid-connection; terrain reflectance; albedometer; irradiation; albedo coefficient; cell temperature; environmental impacts.

INTRODUCTION

Proper design and operation of photovoltaic (PV) power plants in alpine regions are of vital importance in order to achieve low plant cost and high lifetime, efficient and consumer-matched electricity production, low operation and maintenance cost, high plant reliability and availability as well as minimum production losses due to adverse environmental impacts. All these factors play an important role in the economic competitiveness of PV-plants [1], [2], [3]. Furthermore it is well known that snow-covered terrain has a relatively high surface albedo (terrain reflectance), leading to an increased diffuse fraction of the global radiaton [4], [5]. Since PV-plants convert diffuse irradiation too, knowledge of the terrain reflected radiation in inclined PV-generators, in particular in alpine regions, is required for correct planning and design of PV-plants. The main purpose of the present paper is to outline methods to measure the albedo and to report on first measuremsnts related to a grid-connected 2.5 kW_p PV-plant in the Swiss Alps [6]. In addition to the albedo measurements the PV-plant in question is carefully investigated with respect to its performance and system behaviour under alpine weather conditions. Here too, first results are available.

PLANT CHARACTERIZATION

The plant investigated essentially consists of three movable-mounted PV-generators, Fig. 1, Table 1, a grid-connected inverter, Table 2, and extensive high-grade equipment to measure and acquire all relevant climatic and PV-specific data. The generators are supported by steel constructions fixed on a vertical concrete wall of a building, Fig. 1. Using hydraulic devices, the generator support structures can be turned around horizontal axes. In this way all generator rows can be inclined individually to pre-selected tilt angles.

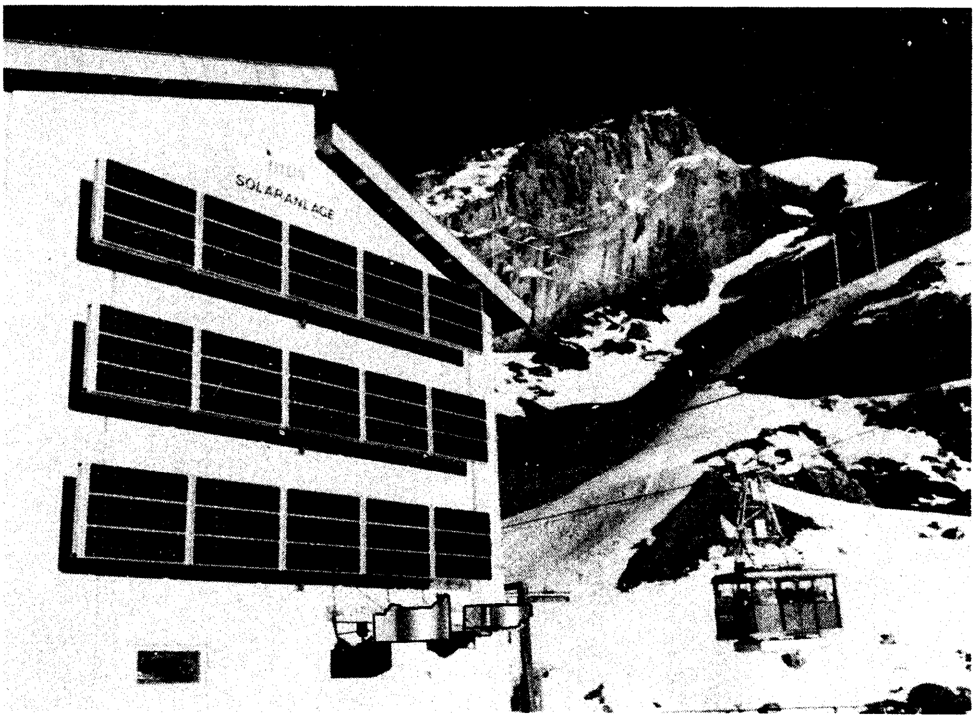

Fig. 1. Photovoltaic Plant, 2.5 kW_p in a high-alpine region (Titlis, Switzerland), 2450 m a.s.l. On the right side, below the lowest generator row, the albedometer and the sky radiation instruments can be identified.

