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Preparation and validation of PV module outdoor performance datasets

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1. Introduction

For investors and operators of PV systems the energy output (Wh) is the most important parameter, even if modules are typically priced according to their nominal power capacity in Wp. To address this need, many producers and research institutes have set up long-term module outdoor measurements facilities, in which a range of the environmental and electrical performance parameters are continuously monitored. The resulting data can be used to assess energy yield in relation to actual operating conditions, as well as providing a basis for models to predicting energy yield. As yet no international standards exist for such measurements and the management of the resulting data, although efforts have been made to develop best-practice guidelines[1].

The JRC's European Solar Test Installation (ESTI) operates an outdoor module performance measurement facility (the ENRA facility) at its site in Ispra (Italy). It has measurement points for various modules mounted on a fixed rack tilted at 45° to the horizontal plane and oriented due south. Measurements are made every 4 minutes approximately, comprising an IV sweep to determine V_{oc}, I_{sc} and P_{max}, as well as the in-plane irradiation from an ESTI sensor and a pyranometer, in addition to the module and ambient temperature. These data can be complemented with environment data (global, direct and diffuse irradiance, wind conditions, temperature and humidity) from the adjacent meteorological tower.

The work reported here came about as a result of a request for outdoor performance data from the SOPHIA European PV Research Infrastructures Project, in which JRC is participating. The data was to be used to validate the performance of various energy yield models implemented by SOPHIA partners. It was decided to contribute with JRC data for four module technologies. This provided an opportunity to:

a) Develop a procedure in Matlab in order to prepare the ESTI data to be provided to the project's partners following the various quality control criteria and format restrictions required by the SOPHIA project. Using this specific procedure created for SOPHIA, another one, more general, was developed to extract the data from the various ESTI databases and export it in a more common format from where users could easily select the variables needed for their particular studies and objectives.

b) Assess the quality of the data recorded and identify potential improvements to the ESTI ENRA facility.

The results of these activities are reported below.

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[1] DERlab technical guidelines on long-term photovoltaic module outdoor tests, Reference No. 100 – 01, 01/2012

2. ESTI outdoor monitoring databases

One of the possible applications of the data registered in ESTI's ENRA facility is the estimation of the energy output provided by the PV modules, which can in turn be used to validate energy yield models, such as those being investigated in the SOPHIA project. In general, estimation models use input data about meteorological variables, such as temperature or wind speed, besides data regarding the solar irradiance received by the PV modules. In addition, the electrical variables and characteristic parameters of the PV modules are also necessary. As for the validation of the predictions from the models, measurements of maximum power output are needed as well. At present on ESTI's set-up for outdoor module performance monitoring these variables are saved in three different databases, which will be briefly described in the following sections.

2.1. General PV module outdoor exposure data

When PV modules are tested outdoors, various daily files are created and stored in the following directory: 'darkroom/noctenra/enra data backup'. The file with the extension ".raw" contains information about several variables measured on the modules, whilst the file ".ene" has the same information but after applying some corrections for temperature and irradiance to some of the variables. The latter will be the file used to extract the general data of the modules.

Outdoor measurements are performed every few minutes and saved in a new row in the daily file "yymmddLLNNN.ene", where 'yymmdd' stands for the year, month and day when the measurement was performed, and 'LLNNN' stands for the code given to the module. The first column contains the hour (UTC hour+1) when the measurement was taken in HH:MM:SS format. Several variables are registered or calculated, and stored in columns. However, according to the requirements of the SOPHIA project, only the following variables are extracted from these files

- global irradiance in the same inclined surface as the fix rack where modules are located, measured by ESTI sensor, G_{ESTI} (W·m^{-2})
- global irradiance in the same inclined surface as the fix rack where modules are located, measured by a pyranometer, G_T (W·m^{-2})
- ambient temperature, Tª amb (ºC)
- module temperature, Tª mod (ºC)
- short circuit current, I_{sc} (A)
- open circuit voltage, V_{oc} (V)
- maximum power point current, I_{mpp} (A)
- maximum power point voltage, V_{mpp} (V)

Both irradiance values saved in the ".ene" file have been corrected with regard to the values stored in the ''.raw' file.

2.2. IV curve data for outdoor module exposure

Besides the parameters mentioned in the previous section, every measurement performed generates an IV curve of 30 points, which is used to determine the maximum power point current and voltage. These data are saved in the file described in section 2.1. with the extension ".raw".

Other variables are saved in the ".raw" file, some of which are also saved in the file ".ene" after applying some corrections. However, variables like the ambient and module temperature are saved in both files with no changes. These repeated values will be used to guarantee that measurements from both databases, that of the general data and that of the IV curves, registered at exactly the same moment are extracted and combined properly.

2.3. Meteorological and irradiance data

The solar radiation received by a photovoltaic module is one of the key parameters that affect the electricity generated by the module. Other meteorological variables can also affect the energy output, such as the ambient temperature or the wind speed.

Out of the several meteorological variables registered in the weather station located in the Ispra site, the following have been selected as relevant to modelling activities as input data:
- ambient temperature, T^a amb (ºC)
- atmospheric pressure, Patm (mbar)
- wind speed, Ws (m·s^{-1})
- wind direction, Wd (º)

Regarding the irradiance data (W·m^{-2}), ESTI has been recording, for several years now, measurements of:
- global and diffuse irradiance on the horizontal plane (G and G_d respectively)
- beam normal irradiance (G_{bn})
- global irradiance on three different tilted surfaces, oriented south, inclined 45º, 60º and 90º with regard to the horizontal plane (G_{45}, G_{60}, G_{90})

The irradiance measurements of G and G_d are selected. However, as measurement of the beam component was only initiated a few years ago and does not cover the full monitoring period of the selected modules, it has not been included here. Out of the three irradiance measurements on tilted planes, G_{45}, G_{60}, $G_{90,}$ only the one measured with the same inclination angle of that employed in the fix rack where modules are tested, is selected.

Both the meteorological and irradiance data registered in the weather station are recorded every minute and saved in daily files, named "mtyymmdd.dat", where 'yymmdd' stands for the year, month and day. They are stored in the following directory: 'darkroom/meteo'.

The first column contains the hour, always as UTC hour +1, in HH.MM format. All the variables are saved in separate columns. Since some of the channels are not connected to any instrument, some of the columns are empty. Those with data are saved in the following columns:

1. Date and time, UTC hour + 1, HH.MM format
2. G (W·m^{-2})
3. G_{90} (W·m^{-2})
4. G_{45} (W·m^{-2})
5. G_{60} (W·m^{-2})
6. G_d (W·m^{-2})
7. G_{bn} (W·m^{-2}) The variables registered in this channel have changed over time. At the present moment it records G_{bn}
9. Ws (m·s^{-1})
10. Wd (º)
11. Rainfall (mm)
15. T^a amb (ºC)
18. Patm (mbar)

3. Quality control

In the first place, for the three databases (General PV data, IV curve data and meteorological data) the night hours between 22:00 and 4:00 UTC are directly excluded. For the data measured in the remaining hours, various quality tests are applied.

The SOPHIA project requested a minimal quality control. Most of the restrictions are defined in regard to the general PV module data. The limits are shown in Table 1.

