Pergamon

PII: S0038-092X(98)00016-4

Solar Energy Vol. 62, No. 5, pp. 319–324, 1998

0038-092X/98 $19.00+0.00

ESTIMATION OF THE ENERGY OUTPUT OF A PHOTOVOLTAIC POWER PLANT IN THE AUSTRIAN ALPS

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Received 4 October 1996; revised version accepted 3 December 1997

Communicated by ROBERT HILL

Abstract—An output simulation is one of the first steps in planning a photovoltaic power plant (PVP) at a certain location. Various computer codes already exist to assess the energy output of a PVP, when fed with the relevant meteorological data. For the alpine area, however, there is no appropriate data considering the altitude of the site available. A computer code has been written to check the available raw data for plausibility and to fill in missing data synthetically. On the basis of 6 yr of measured data a test reference year (TRY) has been developed for the town of Leonding and the summit Loser. They are located just 80 km apart but have a 1250 m difference in their altitudes. For comparison, these new TRYs, together with other already existing TRYs from different places in a surrounding area of about 300 km, are used for calculation of the expected energy output of a PVP. A clear increase of energy yield with higher altitude can be observed. The summit Loser (1550 m), with the highest altitude investigated in this study, proved to be the most productive location. Besides the clearer sky and snow reflection, the lower temperature as well as better cooling of the panels by the wind in the Alps contribute to the higher amount of energy output. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

For planning the use of solar energy it is essential to know the appropriate meteorological data. For some applications, e.g. the estimation of the required heating energy for a building, it may be sufficient to know mean values of the data. For calculating the yield of a photovoltaic power plant (PVP) though, mean values are not sufficient, because the dependence of the technical device on the meteorological data is non-linear. There is a threshold between the irradiation and the output of electrical power. In this case the knowledge of the mean value of the irradiance is not sufficient to estimate the output of electrical energy. At least the complete statistical distribution is needed. The aim of this work was to create a reliable set of meteorological data in order to be able to simulate PVPs in the alpine region.

For this purpose the local utilities from the county of Oberösterreich (OKA) supplied a set of measured meteorological data from the locations of Leonding (300 m above sea level; 6 yr data) and Loser (1550 m above sea level; 7 yr data).

2. CHECKING THE DATA

The set of data supplied by OKA covers hourly values of irradiance on the horizontal plane, irradiance in the plane of the module (45°), air temperature, module temperature, wind velocity and wind direction. These values are saved in ASCII-format. To check the data for their plausibility they were imported into a spreadsheet. Depending on the season and the time of day, all the meteorological quantities have a certain confidence interval. On this basis feasibility checks were done to sort out unrealistic data (Jäger, 1996).

The other task was to interpolate the missing data. The measuring devices proved to be quite reliable, but the data transmission to the central computer failed sometimes and, owing to the limited memory of the local computer, data losses occurred.

The basic requirements for the interpolated data are:

no inconsistencies at the connection points;
the day–night cycle as well as the seasonal cycle must be followed.

To fill in the missing data a computer code was written. A certain amount of days (depending on the season and the gradient of the day length) before and after the gap are considered to be appropriate for filling the gap. This makes sure that the seasonal circle matches. From these chosen days the connecting points are compared with the boundaries of the gap. The gap is than filled with the complete data set of corresponding quantities of the day that shows the minimum difference in the connecting points for all quantities. The different meteorological quantities can be evaluated with factors for their significance to match. For the present work the air temperature was considered to be the most important to match. For larger gaps the procedure is repeated until the gap is filled.

When the whole set of data is checked and completed in this way, 8760 hourly values for each meteorological quantity per year are available for selecting a reference year.

3. SELECTING A REFERENCE YEAR

For simulating a PVP the meteorological data of a typical year are needed. Just calculating the average of various years would lead to wrong results, as the following example shows. A period of high irradiance following a period of low irradiance in one month and the same weather conditions in the opposite order in the same month of the next year would result in a medium amount of irradiance for the whole month; this would not represent a typical weather situation. The aim is to select typical months with the whole set of their meteorological data.

