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Evaluation of actual PV modules performance at low insolation conditions

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In the paper the results of analysis of some data gathered by three independent Data Acquisition Systems, during prolonged outdoor testing of several commercial photovoltaic modules (PV modules) working in Solar Lab of Wrocław University of Technology and University of Opole, are presented and discussed. The effects of solar radiation intensity, ambient temperature, and even wind rate and direction on the actual performance of standard silicon solar cells based PV modules are shown. Special emphasis has been put on potentially cumulated electric charge and energy generated by the modules in different ambient conditions rather than on standard parameters measured. Effect of single-axis sun-tracking is demonstrated showing that in poor insolation conditions using of such systems may be nonbeneficial.

Keywords: PV modules, sun-tracking, data acquisition, insolation.

1. Introduction

One of the most important data that must be predicted when dimensioning photovoltaic (PV) system is potentially available cumulated electrical charge and/or energy that will be generated by PV modules during long periods. This may be done by integration in time of either current or power at a specified point of the module's I-V curve, respectively. In case of low latitudes locations where solar insolation is quite regular and well defined and PV modules work through the most of the time at high insolation level conditions the matter is quite simple. In such case the simplest and most common method of predicting potential gain of electrical charge and/or energy from PV module is assumption that these values change proportionally to global insolation energy while insolation itself is rather regular and easy predictable. However, for high latitudes regions, where the weather is of much more stochastic nature, i.e., incident solar energy, spectrum of the light and ambient temperature are strongly changeable and many days are very cloudy and rainy, this may not be so straightforward. This is due to the fact that the performance of the PV modules is usually nonlinearly dependent on insolation level [1]. This means that for more reliable dimensioning of PV system not only parameters measured at standard test condition (STC) but also data measured in real conditions may be needed. To estimate PV module's performance we calculate maximum theoretical PV generated charge, i.e., at short circuit (I_{SC}) point, charge generated at rated voltage of 12 V battery (I_{12}) and energy generated at maximum power point (MPP) denoted as P_M. For direct comparison of two chosen modules normalised values of measured parameters are used.

2. Data acquisition systems for outdoor testing of PV modules performance

In order to estimate long term performance of the commercial PV modules three independent specialised data acquisition systems (DAS) for outdoor long-term PV modules testing were used. The oldest one was designed and installed in SolarLab nearly five years ago(*) specifically for comparative test of twelve PV modules assembled using Si-cells delivered by four different manufactures, project partners. More detailed description of the system and the way of measured data presentation and analysis together with preliminary results of the tests may be found in Refs. 2–4. Comparative analysis of the performance of the two chosen modules by many possible means, especially in low insolation conditions, is described in Ref. 5.

Quite similar to that of SolarLab two monitoring systems were assembled on the building of University of Opole in March '97 and September '98, respectively. First of two systems is able to monitor only single PV module but it works also as autonomous PV system powering small meteorological station. Software procedures enable PC computer to control charging process of the lead-acid battery like standard charge-controller. The newer system enables monitoring of up to six PV modules with additional option of single-axis sun-tracking. At the present stage only

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two modules have been installed. They were delivered by the same manufacturer and were carefully chosen to ensure almost identical I-V curves under standard test conditions (STC). One of the modules works in single-axis sun-tracking mode while the other one remains fixed south-oriented. Such combination allows for direct estimation of the potential benefits of using costly tracking systems in our climate conditions. Compiling data stored by both DASs allows to show the effect of insolation level, ambient temperature, wind direction and wind speed on the PV module performance. Global insolation intensity at modules plane and module's real temperature (TC) are measured using ESTI-type double silicon solar cell sensor [6,7] manufactured and calibrated in SolarLab. After the installation of the newest system in September '98, solar radiation is also monitored by Kipp&Zonnen CM-11 pyranometer at horizontal plane.

Typical view of computer's screen during data acquisition for all three systems is shown elsewhere [3].

