A new method for estimating insolation based on PV-module currents in a cluster of stand-alone solar systems

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Abstract- In order to evaluate the performance of solar home systems (SHS), data on local insolation is a prerequisite. We present a new method to estimate insolation if direct measurements are unavailable. This method comprises estimation of daily irradiation by correlating photovoltaic (PV) module currents from a number of solar home systems, located a few kilometres apart. The method was tested with a three-year time series for nine SHS in a remote area in Indonesia. Verification with reference cell measurements over a two-month period showed that our method could determine average daily irradiation with a mean bias error of 1.3%. Daily irradiation figures showed a standard error of 5%. The systematic error in this method is estimated to be around 10%. Especially if calibration with measurements during a short period is possible, the proposed method provides more accurate monthly insolation figures compared with the readily available satellite data from the NASA SSE database. An advantage of the proposed method over satellite data is that irradiation figures can be calculated on a daily basis, while the SSE database only provides monthly averages. It is concluded that the new method is a valuable tool to obtain information on insolation when long-term measurements are absent.

Keywords: solar irradiation; insolation; monitoring

1. Introduction

Solar home systems (SHS) are becoming an increasingly popular means of rural electrification in developing countries. The potential market for SHS is huge, as currently about 2 billion people do not have access to electricity. Supply of electricity from SHS depends on maintenance of the systems. It was therefore disappointing to find through field surveys that only about 77% of the installed systems are still working a few years after installation (Nieuwenhout et al, 2001). To study the effect of user behaviour on SHS performance, detailed system monitoring with data loggers is required, supplemented with information from technical system checks and questionnaires. Very few projects have been monitored at the required level of detail, and these were often pilot projects, such as Balde de Leyes in Argentina (Parodi et al, 1998; 2000), and Sukatani in Indonesia (BPPT, 1991 and Reinders et al, 1999).

With the objective to increase knowledge on user behaviour and quality issues in a large scale project, BPPT, the Indonesian Agency for the Assessment and Application of Technology, and the Energy research Centre of the Netherlands ECN, have conducted detailed monitoring of recently installed solar home systems over the period 2001-2003. In 2001, dataloggers were added to nine recently installed solar home systems in

Kolaka district, in the South-eastern part of the island of Sulawesi in Indonesia. About 1400 solar home systems with 53 W_p modules were installed in Kolaka district in 1997-2000. They were financed through a revolving fund from a previous, Australian Aid funded project with 36,400 systems (Dasuki et al, 2001). Preliminary results of the BPPT-ECN monitoring have been presented on different occasions (Djamin et al, 2001, Dasuki et al, 2002, Djamin et al, 2002, Nieuwenhout and Djamin, 2002).

For determining the performance of solar systems over a number of years, information on insolation is required. Local measurements with a reference cell or pyranometer would be the most straightforward and reliable approach. However, in our case, the datalogger that was intended to register insolation failed after two months. Since there is no nearby meteorological station, we had to look for other alternatives. Time series of satellite data are not yet readily available for locations in the tropics. NASA provides a tool where monthly average insolation can be obtained for every location in the world, based on 10 years of satellite monitoring (NASA, 2003) (see sections 2 and 4.3). Such data can be very useful for designing solar systems. But for evaluating system performance, one prefers actual weather data instead of historic, climatic data.

As an alternative, we developed a new method to obtain estimated daily irradiation figures based on combining module current data of a number of nearby solar systems. The objective is to obtain reliable daily and monthly insolation figures that are representative for an area of a few square kilometres. Three key research questions are: is it possible to construct a time series of estimated irradiation figures based on module current data of nearby systems? How reliable are these estimates? Under what circumstances can this new method be applied?

This paper provides an answer to these questions. It describes a method to obtain time series of estimated daily irradiation in the absence of actual insolation measurements. A short introduction to this new method was recently published (Nieuwenhout et al., 2006). Data acquisition is presented in section 2, and the various steps of the procedure are described in section 3. In section 4 our results with this method in Indonesia is validated against three other data sources, i.e., on-site measurements, a reference cell from another project, and climate data from NASA satellites. Section 5 discusses the outcomes. Section 6 summarises the results and presents general conclusions.