Table 1. Main parameters of PV-generator

Manufacturer/type of panels		Arco, M55
Number of panels		45
Number of panel groups		3
Wiring within groups		5 x (3 panels in series)
Panel surface, total, m^2		19.20
Active cell surface, total, m^2		17.10
Tilt angle of cells, degrees:	Winter 88/89	90
	Summer 89	60
	future	50, 60, 70, 80
Orientation of generators, degrees West from South		41
Rated power [1], W		2475
Open circuit voltage [1], V		60
Voltage at maximum power [1], V		52
Rated current [1], A		47
Rated efficiency [1], [2], %		14.5

1) According to manufacturer specifications, at cell temperature of 25 °C and irradiation of 1000 W/m^2

2) Based on active cell surface. If the total generator surface of 19.2 m^2 is taken as reference, the efficiency would be 12.9 %.

Table 2. Main data of grid-connected inverter, according to manufacturer specifications.

Manufacturer	Photoelectric Inc., San Diego, USA
Type of inverter	Model SI 3000
Rated output power, 220 VAC/50 Hz, maximum, W	3000
Nominal input voltage, VDC	48
Accepted voltage, VDC	35 to 65
Maximum power tracking voltage range, VDC	42 to 52
Efficiency at maximum output, %	greater than 93
Efficiency at 25 to 75 % of maximum output, %	95
Minimum input power, W	approx. 120

MEASURING EQUIPMENT

The measuring equipment consists of different sensors for irradiation and temperatures, of four electricity meters as well as of two independent data acquisition systems, Fig. 2.

Electricity measurement

In order to measure current, voltage, power and electricity production of all three PV-generators individually, special electricity meters were developed at PSI. They deliver continuously information not only to built-in displays but also to the data acquisition systems. On the AC-side a slightly modified conventional electricity meter is used. For point-in-time measurements of the inverter efficiency a separate power analyzer is used.

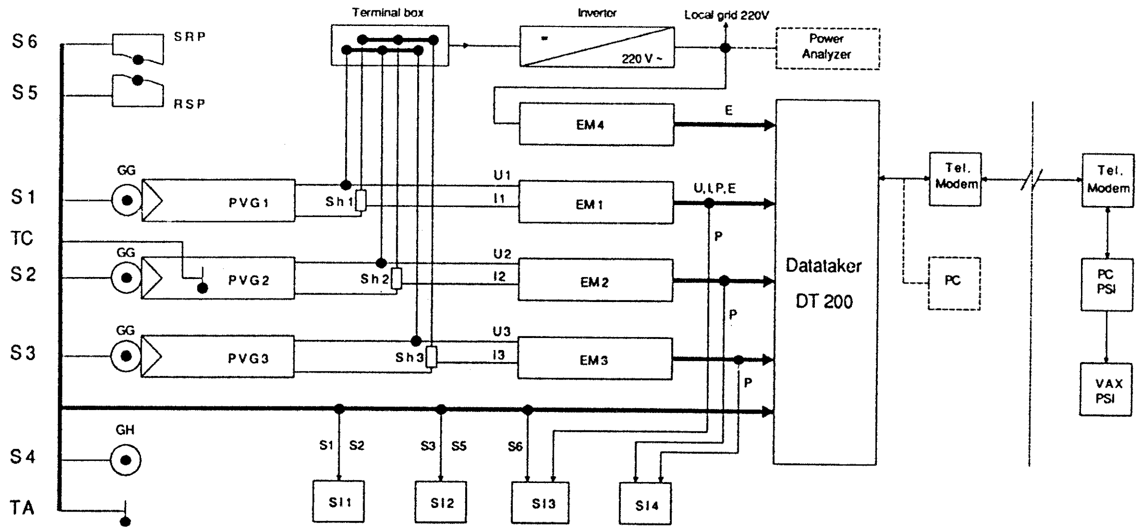

Fig. 2. Layout of grid-connected photovoltaic plant and of measuring equipment

PVG	PV generators
SRP	Shadow roof pyranometer (albedometer), PSI
RSP	Reflection shield pyranometer, PSI
GG	Global-generator pyranometers
GH	Global-horizontal pyranometer
TC	Cell temperature sensor (Pt-100) [1)]
TA	Ambient temperature sensor (Pt-100)
S1 - S6	Solarimeter-channels
Sh	Shunts
SI	solar integrators
EM	Electricity meters, PSI
I, U, P, E	Current, voltage, power and energy signals
1)	The sensor is fixed directly on the rear electrode of a silicon cell

Data acquisition system

For the acquisition of data a comercial datalogger having a buffer capacity of about 80 KB is in use. Storing 10-minute mean values of all signals, except for the electricity counters, the storage capacity covers approximately a measuring period of three weeks. Every three weeks the data are transferred onto a disc using a portable PC. From the disc the data are transferred to a VAX 11/780 for evaluation. It is planned to use also the telephone connection for data transfer. However, there are still some problems to be solved. For redundancy reasons four solar integrators are working in parallel to the data logger, printing out every 24 hours the daily sums of the most important irradiation channels and the daily electricity production of the three PV-generator rows.