3. Results

3.1. I–V curves – temperature and wind effect on PV module's performance

In all three described DASs current vs. voltage curves of the modules have been measured in time intervals 1–2 min using the method described in Ref. 3. Values of open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) were measured directly either by giving 0 or 10 V, respectively on the gate of the MOS transistor loading the module whereas values of I_M, V_M, and P_M correspondig to maximum power point as well as value of I_{12} corresponding to charging current at rating voltage of the standard lead-acid battery, were calculated from the measured curve. Typical shape of the I–V curve measured at noon for fixed and sun-tracking module (the same position of both modules) is shown in Fig. 1. Making use of well-known fact that $I_{dark} = I_{light} - I_{SC}$ dark characteristics were additionally extracted directly from the light I–V curves. They are plotted in Fig. 1(b) in logarithmic scale revealing well-defined double-diode character. In Fig. 2, I–V curves of both modules measured for three different irradiations are plotted in a reduced form according to formula described by Blaesser [8]. As it can be seen in spite of a big spread in irradiation values (250–730 W/m^2) the reduced I–V plots are almost identical confirming adequacy of Blaesser's procedure for analysis of the PV module's performance under different insolation conditions.

Commonly used practice for solar cell analysis is plotting I_{SC}–V_{OC} characteristics for possibly wide range of insolation values and at a constant temperature. In Refs. 2, 5, and 9 this technique was shown to be useful for performance analysis of PV modules as well. In Fig. 3, we show this kind of curves plotted for fixed and sun-tracking modules measured at three different temperatures. On these plots one may

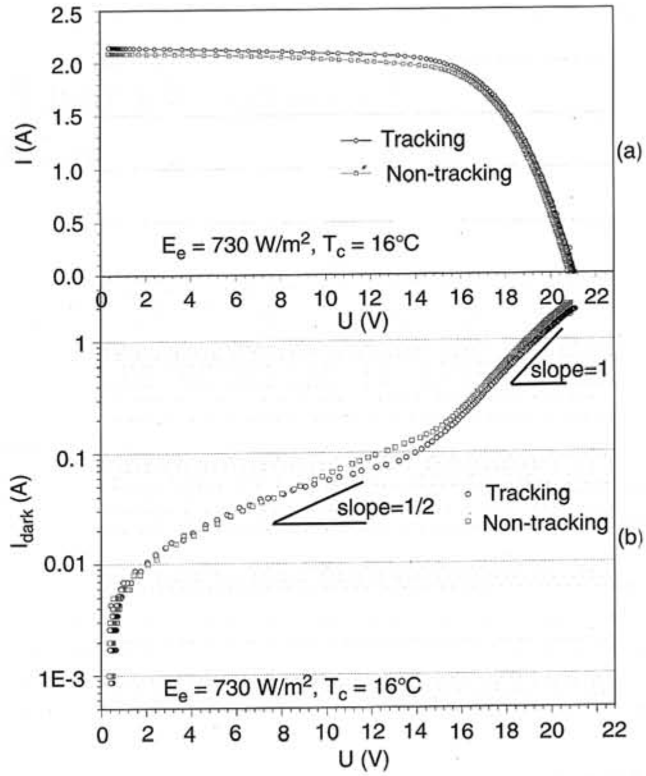

Fig. 1. Current-voltage plots of sun-tracking and fixed south-oriented modules measured at noon. Lower plot shows extracted dark curves ($I_{dark} = I_{light} - I_{SC}$) in linear-log scale with the exposed two slopes corresponding to classic double-diode mode of silicon cell.