2. Data acquisition

Choice of datalogger

Monitoring in remote areas requires reliable data loggers. To reduce possible influencing of the users, a small logger was chosen that can be integrated into the battery box of the solar home system (see figure 1a). This Sentry logger (Sentry, 2003) has its own power source on which it can operate for about five years. Insolation data were obtained from a much more complicated datalogger from a World Bank project, that was installed in the same village (see figure 1b). Failure of the external power source caused interruption of the insolation data acquisition after two months.

Parameters measured with the data loggers

Four parameters are measured at the input and output terminals of the battery charge regulator (BCR) of the solar home system at 7-second intervals, and stored as half-hourly averages. With shunt resistors, the PV-module current and the current to the load are measured. Battery voltage is taken at the battery terminals of the BCR. Voltage at the load terminal of the BCR is also measured.

An important parameter in the analysis is the voltage of the PV-module. Laboratory measurements on the charge regulator (T12.10P, of PT LEN, Indonesia) showed a constant voltage drop of 0.5V between the module and battery connections, caused by a semiconductor in the charge regulator. PV-module voltage has been calculated by adding 0.5 V to the measured battery voltage, omitting the voltage drop over the cables, which is estimated to be around 0.1 to 0.2 V at maximum module current.

PV-module temperature information

Module temperature T_m is not one of the parameters that was measured continuously with the data loggers. Only in a five-day period during an inspection visit in October 2003, horizontal irradiation measurements were made with a MacSolar insolation measurement device (from Solarc). It uses a poly-crystalline cell, of which the cell temperature is also recorded. In these five days, the temperature range was in the order of 20 to 60 ^{o}C (see Fig. 2). Daily ambient temperature variations are typically in the range of 25 to 35 ^{o}C, depending on the time of the day. Results from a least squares fit were used in the rest of the analysis to obtain half-hourly module temperature estimates based on insolation, with an estimated error of about 3 ^{o}C.

Insolation measurements

Measuring insolation in solar systems is usually done with a reference cell that is attached in the same plane as the PV-array. Because only 4 data channels were available, we have chosen not to measure insolation at each solar home system site. Instead, we expected to obtain insolation from a logger, attached to one of the solar homes systems in Polinggona as part of a World Bank project (see figure 3 for a map of the monitoring area with the 9 data loggers installed by BPPT-ECN and the World Bank logger). The World Bank logger uses a reference cell to measure insolation. Fraunhofer ISE in Freiburg, Germany, has built the data acquisition system for the World Bank project around a Gantner datalogger. Two months of reference cell measurements are used to validate the new method.

Validation with 3 days of insolation measurements

At one of the solar home system locations, a MacSolar was installed for a few days in October 2003. It had been calibrated before at ECN by comparing it to a reference module that was calibrated by JRC Ispra. The resulting difference was within ±1%. For the field measurements, the MacSolar was placed horizontally on the roof of Toeng's new house in Pewisoa Jaya that has an un-obstructed horizon in all directions.

Satellite data for validation purposes

With the objective to support the design of solar systems for remote areas where measurement stations are limited, NASA developed the Surface meteorology and Solar Energy (SSE) database. Access is free via internet. The SSE data set is a continuous and consistent 10-year global climatology of insolation and meteorology data on a 1° by 1° grid system. Satellite data over the period 30th June 1983 to 1st July 1993 have been used as input for the SSE database. Release 4 has been used for our analysis. Comparison by NASA with ground based measurements showed an estimated uncertainty of 10 to 17% (RMS) and a bias error of +3% (NASA 2003).

3. Procedure for estimating daily irradiation figures

The procedure to construct a time series of daily irradiation figures uses only two measured parameters: battery voltage V_S and PV-module current I_A. Half-hourly averages of PV-module currents are measured when the battery is being charged. Module currents and voltages are used in a one-diode model to determine the photocurrent, which is directly related to irradiance in the module plane. Deviations between calculated

photocurrents and insolation occur when the battery is full and charging is cut off by the charge regulator, or when there is shading. To reduce these two effects, data of a number of different solar systems are combined. It is unlikely that full batteries or shading occurs with all the systems at the same time.