Albedo measurements

In order to measure the ground- and snow-reflected solar radiation (albedo) impinging on the PV-generators a normal pyranometer was provided with a shadow roof in such a way that the pyranometer absorber can see only snow-covered and snow-free terrain, Fig. 1 and Fig. 3. In order to get reliable data, it is important that the pyranometer absorber is parallel to the generator plane. Furthermore, the shadow roof must be shaped according to the actual horizon in front of the pyranometer. For reasons of comparison a second independent method is applied to measure the albedo. Here again a pyranometer is used. In place of a shadow roof a shield is used, preventing terrain-reflected radiation to reach the pyranometer absorber, Fig. 1 and Fig. 4. Here too, the reflection shield has to be formed according to the actual horizon, and the pyranometer absorber must be parallel to the generator plane. This second method leads to the global radiation reduced by the blocked-out terrain-reflected radiation. Knowing the global radiation in the generator plane (extra, non-modified pyranometer), the albedo is found as difference between these two global irradiation measurements. For more details on these two albedo measurement methods the reader is referred to [7].

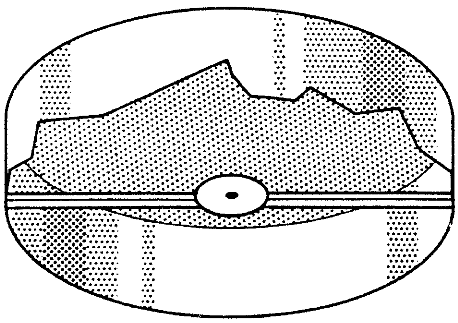

Fig. 3. Shadow-roof pyranometer used as albedometer. Pyranometer only sees snow-covered and snow-free terrain, but nothing of the sky.

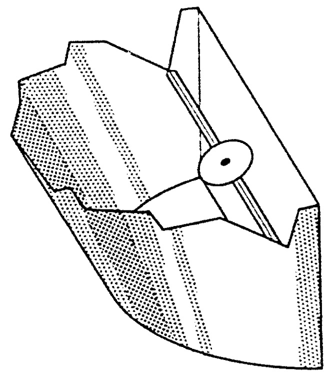

Fig. 4. Reflection shielded pyranometer used in the indirect albedo measurement method. Pyranometer only sees the sky but nothing of the snow-covered and snow-free terrain.

FIRST RESULTS

After installation of the measurement equipment at the end of 1988, first results were available in January 1989. Due to unavoidable problems concerning the power supply of the measuring station and the parallel interfacing of the two different data acquisition systems, some data losses occured. The first complete set of measurements is available for the month of April, Table 3. The results in Table 3 apply to a generator inclination of 90 degrees (vertical position). The daily sums of the global irradiation in the generator plane varies between 2 and 7 kWh/m^2. It is interesting to note that the daily irradiation even during very bad weather does not fall below 2 kWh/m^2. This is probably due to the relatively high altitude of the plant location. The upper value of 7 kWh/m^2 is comparable to measurements at other sites [3], when correcting for non-vertical inclination and different south-orientation. As it was to be expected at an alpine site, the albedo fraction of the global irradiation in a vertical wall is high. It runs up to 44 % on diffuse-cloudy days. But even on clear-sky days, it still exceeds 20 %. The generator efficiency (based on the active cell surface of 17.1 m^2) varies between 11.5 and 14.2 %, except for one lower value due to an inverter failure. It is remarkable that the highest generator efficiencies are not found at clear-sky days but at highly diffuse irradiation and simultaneously low cell temperatures. In general the generator efficiencies measured compare well with those specified by the manufacturer. The inverter efficiency varies between 81 and 90 %. This is notably lower than specified by the manufacturer, Table 2. The reasons for this difference are not yet clear. It has to be mentioned that not only the daily mean values of the inverter efficiency show this difference but

Table 3. Evaluated measurements for the month of April 1989. The GG and Albedo columns refer to the lowest generator row, Fig. 1. The generator efficiency represents the mean value of all three rows, Fig. 1. All efficiencies represent daily mean values.