Variable	Unit	Lower limit	Upper limit
Short circuit current, I_{sc}	A	0	$1.5 \cdot I_{sc\ STC}$
Open circuit voltage, V_{oc}	V	0	$1.5 \cdot V_{oc\ STC}$
Module temperature, T^a mod	ºC	-20	90
Fill factor, FF	-	0	1
Global irradiance tilted plane, G_{ESTI}, G_T	$W \cdot m^{-2}$	0	1500
Maximum power point current, I_{mpp}	A	$0.5 \cdot I_{sc}$	I_{sc}
Maximum power point voltage, V_{mpp}	V	0	V_{oc}

Table 1. Quality control applied to the variables in the general PV module database

As it can be seen I_{sc} and V_{oc} values are limited by the corresponding values under the Standard Test Conditions, $I_{sc\ STC}$ and $V_{oc\ STC}$, respectively. Then, they are in turn used to check the quality of the current and voltage values at the maximum power point (I_{mmp} and V_{mmp} respectively).

Whenever one variable is outside the applicable limits, the whole measurement is removed from the database.

No more detailed exclusion criteria have been applied (for instance exclusion of very low irradiance values). This is left to the discretion of the user of the data.

No specific quality control measures have been applied to the IV curves database. However the measurements times removed from the general PV database are also removed from the IV database to ensure consistency

Regarding the third database with the irradiance and meteorological data, the tolerance intervals applied to the variables are shown in Table 2. It was decided, following the SOPHIA project's requirements and recommendations, that if for a particular measurement time some of the meteorological variables were missing, the measurement could still be considered valid. Therefore, whenever there is a missing value in the meteorological variables, the NaN notation is replaced by the value "-29998" and the measurement is kept. However, in the same way as with the general module data database, if the value of the global, diffuse or inclined irradiance is missing, the whole measurement of the third database is removed. It was decided like this as the meteorological variables are generally not as critical as the irradiance data in the modelling activities.

Variable	Unit	Lower limit	Upper limit
Ambient temperature, T^a amb	ºC	-20	50
Atmospheric pressure, P atm	mbar	950	1050
Wind speed, Ws	$m \cdot s^{-1}$	0	30
Wind direction, Wd	º	0	360
Global horizontal irradiance, G	$W \cdot m^{-2}$	0	1500
Diffuse horizontal irradiance, G_d	$W \cdot m^{-2}$	0	800
Global irradiance tilted plane, G_{45}	$W \cdot m^{-2}$	0	1500

Table 2. Limit values applied to validate the quality of the meteorological and irradiance data

4. Matlab code to extract and export the ESTI data

The Matlab program created to extract the ESTI data of the outdoor PV measurements is called "**PV performance data.m**".

The program extracts the data from the three previously described databases, filter the data according to the corresponding quality control criteria and organize all the variables in a column format file, from where information about any variable can easily be extracted.

4.1. Input data required

In order to extract the data, the user needs to provide the Matlab program with the following information:
- the code of the PV module, 'LLNNN'
- period of time where data has to be extracted
- technical parameters of the module under the Standard Test Conditions

In the first place, the code of the PV module has to be provided to the program. The modules' codes are composed of four or five alphanumerical characters. The first two are capital letters followed by two or three numbers. This code, named *module* in the Matlab program, has to be written between '', like 'AI01' or 'KX712'.

Secondly, the user has to define the time period in which data is going to be extracted. In order to do so, the user needs to specify the year or years to analyse and for each year, the first and last month from which data has to be extracted. For instance, if the period of time to analyse goes from May 2009 to November 2010, the user should define the variables *selectedyears*, *firstmonths* and *lastmonths* as follows:
selectedyears = [2009,2010]
firstmonths = [5,1]
lastmonths = [12,11]

Finally, in order to perform the quality control of the data, the user needs to provide the Matlab program with the values of $I_{sc\ STC}$ and $V_{oc\ STC}$, denoted as *Ics_stc* and *Voc_stc* respectively.

4.2. General description of the procedure followed

The whole procedure can be divided in three main steps.

4.2.1   General PV module data

With the information provided by the user, in this first step the Matlab program, reads all the '.ene' files that correspond to the defined module and time period, while it extracts the information of the variables described in section 2.1. The outcome of this step is a matrix, named '*General_data_module_aQC_*LLNNN' with the variables related to the general PV module data distributed into the following columns:

1. Date and time, UTC hour: yyyy-mm-dd HH:MM:SS format
2. G_{ESTI} (W·m^{-2})
3. G_T (W·m^{-2})
4. Tª amb (ºC)
5. Tª mod (ºC)
6. I_{mpp} (A)
7. V_{mpp} (V)
8. I_{sc} (A)
9. V_{oc} (V)

At this point, data from night hours have been removed, the hour has been transformed to UTC format, in opposition to the UTC+1 of the ".ene" files and the quality control criteria shown in Table 1 have been applied.

4.2.2   IV curve data

In this second step, the Matlab program reads all the ".raw" files and extracts the IV curve data of the measurements performed during the period of time defined by the user. Every IV curve contains 30 points so every measurement in these ".raw" files results in a row of 60 columns with 30 voltage values followed by the 30 current values.

Since no quality control is applied to the IV curve data, only the IV data from those moments present in '*General_data_module_aQC_*LLNNN' are used.

As mentioned in section 2, there are some variables that are saved in both the ".ene" and the ".raw" files without applying any correction. These variables are extracted along with the IV curve data and saved only to guarantee that the same moments are extracted from both datasets and are properly combined afterwards.

The resulting matrix of this second step is named '*IV_data_module_aQC_*LLNNN' and contains the following columns:

1. Date and time, UTC hour: yyyy-mm-dd HH:MM:SS format
2. Tª amb (ºC)
3. Tª mod (ºC)
    Columns 4 to 33 contain the 30 voltage values of the IV curves, whilst columns from 34 to 63 contain the corresponding current values

It may happen that for a particular moment of '*General_data_module_aQC_*LLNNN', the corresponding IV curve was not registered. In this case, the moment is removed from '*General_data_module_aQC_*LLNNN'. As a result, two new matrices are generated with those moments in common from both databases: '*General_data_module_aQC_common_*LLNNN' and '*IV_data_module_aQC_common_*LLNNN'.

4.2.3   Meteorological and irradiance data. Interpolation and quality control

The general PV module data and the IV curves are registered simultaneously every few minutes. Ideally, the meteorological and irradiance data should have been measured at the same time as the other two databases. However, the data from the weather station is registered every minute.

The procedure applied to obtain the meteorological and irradiance values for the same timestamps of the other two databases is the following

    1. In order to have the closest possible timestamps in the data selected from the three datasets, for every moment when there is general PV module and IV curve data, the closest two measurements in time from the weather station are selected. The time difference has to be below the minute, otherwise data from the weather station is not chosen.

    2. In principle, there should be two measurements from the weather station within the minute around the timestamp of the general module data. If there are none, the data regarding the module, both general and IV curve, are dismissed. If for any reason there are more than two measurements, the closest two in time are selected. As a result, for every general PV module data in '*General_data_module_aQC_common_LLNNN*' and IV curve data '*IV_data_module_aQC_ common_LLNNN*', there are two measurements from the weather station.

    3. The quality control defined in Table 2 is applied to the two values of every meteorological variable and to the measurements of the global, diffuse and inclined irradiances, G, G_d and G_{45}. There may be different scenarios as the irradiance values are considered more important than the other meteorological variables.

        – If both G values or both G_d values or both G_{45} values fall out their tolerance interval, all the measurements from the three databases, corresponding to this timestamp are dismissed.

        – As long as, at least, one of the two values of G, one of the two values of G_d and one of the two values of G_{45} are correct, the measurements of the timestamp from the three databases are kept. The correct irradiance value is assigned to the timestamp, if there is only one.