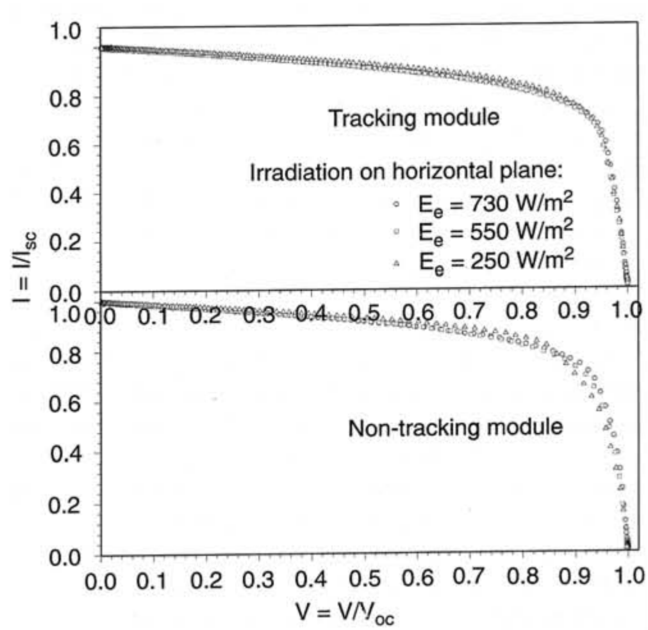

Fig. 2. Reduced current-voltage characteristics for sun-tracking and fixed south-oriented modules according to simple recipe given in Ref. 8. Note excellent similarity of all curves in spite of big spread in insolation values under which they were measured.

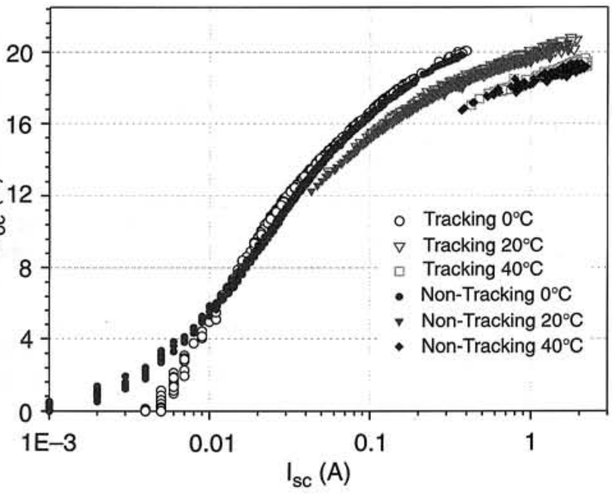

Fig. 3. Open-circuit voltage vs. short-circuit current plots for sun-tracking and fixed south-oriented modules measured at different temperatures. Note short range of linearity of the plots which is probaly the result of increase of module's temperature, followed by decrease of V_{OC}. From the plot practical limit of about 250–300 mA regardless of the ambient temperature for the effective charging 12 V battery may be easily deduced.

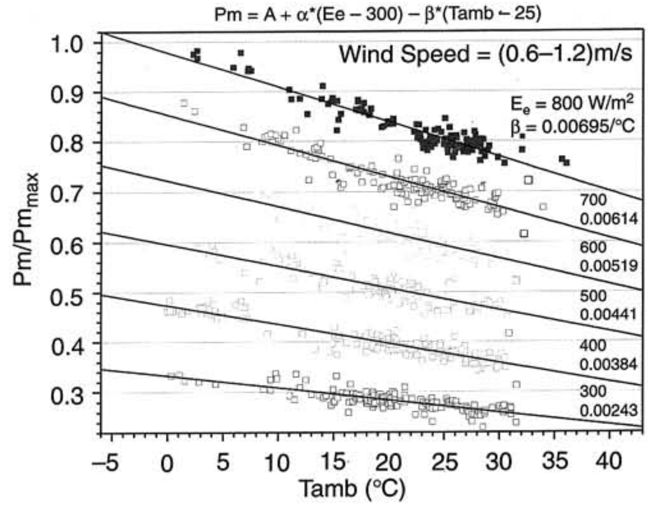

Fig. 4. Plots of PV module's normalised power as function of ambient temperature and solar irradiation. Temperature coefficient of P_m increases with irradiation value due to the effect of faster module's temperature rise resulting from dissipation of excessive energy of absorbed photons.

see clearly practical limits for effective charging of 12 V battery (e.g., for the present case for both modules this limit is practically for I_{SC} exceeding value of about 250–300 mA, regardless of the ambient temperature).