There are various ways of selecting a reference year described in literature. For our purpose the method of Festa and Ratto (1993) seemed to be the most appropriate one, because it is based on statistical values which allow an automatic selection by computer. The advantages of this method are that the procedure can be repeated with a minimum of effort and the reference year can be refined every year as soon as new data are available. In addition, this method promised high accuracy because there are not only average and standard deviation values being used as the basis for the selection of a month to qualify for the test reference year (TRY). The frequency distribution of the weather data relative to every single month is compared with the long-term frequency distribution of all the months with the same name (e.g. all the "Aprils") as well.

If the number of relevant meteorological parameter is N, every month will be characterized by N "distances" as described by Festa and Ratto (1993). For each month the worst (maximum) of its N distances is identified. Then from all the months with the same name the one with the minimum of these selected maximum distance months is chosen to be of the first priority for the TRY. Repeating this procedure, months with second priority and so on can be identified.

Just simply lining up these months to a TRY would result in a discontinuity of the meteorological data at the connecting points. To minimize these irregularities the months are connected during the night, where there will be no step in the irradiance. However, instead of strictly defining midnight as the connecting point the chances of finding an optimal connection increase if every full hour of the particular night is allowed as a connecting point according to Heindl *et al.* (1990). If the connection is still not satisfactory, a month with second priority may be chosen instead.

4. SIMULATION OF A PVP

The simulation of a PVP was done with the data bank oriented computer code developed by Gabriel (1993). A selection of different parameters for various models of PVPs is saved in a data bank. The irradiance is calculated for the specific inclination of the proposed module. The module temperature is essential for the efficiency of the cells. Therefore, there is a demand for a function of the module temperature that is dependent on irradiation, air temperature and wind speed. The temperature model is derived from the balance of power for the module (Gusenleitner, 1989; Gabriel, 1993). The formula applied for the calculation of the module temperature is

$$t_{\mathrm{sz}} = t_{\mathrm{a}} + \frac{S(a_{\mathrm{sz}} - \eta_{\mathrm{mod}})}{2(c_{\mathrm{sz},1} + c_{\mathrm{sz},2} v_{\mathrm{w}})} \xi_{\mathrm{sz}} \tag{1}$$

where η_{mod} is the module efficiency, ξ_{sz} is a ventilation factor, a_{sz} is the absorption coefficient, $c_{\mathrm{sz},1}/\mathrm{W\,K^{-1}\,m^{-2}}$ is the heat transfer coefficient, $c_{\mathrm{sz},2}/\mathrm{W\,s\,K^{-1}\,m^{-3}}$ is the wind speed coefficient, $S/\mathrm{W\,m^{-2}}$ is the irradiance on the inclined surface, $t_{\mathrm{a}}/^{\circ}\mathrm{C}$ is the air temperature, $t_{\mathrm{sz}}/^{\circ}\mathrm{C}$ is the module temperature and $v_{\mathrm{w}}/\mathrm{m\,s^{-1}}$ is the wind speed.

The factor a_{sz} is the total absorption coefficient of the module for the plane oriented to the sun. It varies between 0.5 and 0.7 (Schott, 1985). Smaller values are for a larger fraction of diffuse radiation. The more short-wave radiation the module absorbs the higher is the value of a_{sz}.

For the coefficients $c_{\mathrm{sz},1}$ and $c_{\mathrm{sz},2}$ the values $7\ \mathrm{W\,K^{-1}\,m^{-2}}$ and $2.1\ \mathrm{W\,s\,K^{-1}\,m^{-3}}$ respectively are used (Oluschinski and Leisen, 1987). The ventilation factor $\xi_{\mathrm{sz}} = 1$ for free standing modules, 1.5 for modules fixed to a wall with a ventilation gap behind, and 2 for modules with no ventilation. This temperature model agrees well with the measured module temperature on the PVP at Loser.