        – If both G, G_d and G_{45} values are correct, a linear interpolation is applied in order to calculate the G, G_d and G_{45} value corresponding to the timestamp being considered.

        – Regarding the meteorological variables, if both values are correct, a linear interpolation is applied and the resulting value is the one assigned for the timestamp. If only one of the two values passes the quality control, it is directly assigned as the value for the timestamp. And if both values are wrong, this variable's value for the timestamp will be "-29998" as if the values were missing.

The interpolation procedure applied to the weather station data makes that the final values assigned to this third database for two PV modules tested in the outdoor filed during the same period of time, are not the same. Since modules are not measured at the exact same moment, the result of the interpolation procedure, even if the two closest moments from the weather station to every timestamp are the same, won't result in the same interpolated values.

The described procedure is performed in the third part of the Matlab program. Since some of the data regarding the module may be removed if no valid irradiance data is available for that particular moment, after this third step, three new matrices are generated, all with the same timestamp and number of data:

        – with the general PV module data: '*General_data_module_final_LLNNN*'
        – with the IV data: '*IV_data_module_final_LLNNN*'
        – with the meteorological and irradiance data: 'Meteo_*data_module_final_LLNNN*'

This last matrix has the following columns:

    1.   Date and time, UTC hour: yyyy-mm-dd HH:MM:SS format
    2. G (W·m^{-2})
    3. G_d (W·m^{-2})

4. G_{45} (W·m^{-2})
5. Tª amb (ºC)
6. P atm (mbar)
7. Ws (m·s^{-1})
8. Wd (º)

4.3. Output files

At the end of the Matlab program it is possible to export the final data extracted from the three ESTI datasets to an Excel file. The user can decide whether to export the data from the three databases separately or combined in a single file. When combined, the order of the various variables in the file's columns is the following:

1. Date and time, UTC hour: yyyy-mm-dd HH:MM:SS format
2. G (W·m^{-2})
3. G_d (W·m^{-2})
4. G_{45} (W·m^{-2})
5. Tª amb from the weather station (ºC)
6. P atm (mbar)
7. Ws (m·s^{-1})
8. Wd (º)
9. G_{ESTI} (W·m^{-2})
10. G_T (W·m^{-2})
11. Tª amb measured next to the tested modules (ºC)
12. Tª mod (ºC)
13. I_{mpp} (A)
14. V_{mpp} (V)
15. I_{sc} (A)
16. V_{oc} (V)
17. – 46. 30 V measurements from the IV curve (V)
47. – 76. 30 I measurements from the IV curve (A)

The name of the output file is "*Combined_data_module_final_LLNNN.xls*"

If data from the three databases is exported separately, the names of the Excel files are:

"*General_data_module_final_LLNNN.xls*" with the general PV module data

"*IV_data_module_final_LLNNN.xls*" with the IV curve data

"*Meteo_data_module_final_LLNNN.xls*" with the variables selected from those registered in the weather station.

The distribution of columns of every Excel file is the same one as the one described in section 4.2.

5. ESTI data provided to SOPHIA project

The SOPHIA activities for energy yield modelling can be divided in two parts. First, the models for the estimation of the PV output are "trained" and/or calibrated on a limited data set that includes power measurements. These are then validated in the second stage. It was therefore necessary to provide two different datasets. The first one, destined to the calibration of the models, should contain three months of valid data and should preferably run from April to June in order to cover a wide range of temperatures. The second one, used for the simulation and validation, should have one year of data in order to cover a broad range of possible weather conditions.

5.1. Selected module technologies

The JRC was able to provide information of four different technologies: polycrystalline silicon, cadmium telluride (CdTe), amorphous silicon, copper indium selenide (CIS). Other module technologies were covered by other partners. Beside the PV technology, different installation conditions were available. At the Ispra site modules are set in a fixed rack tilted 45 degrees with regard to the horizontal plane and due south, while in other locations, different inclination angles were used according to the local latitude. Besides a fixed setting, some partners located their modules on biaxial tracking systems.

The modules tested by JRC and whose data was provided to SOPHIA project are the following:

- Polycrystalline, Kyocera KC60
- CdTe, First Solar FS-270
- Amorphous silicon, Kaneka LSU020
- CIS, Wuerth Solar WSG0036E075

The four modules were not measured simultaneously neither were they measured in a continuous way. Consequently, the 15 months period of time required by the SOPHIA project is generated combining shorter periods of time, as shown in Table 3. As an example, for the Wuerth Solar module, the three months period contains data from April to June 2011. While, for the twelve months period of time, due to the available data and to avoid using the data already destined to the calibration of the models, we could not provide data from 12 consecutive months. Therefore, data from June 2010 to March 2011, plus data from July and August 2011 was prepared.

Module	SOPHIA Code	ESTI Code	Technology	3 months period	12 months period
Kyocera KC60	1	AI01	Polycrystalline	2008 [4-6]	2010: [6-12] 2011: [1-5]
First Solar FS-270	4	KX712	CdTe	2009 [4-6]	2010: [6-12] 2011: [1-5]
Kaneka LSU020	2	CQ01	Amorphous silicon	2006 [4-6]	2005: [9-12] 2006: [1-3], [7-11]
Wuerth Solar WSG0036E075	3	NW71	CIS	2011 [4-6]	2010: [6-12] 2011: [1-3], [7-8]

Table 3. Data provided for the different PV technologies

Finally, data from power measurements at STC was prepared and shared with the project's partners. The main parameters values are shown in Table 4.

Module	I_{sc} (A)	V_{oc} (V)	I_{mmp} (A)	V_{mmp} (V)	P_{max} (W)	FF (%)	Date
Kyocera KC60	3.48	21.3	3.23	16.8	54.2	73.2	27/08/2010
First Solar FS-270	1.18	91.4	1.01	65.7	66.4	61.5	13/06/2012
Kaneka LSU020	1.11	84.8	0.86	59.3	50.8	53.9	24/08/2005
Wuerth Solar WSG0036E075	2.40	42.9	1.97	33.5	66.1	64.2	27/08/2010

Table 4. Performance parameters under STC indoor measurements

5.2. Data preparation

The procedure to extract the data from the three ESTI databases is essentially as described above. The only thing different is the format in which the data for SOPHIA is exported. Instead of variables distributed across columns with the first one containing the date and hour the measurement was taken, for SOPHIA dataset, the information from different variables were required to be listed, apparently for compatibility with the database structure (MySQL).

5.2.1 SOPHIA data format

The way variables are distributed in columns in the Excel files derived from section 4, facilitates their analysis when using that software. However, it does not follow the project's requirements that need the data to be uploaded into the SOPHIA project MySQL database. Therefore it is necessary to apply a final modification to the extracted data from the ESTI databases in order to rearrange it. The general PV module data is already distributed accordingly to the SOPHIA criteria. However the other two databases need to be rearranged so that data is distributed as follows.

IV curve data has to be rearranged and distributed in the following columns:

1. ID module
2. Date and time, UTC hour: yyyy-mm-dd HH:MM:SS format
3. Step: if goes from 1 to 30, as the number of points that form the IV curve
4. Current value of the curve in the step i, I_i (A)
5. Voltage value of the curve in the step i, V_i (V)

Each module considered had to be assigned with an ID number as indicated in Table 3.