It is well known fact that with increasing insolation level also module's temperature rises rapidly what is the effect of excessive energy dissipation for photons with energy values higher than semiconductor's energy gap. This effect may be observed in Fig. 4 where the normalised power of PV module is shown as a function of the ambient temperature and insolation. Regular dependence of the slope β of the plotted lines on isolation level ranging from value –0.00243/°C for 300 W/m^2 up to –0.00695/°C for insolation equal to 800 W/m^2, respectively is well visible. For the purpose of simplified dimensioning procedure of PV systems it is usually assumed that value of β is constant and ranges from –0.004/°C to –0.0046/°C for PV modules made of single crystal or multicrystalline silicon cells, respectively [1].

Analysis of wind effect on PV module performance is not a simple task. It is due to the fact that influence of wind speed and/or direction on module's actual parameters is usually very weak when compared to effects of ambient temperature and insolation. Additionally, selection of the appropriate data is not easy and may be time-consuming. The result of such analysis is presented in Fig. 5(b). It shows weak clear tendency of some increase in module's performance for higher wind rates. This is an obvious effect of the module's temperature decrease shown in Fig. 5(b).

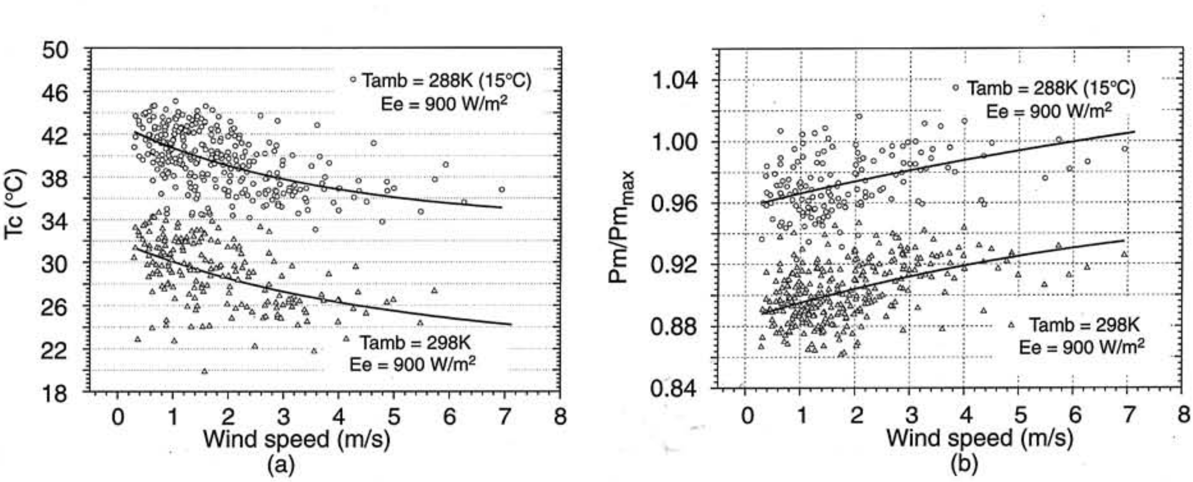

Fig. 5. Effect of wind speed on module's temperature and output power; data measured by DAS in University of Opole for module made on aluminium sheet and covered by Tedlar™ foil; module's temperature was measured using ESTI-type sensor manufactured and calibrated in Solar Lab (Wrocław).