The behavior of the solar cell is calculated from its short circuit current, open circuit voltage, current and voltage in the maximal power point. For normalized conditions these parameters are supplied by the manufacturer. The short circuit current depends linearly on the irradiance. The slope of this straight line is a function of the module temperature. The open circuit voltage is a linear function of the temperature. The dependence of the open circuit voltage on the irradiance is described by a logarithmic function. The module efficiency is then calculated as

$$\eta_{\mathrm{mod}} = \frac{P_{\mathrm{MPP}}}{SA_{\mathrm{mod}}} \tag{2}$$

where η_{mod} is the module efficiency, $A_{\mathrm{mod}}/\mathrm{m}^2$ is the module area, $P_{\mathrm{MPP}}/\mathrm{W}$ is the power at maximum power point and $S/\mathrm{W\,m}^{-2}$ is the irradiance on the inclined surface. The module efficiency decreases with increasing module temperature.

The output power of the modules minus the losses of the connecting lines amounts to the input power of the inverter. Taking into account the characteristic efficiency function of the inverter, the simulation program is able to quantify the inverter efficiency for each load condition. On this basis an output simulation for a year can be done.

5. RESULTS AND DISCUSSION

There are PVPs installed in Leonding and at mount Loser with a rated power of 10 kW each, so the calculated values can be compared with the actual energy outputs of the plants for the last few years. Figures 1 and 2 show the energy outputs of the PVPs over the last few years and the calculated rates based on the new TRY for Leonding and Loser respectively. It can be determined which month of the different years has been selected for the TRY. The fact that it is not always the month that is closest to the average is due to the requirement that consistent connection points from one month to the next have to be found, so that sometimes a month with second priority, as described in Section 3, has been taken. The mean deviations of the complete energy yield of the different years to the predicted yields using the new TRYs are 2.4% for Loser and 3.6% for Leonding.

The yearly course of the efficiencies of the PVPs (ac-power output to solar radiation input) for Leonding and Loser are illustrated in Fig. 3 (based on the simulation with the new TRYs). The efficiency of the PVP at the summit Loser is significantly higher. For both sites the generator efficiency is lower in summer owing to the higher temperature of the panel. The inverters show better efficiency in summer, because full load conditions with an optimal load factor are more likely to occur. The low efficiency in November and December in Leonding results from partial load conditions for the inverter over a long period of time.

To support the presumption that the energy yield of a PVP increases with increasing altitude of its location, four other TRYs were used as input values for the computer code to simulate the yield of a PVP. All of them are within a surrounding area of about 300 km to Leonding to make sure they are all based on the same general weather situation. One of them was a TRY of Vienna made by Heindl *et al.* (1990) and three official German TRYs, named TRY8, TRY9 and TRY10 valid for Bavaria. The different TRYs are based on regions with different altitudes. Figure 4 shows the possible yearly energy yield per installed kilowatt for a PVP (inclination 45°, oriented to the south) of different locations depending on the altitude of the site. There is a clear correspondence between the energy output and the altitude of a PVP. The linear approximation we found was

$$e = 0.2a + 813 \tag{3}$$

where a/m is the altitude and $e/\mathrm{kWh\,(kWa)}^{-1}$ is the yearly energy yield per rated power.

A relationship between the solar input and the altitude of the site due to clearer sky and snow reflection has already been observed by Dirmhirn *et al.* (1978) and Kierkus and Colborne (1989). In addition to an increased solar input at higher altitudes, our simulation also takes into account the air temperature and the wind speed of the site. The generally lower temperatures and higher wind speeds at higher altitudes contribute to more output of a PVP at higher altitudes because of better cooling of the panels.