Four steps are required to calculate insolation from PV module currents. These are described in subsections 3.1 to 3.4:

1) calculation of photocurrents from PV-module currents;

2) scaling of photocurrents to obtain in-plane irradiance by equating maximum photocurrent in a year to maximum clear sky irradiance;

3) conversion of in-plane irradiance to global horizontal irradiance;

4) combining global horizontal irradiance data of different solar systems to calculate daily global horizontal irradiation that is representative for a larger area.

In Figure 4, a flow chart is presented of the first three steps to obtain a half-hourly average value of global horizontal irradiance for an individual solar system (steps 1 to 3).

3.1 Calculating photocurrents based on PV module currents

The current-voltage (I-V) characteristic of a PV module can be described with a one-diode equation. Generally the short circuit current I_{sc} is related to the photocurrent I_L, which is directly related to the in-plane irradiance G_I whenever spectral effects can be ignored and temperature is constant. It increases with increasing temperature since semiconductor band-gaps generally decrease with temperature. In this section the photocurrent is estimated, based on the measured module current I_A.

I-V characteristic of a PV module

The standard one-diode model of an illuminated PV-module consists of a current source, a diode and a shunt resistance R_{sh} in parallel, and a resistance R_s in series. Module current I and voltage V are related as follows (Duffie and Beckman, 1991):

$$I = I_L - I_0 \left(e^{\frac{V + IR_s}{nV_T}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

I_0 is the diode reverse saturation current, which strongly depends on temperature and is typically in the order of microamperes. The fit parameter n is known as the *ideality*-, or *diode quality factor*, which varies between 2 at low currents and 1 at higher currents (Green, 1998). V_T is defined as:

$$V_T = \frac{kT_m N_s}{q} \quad (2)$$

in which q is the elementary charge (1.602 10^{-19} C), k the Boltzmann constant (1.381 10^{-23} J/K), and N_s is the number of cells in series. V_T is linearly related to the module temperature T_m.

Temperature dependence of I-V-curve parameters

      To determine module temperature based on the relation with irradiance as shown in Fig. 2, estimated insolation is sufficient. Insolation is assumed to be linearly related to the module current, with a scaling factor that is determined by equating the maximum module current in a year to the maximum clear sky irradiance (G_{cs}) in a year. This results in the following relation for a first estimate of in-plane irradiance $G_{I,\,est}$ [W/m^2] that is only used for calculating module temperatures:

$$G_{I,est} = \frac{annual\ \max(G_{cs})}{annual\ \max(I_A)} I_A \quad (4)$$

This estimated irradiance is used with the empirical relation between cell temperature and insolation of Fig. 2 to obtain calculated PV module temperatures for the whole 2.5-year measurement period. In the rest of the analysis, the following empirical relation is used for the module temperature [in kelvin]:

$$T_m = 294.4 + 0.03717 G_{I,est} \quad (5)$$

      For irradiance estimates based on measured module currents it is crucial to explicitly include temperature effects of the module. According to Townsend (1989), the parameters of many PV modules obey the following temperature dependence in relation to a reference temperature $T_{m,\,ref}$ (e.g., at the STC temperature of 298K):

$$V_T = V_{T,ref} \left(\frac{T_m}{T_{m,ref}} \right) \qquad (6)$$

$$I_0 = I_{0,ref} \left(\frac{T_m}{T_{m,ref}} \right)^3 \exp\left[\frac{E_g N_s}{n V_{T,ref}} \left(1 - \frac{T_{m,ref}}{T_m} \right) \right] \qquad (7)$$

with E_g the band-gap energy of 1.12 eV for silicon, and N_s the number of cells in series (36 for the MSX53).