3.2. Cumulated charge and energy generated by PV modules

The most important determinant of PV module's quality is its ability to generate electrical charge and/or electrical energy. Figure 6 shows values of the cumulated charge Q_{12}, Q_{max} and the energy E_{max} which are the values of I_{SC}, I_{12} and P_m integrated in time, respectively. Data were stored during two dramatically different days by DAS in Opole University for very similar single-crystal silicon PV modules. One of the modules was single-axis east-west sun-tracking and south-tilted while the other one was fixed, south-oriented with the same tilt angle. As it can be seen while beneficial effect of sun-tracking option is undoubtful in the case of clear and sunny day yet it is not very convincing during cloudy day. This is confirmed in Fig. 7 showing process of charge and energy cumulation for the two days. During sunny day gain in cumulated energy resulting from sun-tracking option has reached almost 30% whereas for cloudy day this gain is below 10%. However, Figs. 6 and 7 are merely the examples obtained during specific days and one should be aware that the problem of advantages or disadvantages, following application of sun-tracking system, can be much more complicated considering all weather and climate conditions, like cloudiness, ambient temperature, percentage of diffused radiation, possible reflections from snow, etc.

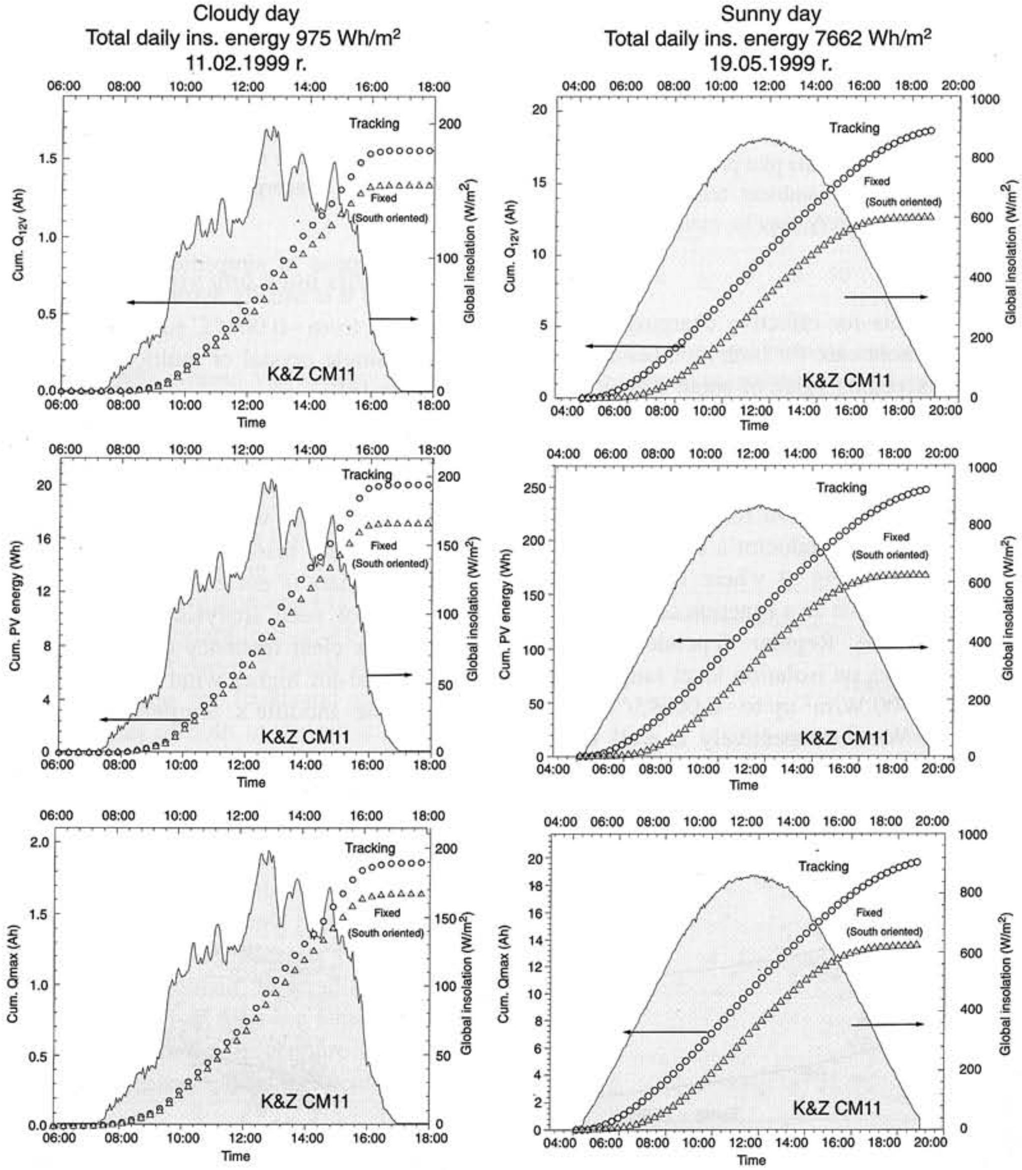

Fig. 6. Plots of cumulated values of the electrical energy (calculated at MPP point), maximum charge (calculated at I_{SC} point) and average charge potentially usable for typical 12 V lead-acid battery charging (calculated at 12 V of I–V curve) generated by fixed (south-oriented) and single-axis (east-west) sun-tracking tilted (south-oriented) module for two days characterised by extremely different insolation conditions as shown on the background plots. The data were obtained in February and May '99 by DAS installed on the roof of the Opole University building. Poor benefits in gain of cumulated energy and charge when using tracking system during cloudy day is visible. Note different scale of both sets of plots.