Haze and fog seem to be most responsible for less energy output in the valley in autumn and winter. For illustration, Fig. 5 shows the measured irradiance on the 45° tilted surface in

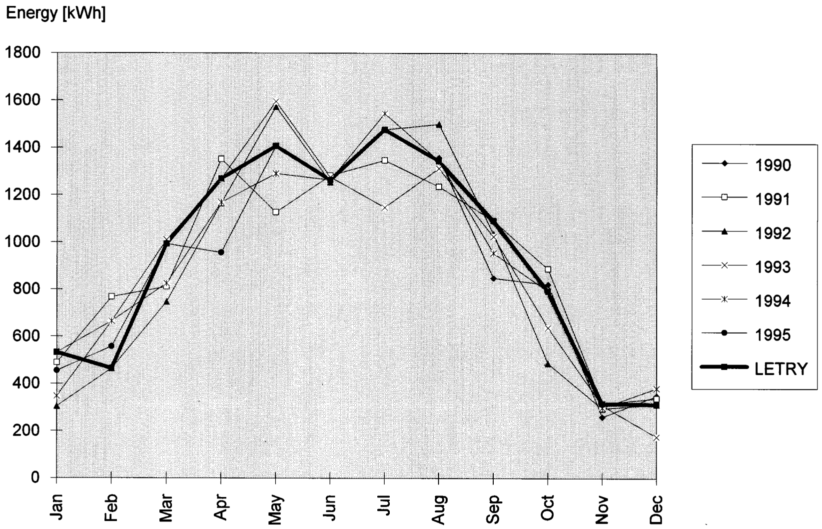

Fig. 1. Measured electrical energy supplied by the PVP Leonding (rated power 10 kW) 1990–1995 and calculated energy by use of the new TRY for Leonding (LETRY): ◆, 1990; □, 1991; ▲, 1992; ×, 1993; *, 1994; ●, 1995; ■, LETRY.

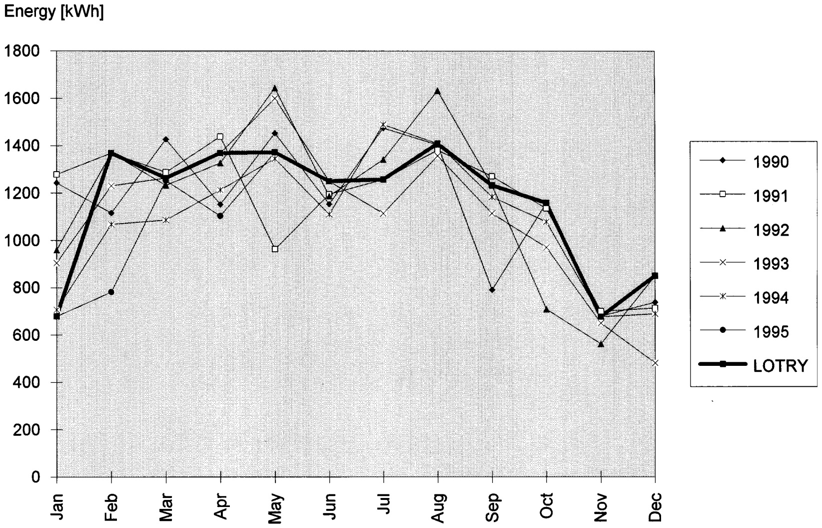

Fig. 2. Measured electrical energy supplied by the PVP Loser (rated power 10 kW) 1990–1995 and calculated energy by use of the new TRY for Loser (LOTRY): ◆, 1990; □, 1991; ▲, 1992; ×, 1993; *, 1994; ●, 1995; ■, LOTRY.

Leonding and at Loser for December 1992. On days with no mist, e.g. 4 December, the irradiation in Leonding reaches almost the same value as on Loser. Only the generally clearer sky and the snow reflection in the mountains might make some difference.

According to the investigations of Dirmhirn *et al.* (1978) for overcast sky, multiple reflections between snow cover and clouds might increase the irradiance in the mountains by up to 25%. This agrees well with our observations for instance on 12–13 December 1992.