Similarly, the variables from the meteorological and irradiance ESTI database need to be rearranged into the following columns:

1. ID sensor
2. Date and time, UTC hour: yyyy-mm-dd HH:MM:SS format
3. Value

In addition to the variables selected from the weather station for this particular project (G, G_d, Tª amb, P atm, Ws and Wd), in the files to provide to the SOPHIA partners with the meteorological and irradiance values, the two irradiance variables measured along with the modules, G_{ESTI} and G_T were joined to this file. As a result, the first column (ID sensor) goes from 1 to 8. Being G the first one, (ID sensor 1) and G_T the last one, (ID sensor 8).

1. G (W·m^{-2})
2. G_d (W·m^{-2})
3. Tª amb (ºC)
4. P atm (mbar)

5. Ws (m·s^{-1})
6. Wd (º)
7. G$_{ESTI}$ (W·m^{-2})
8. G$_T$ (W·m^{-2})

This format required by SOPHIA project results in a very large number of rows that makes it difficult to export the data into Excel files. However, this format is appropriate for the MySQL language used in the project.

5.2.2 Alternative Excel data format

To facilitate the use of the data internally at ESTI and for its distribution via the ESTI web site, for each module we have prepared an Excel file, entitled *"Combined_data_module_final_LLNNN.xls"* where LLNNN stands for the module's code. In this case the data from various variables and parameters is provided in separate columns.

The first column contains the date and time when the measurement was recorded, in UTC hour with 'yyyy-mm-dd HH:MM:SS' format.

Variables in columns 2 to 10 regard atmospheric and environmental variables, such as temperature and wind speed, plus information about the irradiance levels recorded at the modules' location. Note that sensor 8, the global module in-plane irradiance, is that of the meteo tower G$_{45}$ pyranometer. It replaces the data from the pyranometer mounted in-plane beside the module (G$_T$) due to evidence of intermittent malfunctioning of this instrument.
Columns 11 to 15 contain information related to the modules, like temperature or current and voltage values of the characteristic points of the IV curves.

In every measurement, an IV curve is recorded, with a total of 30 points. Such information is contained in columns 16 to 75. Firstly, the 30 voltage measurements (V), followed by their corresponding 30 current values (A)

The distribution of the above mentioned variables in the Excel file is as follows:
1. Date and time, UTC hour: 'yyyy-mm-dd HH:MM:SS' format
2. Global horizontal irradiance, G (W·m^{-2})
3. Diffuse horizontal irradiance, G$_d$ (W·m^{-2})
4. Ambient temperature measured two meters above ground level, T^a amb (ºC)
5. Atmospheric pressure, P atm (mbar)
6. Wind speed measured ten meters above ground level, Ws (m·s^{-1})
7. Wind direction measured ten meters above ground level, Wd (º)
8. Global irradiance measured in the same tilted plane as the modules, measured by an ESTI sensor, a PV cell type, G$_{ESTI}$ (W·m^{-2})
9. Global irradiance measured by an inclined pyranometer 45º with regard to the horizontal plane, G$_{45}$ (W·m^{-2})
10. Ambient temperature measured next to the tested PV modules, T^a amb_mod (ºC)
11. Module temperature, T^a mod (ºC)
12. Current at the maximum power point, I$_{mpp}$ (A)
13. Voltage at the maximum power point, V$_{mpp}$ (V)
14. Short-circuit current I$_{sc}$ (A)
15. Open-circuit voltage, V$_{oc}$ (V)
16. – 45. 30 V measurements from the IV curve (V)
46. – 75. 30 I measurements from the IV curve (A)

6. Data Characterisation

6.1. Approach

The SOPHIA quality control criteria described in section 3 provide a basic means of eliminating obviously spurious data. However, a more detailed check is appropriate to better understand the characteristics of the data and any inherent limitations. For this purpose the following aspects were examined:

a) Variation of in-plane irradiance values from the ESTI sensor (G_{ESTI}) and the 45° inclined pyranometer of the meteo tower (G_{45}), against the global irradiance from the meteo tower instrumentation (G). As noted above, for the ESTI data files it was decided to remove the data from the inclined 45° pyranometer (G_T) situated on the module rack and use instead, as pyranometer data, the measurements from the 45° inclined pyranometer located in the meteo tower (G_{45}). Although it had passed the rudimentary SOPHIA quality checks, it was subsequently found that the G_T data contained some erroneous measurements and cannot be considered reliable. The instrument has been replaced in the meantime.

b) Variation of I_{sc} to in-plane irradiance (G_{ESTI} and G_{45}).

c) Variation of P_{max} at 1000 W·m^{-2} ± 20 W·m^{-2} against time. For this check the data is filtered to leave only values corresponding to an irradiance interval between 980 and 1020 W·m^{-2}. The STC value reported for the module is taken as reference for stability and/or seasonal effects. The resulting plot can indicate if any substantial change has occurred in a module's electrical characteristics over the monitoring period, evidenced by a consistent and substantial net increase or decrease of P_{max}. It also shows up gaps in the data, which occur for example due to instrument problems or to periods when the modules were removed from the outdoor rack for STC measurements under controlled conditions.

The above characteristics have been checked for each of the four modules. Two sets of plots are presented per module, one based on the irradiance measured by the ESTI sensor, G_{ESTI}, while the second set take as reference the inclined pyranometer of the meteo tower G_{45} i.e. in the same plane as the modules.

6.2. Results

Figs. 1 and 2 present the data plots for the polycrystalline silicon module. The plots of the variation of P_{max} in time indicate a fairly stable behaviour. The values tend to lie below the STC reference value, which is expected since the module temperatures in operation are generally much higher than the STC value.

Figs. 3 and 4 present the data plots for the amorphous silicon module. The plots of the variation of P_{max} in time indicate a season variation (increased Pmax in summer and decrease in winter) characteristic of this technology.

Figs. 5 and 6 present the data plots for the cadmium telluride module. The plots of the variation of P_{max} in time indicate a fairly stable behaviour.