When the conditions for an open circuited module are entered in Eq. (1) and solving for I_0, while using Eq. (7) and (3), the reverse saturation current at the reference temperature, $I_{0,ref}$ can be determined:

$$I_{0,ref} = \left[\left(1 + \frac{R_s}{R_{sh}} \right) I_{sc} - \frac{V_{oc}}{R_{sh}} \right] \exp\left(- \frac{V_{oc}}{n V_{T,ref}} \right) \qquad (8)$$

With the module parameters of Table 1, $I_{0,ref}$ amounts to 0.116 µA. With cell temperatures in the range of 20 to 60 ºC, the reverse saturation current I_0 varies between 0.062 and 5.53 µA

Calculation of the photo current

Based on half-hourly averages of module current I_A and voltage V_A, the light current I_L can be calculated by using Eq. 1:

$$I_L = I_A + I_0 \left(e^{\frac{V_A + I_A R_s}{n V_T}} - 1 \right) + \frac{V_A + I_A R_s}{R_{sh}} \qquad (9)$$

Assumptions on PV module parameters for modelling of the I-V curve

Field measurements of the module parameters were not accurate enough to be useful. Therefore we assume typical values for V_T, R_s and R_{sh} and use the manufacturer's data sheet for values of V_{oc} and I_{sc}. The

simulation tool PVSYST of the University of Geneva (PVSYST) recommends using a constant diode quality factor $n = 1.3$ for polycrystalline modules, resulting in a value for $nV_{T,ref}$ of 1.2 V for 36-cell modules. PVSYST also recommends using a default module shunt resistance R_{sh} of 200 Ω. Most poly-crystalline modules with 10 x 10 cm^2 cell tested at ECN have a series resistance in the order of 10 mΩ per cell. 10 metre of 2.5 mm^2 cable to connect the module to the charge regulator, results in an additional resistance of 70 mΩ. To account for contact resistance and some module degradation, another 50 mΩ is assumed, resulting in a total series resistance of 0.48 Ω. In Table 1 the module parameters are presented that have been used in the IV-curve modelling.

An example of calculated photocurrents using module parameter values of Table 1 and measured values of battery voltages V_s and module currents I_A is shown in Fig. 5. For the module currents at the high insolation end, the photocurrent is about 20% higher than the measured module current. This difference is mainly determined by the diode term in Eq. 9. The offset from a straight line has a value of about 15 V/200 Ω = 75 mA, and is caused by the right hand term in Eq. 9.

All systems show similar graphs as shown in Fig. 5. It can be concluded that the assumption that irradiance is proportional to the module currents (the straight line in Fig. 5) is a first estimate that leads to errors up to about 20%.

3.2 Time series of in-plane irradiance per solar home system

In this section, the steps are described to convert photocurrents into in-plane irradiance. With a clear sky model, the maximum clear sky irradiance is related to the highest values of the photocurrent in a year. To be able to select a maximum value in a frequency distribution of photocurrents, a small correction has to be applied to take into account variations in the distance from the earth to the sun. It is only a small correction, but easy to apply and helpful in reducing the spread in the distribution of the photocurrents (see Fig. 6).

Compensation for seasonal variations in the earth-sun distance

Differences of the earth-sun distance of about 1.7% over the year, result in a variation of the extraterrestrial solar flux G_{0m} in a plane normal to the radiation of about 3%, with G_{sc} the solar constant of 1367 W/m^2 (Duffie and Beckman, 1991):

$$G_{0m} = G_{sc}\,\varepsilon_{ES} \qquad (10)$$

where ε_{ES} is the correction for the earth-sun distance on day m of the year:

$$\varepsilon_{ES} = 1 + 0.033\cos\left(\frac{360m}{365}\right) \qquad (11)$$

The time series of light current I_L can now be normalised to the average distance according to:

$$I_{Lnorm} = \varepsilon_{ES}^{-1}\,I_L \qquad (12)$$

Maximum light current throughout the year

A typical frequency distribution function of normalised light currents of a PV module in Kolaka is shown in Fig. 6. A photocurrent of 3.2 A corresponds to the maximum clear sky irradiance. With reflection of direct light on clouds, irradiance can reach 1300 W/m^2 for short periods of time (seconds to minutes). Usually, half-hourly averages are below 1000 W/m^2. However, in a small number of half hourly periods high irradiance can persist, which then results in a higher irradiance figure than the clear sky maximum.