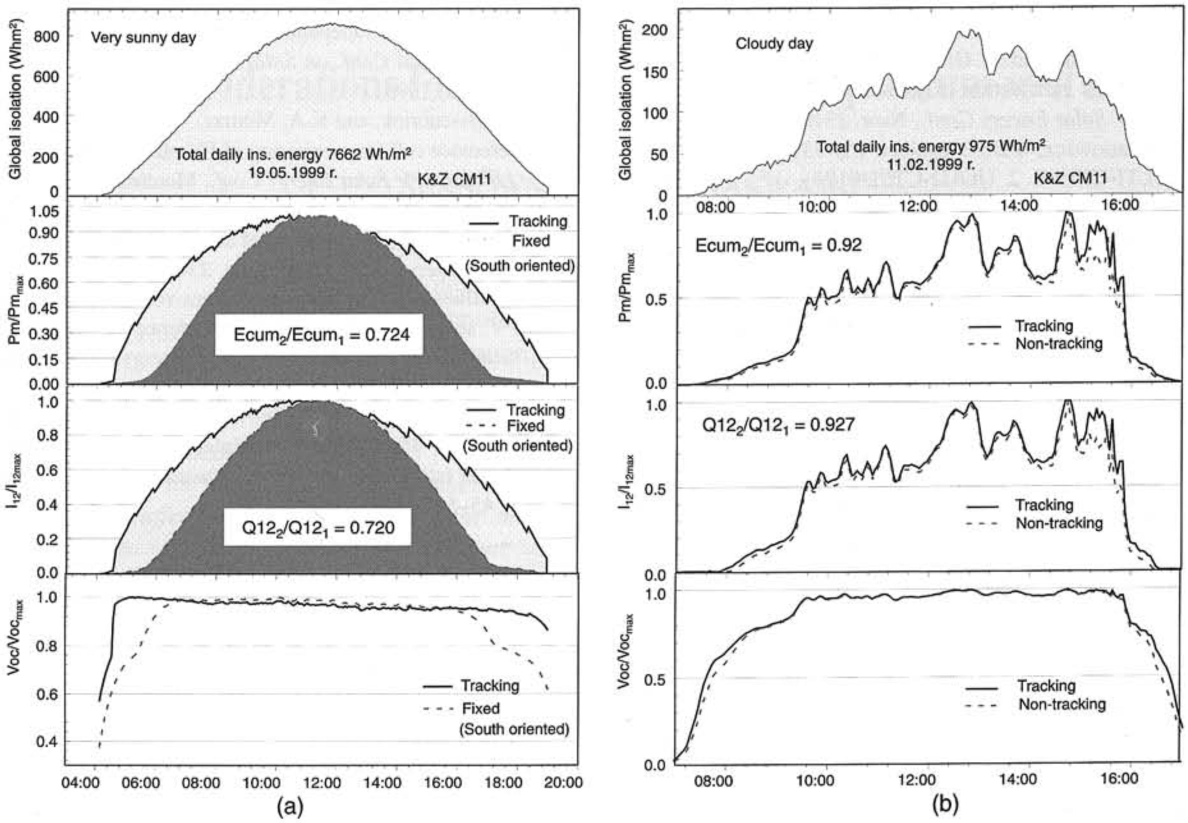

Fig. 7. Plots of normalised values of the maximum power P_M, current at 12 V (I_{12}) and the open circuit voltage V_{OC} measured for fixed (south-oriented) and single-axis (east-west) sun-tracking tilted (south-oriented) module during (a) very sunny and (b) very cloudy day (values indexed as 'max' are maximum values measured during a day). The data were obtained in May '99 and February '99 by DAS installed on the roof of the Opole University building. Characteristic teeth which can be seen for the normalised P_M and I_{12} curves during sunny day result from movement of tracking system activated about once per hour. Relative gain in cumulated energy and charge shown on both plots confirms doubtful usefulness of tracking system during cloudy day. Note different scale of both sets of plots.

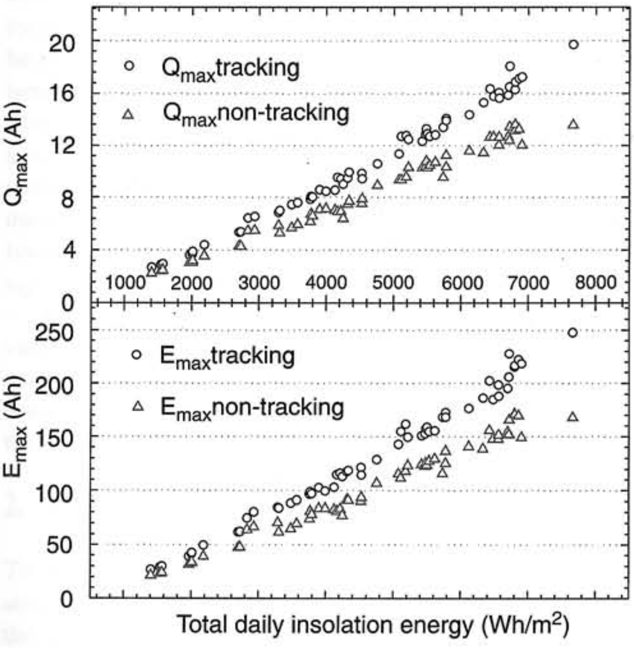

Fig. 8. Plots of cumulated values of the cumulated charge Q_{max} (measured at I_{SC}) and the cumulated energy (measured at P_M) vs. daily insolation energy. Data were collected during six-month period for fixed and sun-tracking modules by DAS in Opole.

In Figs. 8(a) and (b), dependence of cumulated energy and charge on daily global insolation energy is shown. To make the plots averaged values of the data collected during several months have been used. This way effects of temperature, spectral distribution of radiation, wind parameters, etc. have been averaged as well.

4. Conclusions

Some results stored during outdoor testing of PV modules have been presented. They show that the module performance may strongly depend on ambient conditions and does not have to be related to the values given by manufacturer in a simple way. For PV system dimensioning purpose knowledge of PV modules performance measured in the conditions close to those for which PV system has been assigned may be very helpful for a proper design. Expected advantages of using of usually costly and unreliable in a long-term scale sun-tracking option may be not satisfactory during periods characterised by low insolation that are typical for middle and northern parts of Europe.

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