Figs. 7 and 8 present the data plots for the CIS module. The plots of the variation of P_{max} in time indicate a fairly stable behaviour.
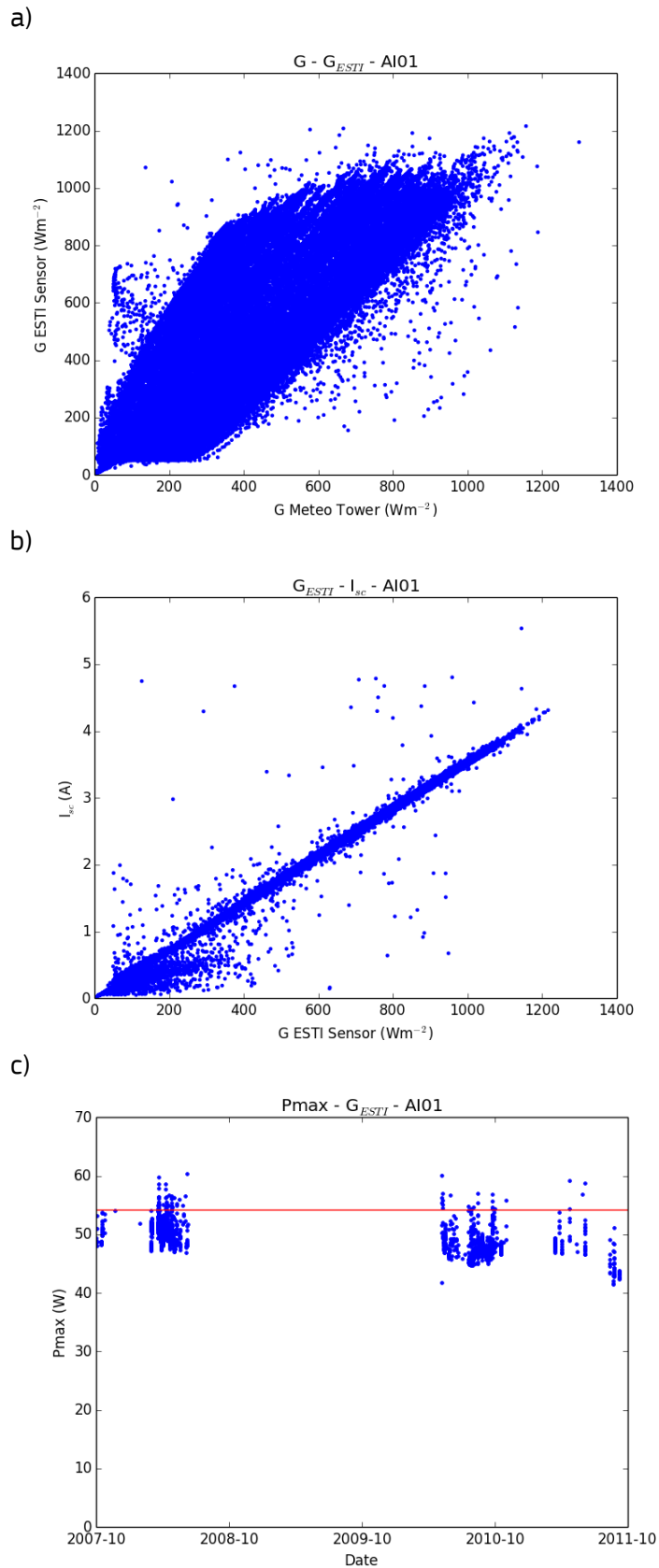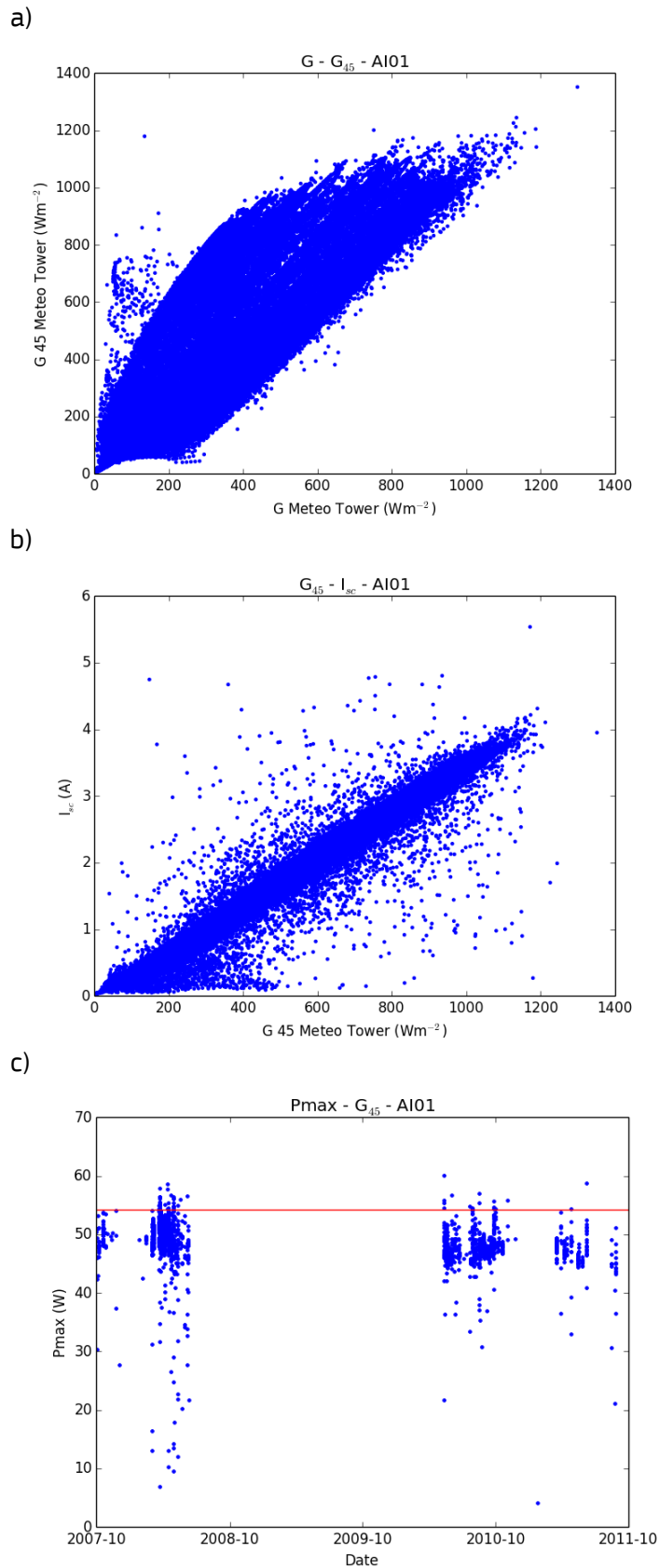
a)

b)

c)

Fig. 1 Poly-crystalline silicon module AI01: a) variation of in-plane ESTI sensor irradiance with the global horizontal irradiance; b) variation of I_{sc} with ESTI sensor in-plane irradiance and c) variation of P_{max} at 1000 W.m^{-2} ± 20 W.m^{-2} against time

a)

b)

c)