From 18–24 December there was a period of fog in the valley. The irradiation in the valley sometimes only reaches about 10% of the irradiation above the mist. The measured energy output at Loser in December 1992 was three times higher than in Leonding. In the summer months the yield of electrical energy on Loser can be expected to be in the same ratio as in Leonding. Figure 6 shows a comparison of the yearly course between the energy output on Loser and in Leonding calculated with the new TRYs. The higher energy output of the PVP on Loser in autumn and winter is significant.

6. CONCLUSIONS

This study was initiated to investigate the energy output dependence of a PVP on the

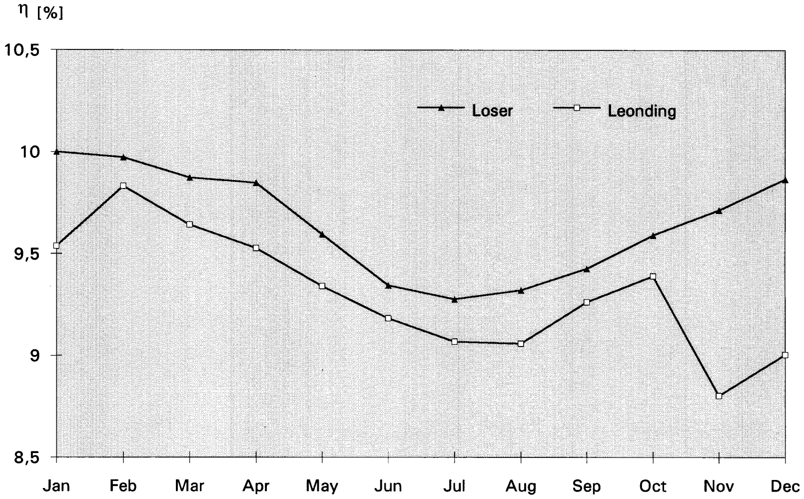

Fig. 3. Efficiency of the PVP–Leonding (300 m) and the PVP–Loser (1550 m); mean values of 6 yr.

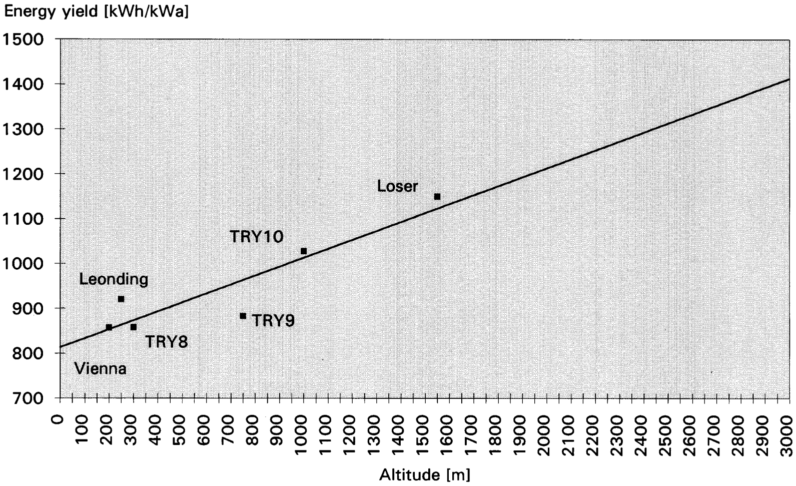

Fig. 4. Calculated energy yield of 1 yr of a PVP with a rated power of 1 kW based on various TRYs valid for locations with different altitudes.