Day	GG kWh/m2/d	Albedo kWh/m2/d	Albedo %	Gen-Eff %	El-prod plant kWh/d	Inv-Eff %	Plant Eff %
1	1,903	0.646	33,95	12.05	3,354	81,47	9,82
2	2,054	0,774	37,68	12,49	3,877	84,15	10,51
3	2,444	0,834	34,12	12,37	4,608	85,65	10,59
4	2,766	1,014	36,66	12,75	5,402	86,14	10,98
5	3,610	1,442	39.94	11,53	6,438	86,96	10,03
6	3,785	1,559	41,19	13,37	8,023	88,68	11,85
7	4,958	1,338	26,99	12,35	9,633	89,02	10,99
8	2,972	0,983	33,08	12,73	5,813	86,45	11,00
9	5,937	1,385	23.33	11,69	10,852	89,20	10,42
10	2,124	0,734	34,56	12,80	4,029	83,68	10,71
11	5,911	1,286	21,76	12,73	11,613	88,57	11,28
12	2,037	0,786	38,59	12,54	3,740	82,02	10,28
13	2,505	1,139	45,47	13,09	5,008	85,58	11,20
14	3,480	1,480	42,53	8,80	4,663	85,97	7,56
15	4,648	1,648	35,46	12,80	9,338	88,68	11,35
16	3,336	1,153	34,56	12,19	6,396	87,31	10,64
17	3,357	1,343	40,01	13,68	7,250	88,05	12,04
18	3,708	1,514	40,83	12,96	7,563	87,73	11,37
19	3,563	1,465	41,12	12,54	7,035	87,76	11,01
20	4,599	1,589	34,55	12,70	9,050	88,41	11,23
21	2,817	1,253	44,48	13,29	5,860	87,35	11,61
22	4,848	1,720	35,48	11,69	9,002	88,51	10,35
23	7,148	1,922	26,89	11,83	13,125	89,66	10,61
24	6,538	1,760	26,92	12,18	12,254	88,87	10,82
25	2,564	0,933	36,39	13,03	5,008	84,34	10,99
26	2,957	1,121	37,91	12,77	5,748	85,73	10,95
27	3,903	1,658	42,48	14,06	8,481	87,39	12,29
28	2,933	1,257	42,86	13,43	6,013	86,15	11,57
29	3,509	1,473	41,98	14,24	7,869	88,25	12,57
30	3,125	1,306	41,79	13,83	6,773	87,70	12,13
Month	110,04	38,515	35,00	12,55	213,82	87,44	10,97

difference but also point-in-time measurements. Similar observations were made with other inverter products [8]. Concerning the plant efficiency of the grid-connected PV-plant (last column in Table 3): A monthly mean value of 11 % seems to be quite a success.

CONCLUSIONS/DISCUSSION

The albedo measurement methods applied in this investigation have proven to be useful. First results confirm the expected high albedo of snow-covered ground in the Alps. Albedo coefficients of up to 44 % were measured. The power/electricity meters developed at PSI work to our satisfaction. Evaluation of their output together with the irradiation measurements led to solar generator efficiencies in good agreement with the manufacturer specifications. Inverter efficiency measurements lie considerably lower than specified by the manufacturer. There were also some inverter synchronizing problems leading to minor production losses. But all in all the grid-connected operation of the 2.5 kW PV-generator was fairly successful up to now. Some already installed improvements with respect to the inverter will further improve the plant performance, so that in winter months the plant overall efficiency (monthly mean) will exceed the already reached high value of 11 %. Up to now no detrimental environmental impacts were observed. On the contrary, alpine ambient temperatures led to increased generator efficiencies, in spite of the extremely mild weather conditions in winter 1988/89. The measurements will be continued during the next two-and-a-half years. To date there are not yet enough data available to draw detailed and general conclusions. The same holds with respect to guide-lines for the proper planning and design, as well as for hints to the optimum operation of PV-plants in alpine regions. Concerning the measuring system, some minor improvements will help to avoid data losses. Due to the fact that the generator orientation deviates considerably from the South direction, yearly losses in the electricity production of approx. 20 % (at vertical generator position) are to be expected (estimate). In winter, some additional production losses are also caused by mountains throwing shadow on the gnerators. In summer, at inclined generators, some production losses also result from mutual shading of the generators and shadow cast by the slightly overhanging roof of the building. From fine evaluation of the data, results in this direction are to be expected.

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