Fig. 2 Poly-crystalline silicon module AI01: a) variation of in-plane pyranometer irradiance with the global horizontal irradiance; b) variation of I_{sc} with the in-plane pyranometer irradiance and c) variation of P_{max} at 1000 $W.m^{-2}$ ± 20 $W.m^{-2}$ against time
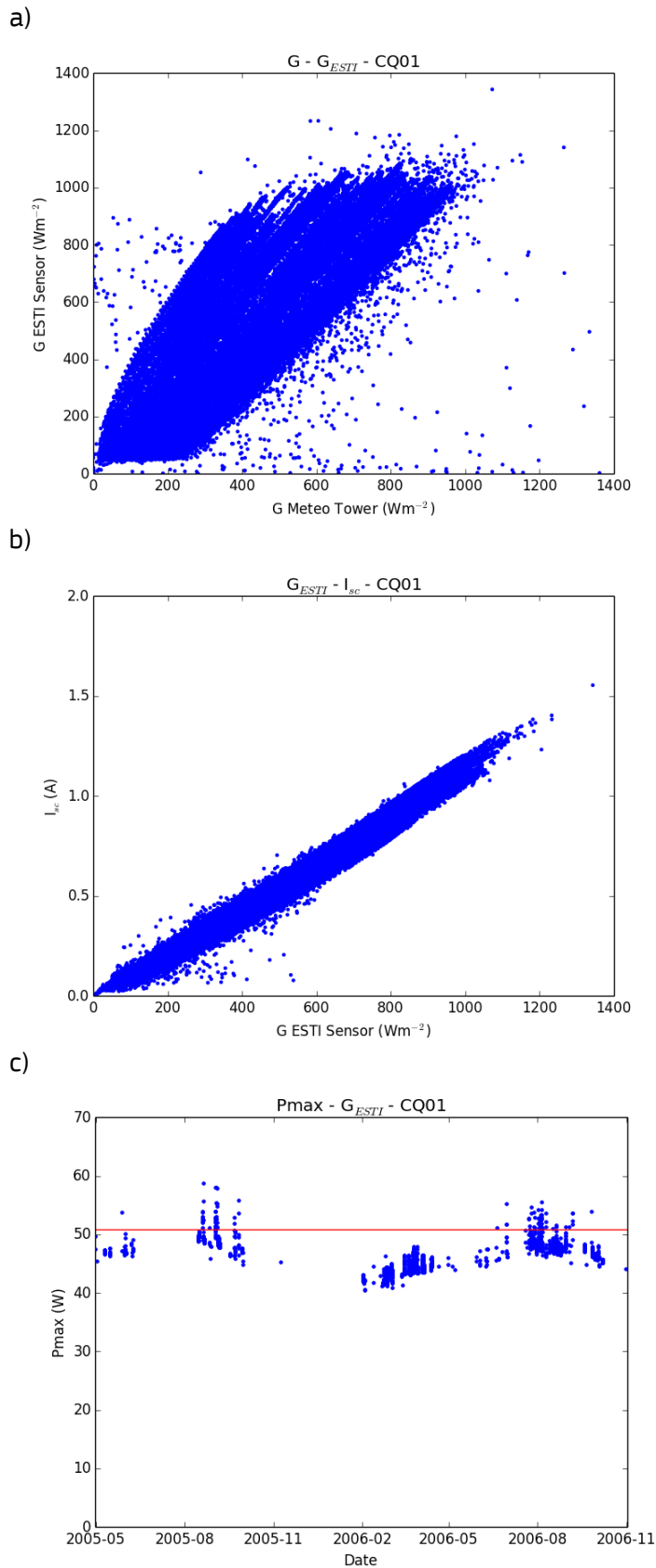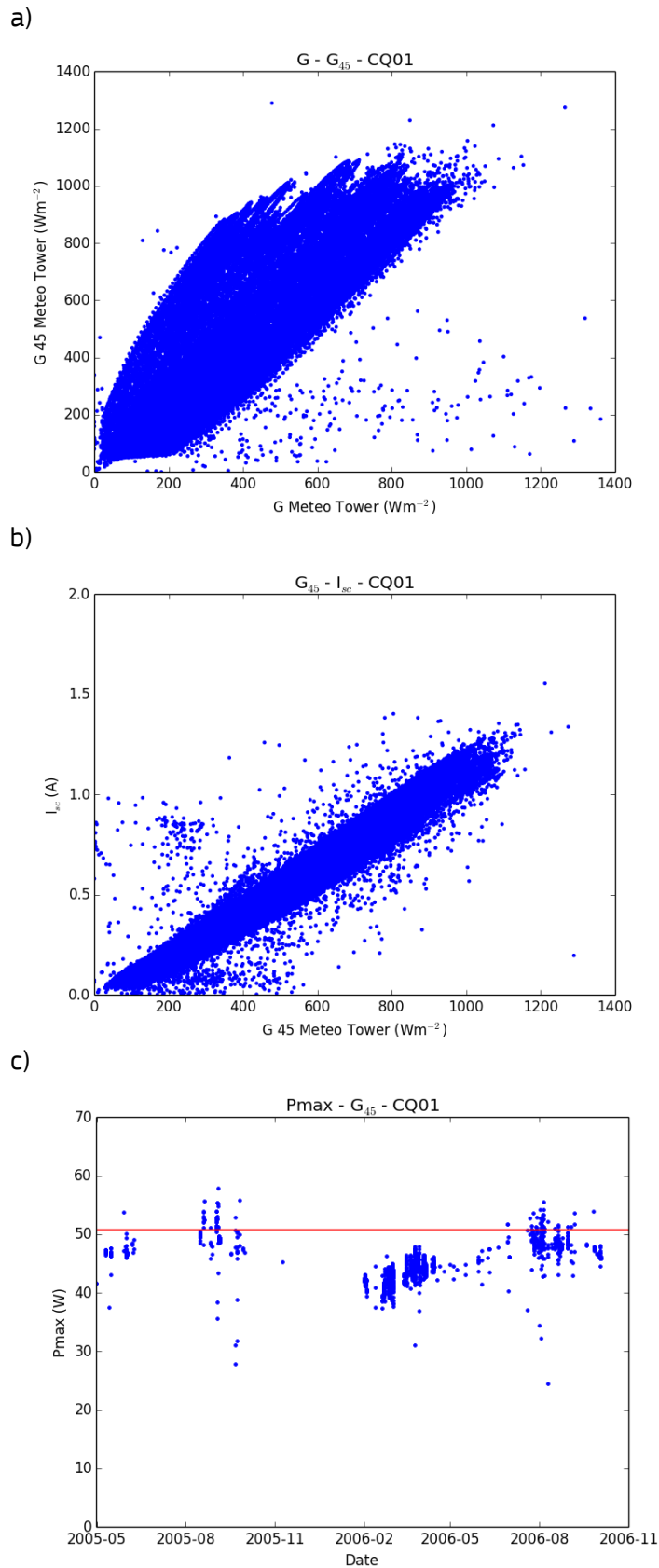
a)

b)

c)

Fig. 3 Amorphous silicon module CQ01: a) variation of in-plane ESTI sensor irradiance with the global horizontal irradiance; b) variation of I_{sc} with ESTI sensor in-plane irradiance and c) variation of P_{max} at 1000 W.m^{-2} ± 20 W.m^{-2} against time

a)

b)

c)

Fig. 4 Amorphous silicon module CQ01: a) variation of in-plane pyranometer irradiance with the global horizontal irradiance; b) variation of I_{sc} with the in-plane pyranometer irradiance and c) variation of P_{max} at 1000 W.m^{-2} ± 20 W.m^{-2} against time
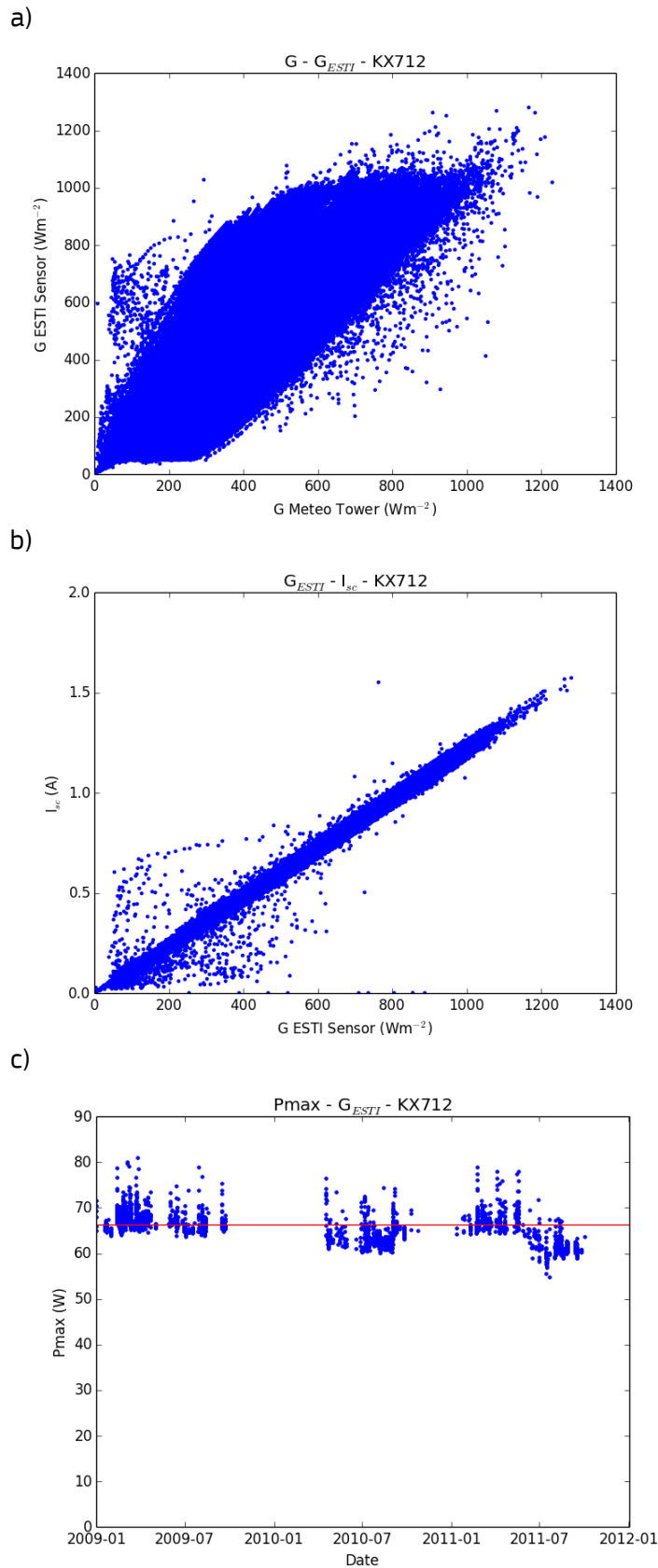
a)