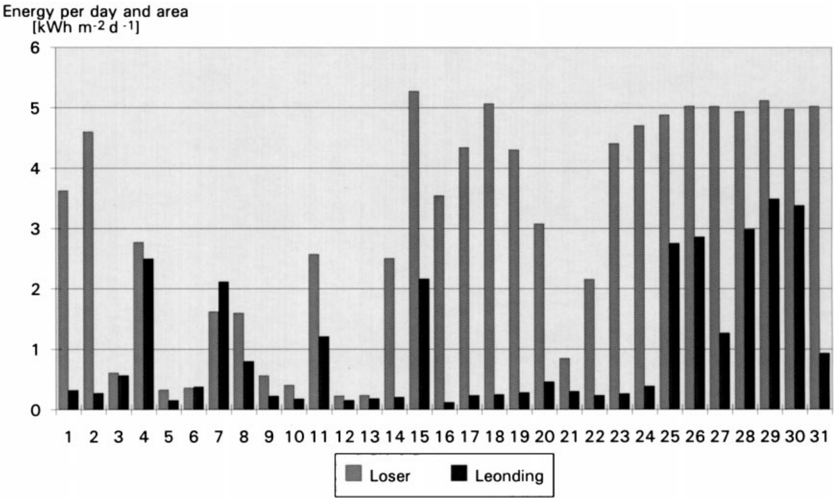

Fig. 5. Measured irradiance on a 45° tilted surface for Leonding and Loser in December 1992.

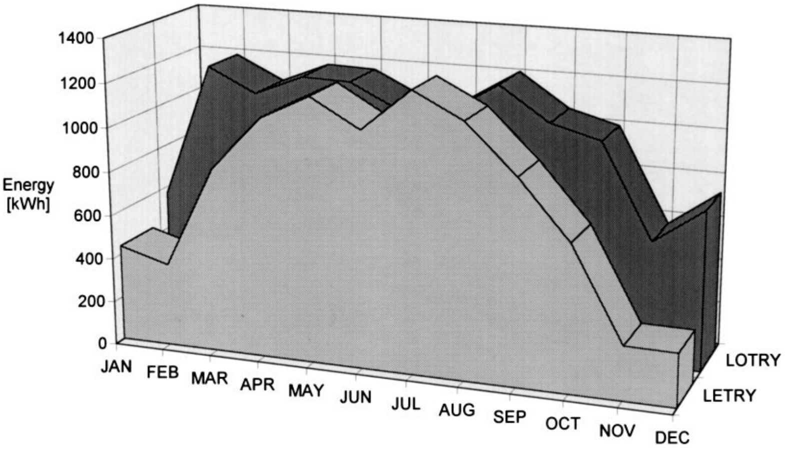

Fig. 6. Yearly course of the energy output of a PVP at the locations Loser and Leonding calculated with the new TRYs.

altitude of the site in the Austrian Alps. Two new TRYs were generated for the location: Leonding (altitude 300 m) and Loser (altitude 1550 m). These new TRYs, together with other already existing TRYs from different places in a surrounding area of about 300 km, are used for calculation of the expected energy output of a PVP. A clear increase of energy yield with increasing altitude can be observed. Whereas in the summer months the output of electrical energy on Loser can be expected to be in the same ratio as in Leonding, in autumn and winter the yield is up to three times higher in the Alps, which is mainly due to fog and mist in the valley. Besides the clearer sky and snow reflection at higher locations, the lower temperature and better cooling of the panels by the wind in the alpine area contribute to the higher energy output.

NOMENCLATURE

a	altitude (m)
η_{mod}	module efficiency
ξ_{sz}	ventilation factor
A_{mod}	module area (m^2)
a_{sz}	absorption coefficient
$c_{sz,1}$	heat transfer coefficient (W K^{-1} m^{-2})
$c_{sz,2}$	wind speed coefficient (W s K^{-1} m^{-3})
e	yearly energy yield per rated power (kWh (kWa)$^{-1}$)
P_{MPP}	power at maximum power point (W)
S	irradiance on the inclined surface (W m^{-2})
t_a	air temperature (°C)
t_{sz}	module temperature (°C)
v_w	wind speed (m s^{-1})

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