b)

c)

Fig. 5 Cadmium telluride module KX712: a) variation of in-plane ESTI sensor irradiance with the global horizontal irradiance; b) variation of I_{sc} with ESTI sensor in-plane irradiance and c) variation of P_{max} at 1000 W.m^{-2} ± 20 W.m^{-2} against time
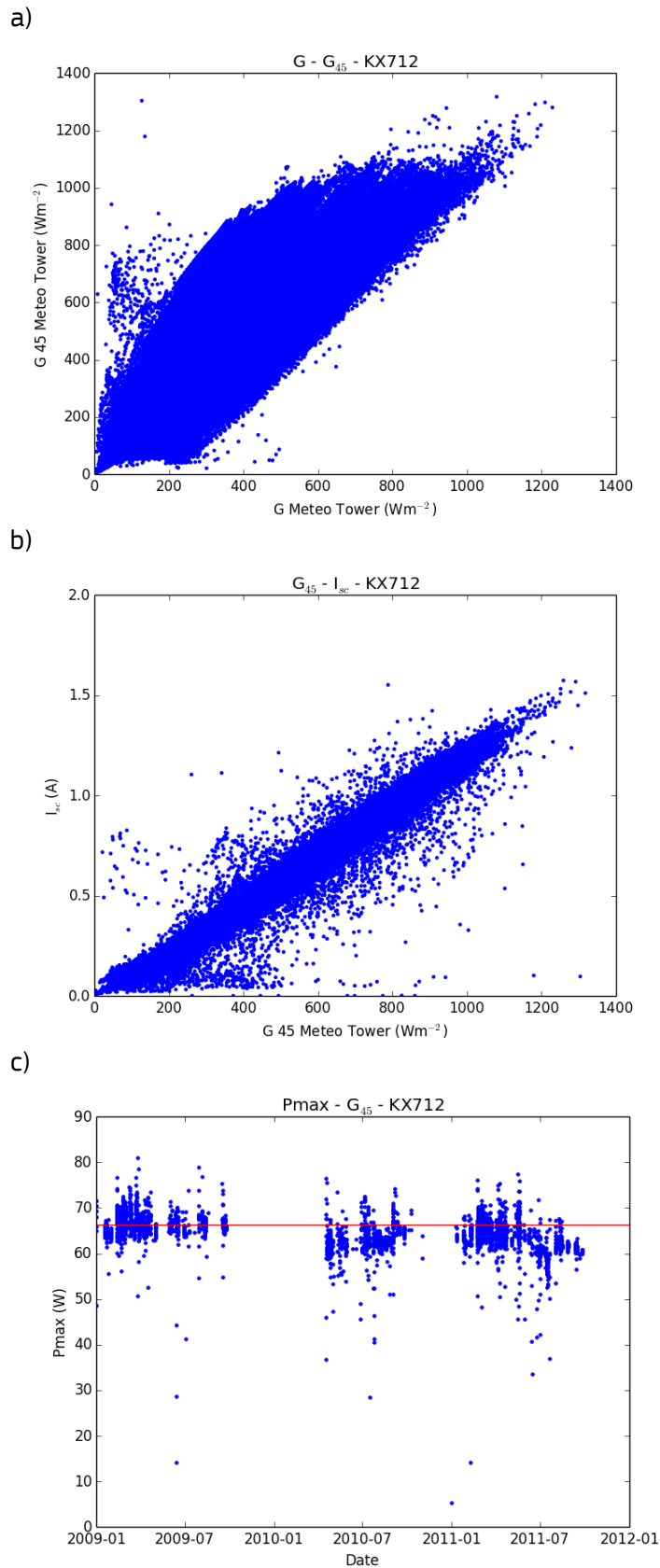
a)

b)

c)

Fig. 6 Cadmium telluride module KX712: a) variation of in-plane pyranometer irradiance with the global horizontal irradiance; b) variation of I_{sc} with the in-plane pyranometer irradiance and c) variation of P_{max} at 1000 W.m^{-2} ± 20 W.m^{-2} against time
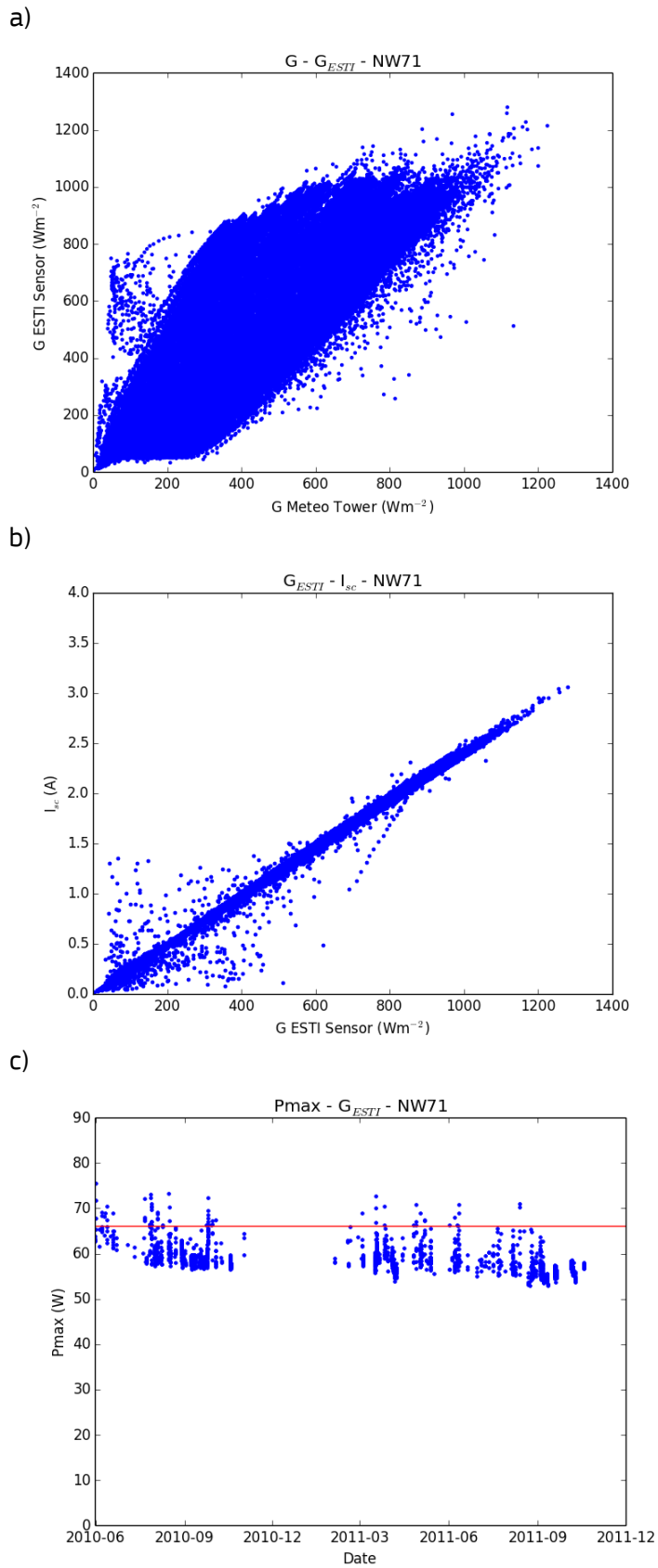
a)

b)

c)

Fig. 7 CIS module NW71: a) variation of in-plane ESTI sensor irradiance with the global horizontal irradiance; b) variation of I_{sc} with ESTI sensor in-plane irradiance and c) variation of P_{max} at 1000 W.m^{-2} ± 20 W.m^{-2} against time
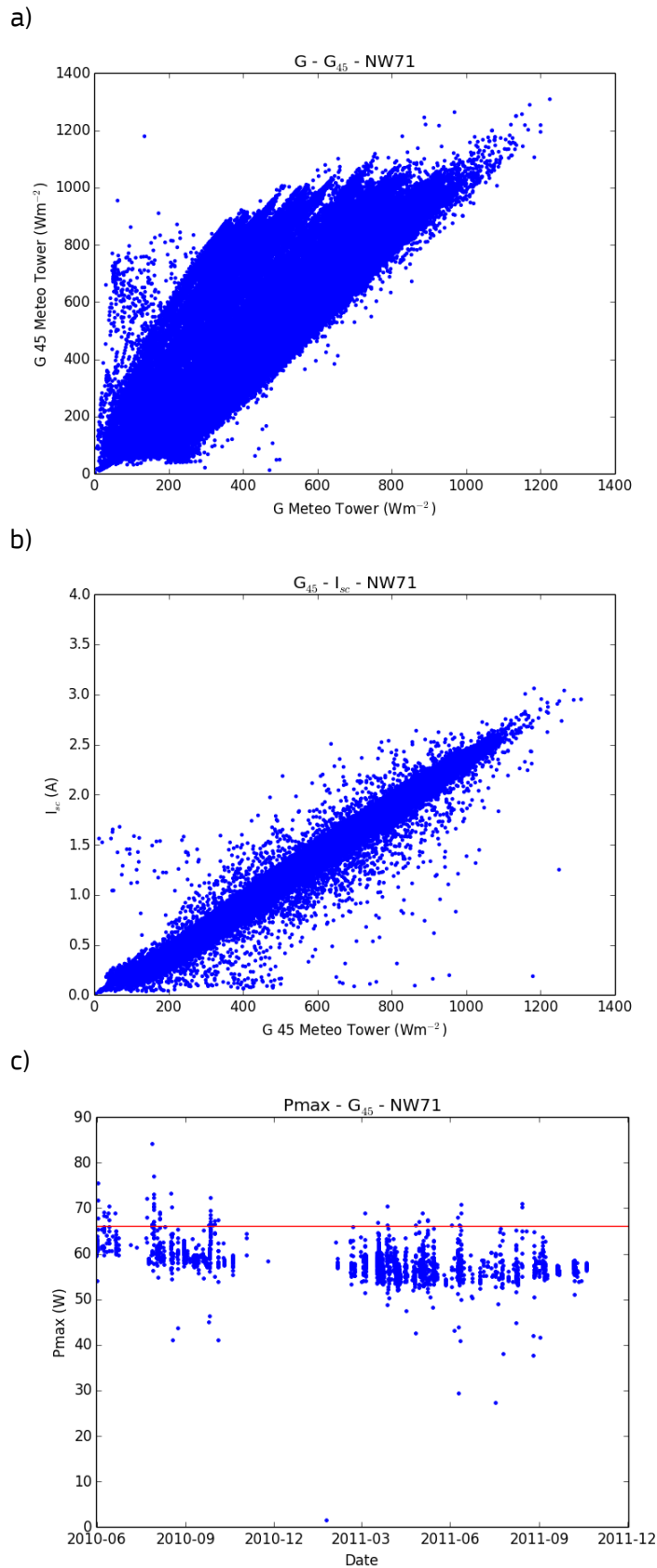
a)

b)

c)

Fig. 8 CIS module NW71: a) variation of in-plane pyranometer irradiance with the global horizontal irradiance; b) variation of I_{sc} with the in-plane pyranometer irradiance and c) variation of P_{max} at 1000 W.m^{-2} ± 20 W.m^{-2} against time

7. Conclusions and Recommendations

- Software routines have been developed to allow the extraction of performance data for individual modules monitored at the JRC's energy rating ("ENRA") test facility, part of the European Solar Test Installation at the Ispra site. This involves combing daily data files from the ENRA set up and from the meteorological instruments, as well as applying basic quality control rules on the data.

- Data sets have been prepared for 4 module technologies (polycrystalline silicon, amorphous silicon, cadmium telluride and copper indium selenide) according to the requirements of the energy yield modelling exercise carried out as part of the SOPHIA project. For each module it was required to submit a set of 15 months' of data (split into a 3 month set and a 12 month set), comprising module performance and environment parameters. Excel versions of these data sets have also been prepared and are available on request to esti.services@jrc.ec.europea.eu.

- This exercise has also provided an opportunity to evaluate the quality of the ESTI ENRA data and the handling procedures. The following recommendations are made:
    - A common time stamp and logging frequency should be implemented for the ENRA and meteo tower data acquisition systems.
    - More regular checks or an active monitoring system for the instrumentation would be advisable to detect any technical problems as early as possible.
    - A simple but regular quality control of the data would also help assure its reliability and completeness. For instance, comparisons of each variable with corresponding tolerances and/or checks in the coherence between different parameter values.

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Title: Preparation and validation of PV module outdoor performance datasets
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Abstract
For investors and operators of PV systems the energy output (Wh) is the most important parameter. To address this need, many producers and research institutes have set up long-term module outdoor measurements facilities. The resulting data can be used to assess energy yield in relation to actual operating conditions, as well as providing a basis for models to predicting energy yield.

The JRC's European Solar Test Installation (ESTI) operates an outdoor module performance measurement facility (the ENRA facility) at its site in Ispra (Italy). It has measurement points for various modules, and several variables are registered.

The work reported here came about as a result of a request for outdoor performance data from the SOPHIA European PV Research Infrastructures Project, in which JRC is participating. The data was to be used to validate the performance of various energy yield models implemented by SOPHIA partners.

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Key policy areas include: environment and climate change; energy and transport; agriculture and food security; health and consumer protection; information society and digital agenda; safety and security including nuclear; all supported through a cross-cutting and multi-disciplinary approach.