Global clear sky irradiance

On a clear day, the global horizontal clear sky irradiance G_{cs} can be modelled as follows [Rigollier et al. 2000]

$$G_{cs} = \alpha\ \ G_{sc}\varepsilon_{ES}\left(\cos\theta_z\right)^{1.15} \qquad (13)$$

where α depends on the turbidity of the atmosphere. According to a model of Bourges (1979) $\alpha = 0.70$, while according to a model of Perrin de Brichambaut and Vauge (1982) $\alpha = 0.81$. Two measurements of global

horizontal irradiance at different times on the same clear day in the rainy season in Kolaka resulted in an average value of $\alpha = 0.765$. It implies a maximum clear sky irradiance, when the sun is in zenith, of 1045 W/m^2.

Scaling of light currents to in plane irradiance

Due to the small tilt angles of the PV-modules in Kolaka, part of the year, the sun will be exactly perpendicular to each module. It is very likely that a few times a year the sun is more or less perpendicular to the PV module when the sky is clear. Therefore, it can be safely assumed that the maximum value of the light current in a year takes place at the time of maximum clear sky irradiance in the module plane. This provides the means to gauge the photocurrent time series and to convert them into in-plane irradiance values:

$$G_I = \frac{annual\ \max(G_{cs})}{annual\ \max(I_{L,norm})}\ I_L \qquad (14)$$

3.3 From in-plane to horizontal global insolation

To make time series from different solar systems comparable, the next step is to transform each series from in-plane to global horizontal insolation. The isotropic diffuse model of Liu and Jordan relates insolation on a tilted plane to horizontal insolation (Duffie and Beckman, 1991). When the PV module tilt angle β is small, ground reflection can be ignored, which results in the following relation between G_I and the beam component (G_b) and diffuse component G_d of G (with R_b a geometrical factor depending on the position of the sun in relation to the module):

$$G_I \quad = \quad G_b R_b + G_d \left(\frac{1 + \cos(\beta)}{2} \right) \qquad (15)$$

The hourly clearness index k_T is defined as the ratio between the hourly horizontal insolation at the earth surface and hourly horizontal insolation at the top of the atmosphere:

$$k_T \quad = \quad \frac{G_h}{G_0} \qquad (16)$$

For the diffuse component G_d the empirical model of Erbs et al. (1982) was used, which states the following relations for the ratio between hourly diffuse and total insolation as a function of the hourly clearness index:

$$\frac{G_d}{G} = 1.0 - 0.09k_T \quad for \ k_T \leq 0.22 \qquad (17a)$$

$$\frac{G_d}{G} = 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 \quad for \ 0.22 \leq k_T \leq 0.80 \quad (17b)$$

$$\frac{G_d}{G} = 0.165 \quad for \ k_T \geq 0.80 \qquad (17c)$$

Since we start with insolation figures in a tilted plane and want to calculate the horizontal component, the value of k_T is not directly known. In an iterative procedure, in plane irradiance G_I is used as a starting value for the horizontal insolation G_h for the calculation of k_T. This iterative procedure is stopped when the difference between the calculated G'_I and the originally measured G_I is less than 0.01%. Usually this occurs within 10 iteration steps.

3.4 Combining time series of global horizontal irradiance of nearby systems

The objective of our procedure is to obtain reliable daily and monthly insolation figures that are representative for an area of one or more villages. Each individual time series of module currents is unreliable, because part of the time one can expect shading or a full battery. For a single system, this will result in an underestimate of the insolation during these periods of the day. By comparing half-hourly data from different systems, and discarding the data from systems that are substantially lower than the others, one can reduce the chance of underestimation of the daily insolation of the area. An example of the effect of shading is shown in Fig. 7.

Exclusion of outliers

In combining the values from different systems, there is an asymmetry in the direction of expected outliers. In none of the time series there have been any indication of measured module currents that are higher than the value that could have been expected for that time of the day. On the other hand, all time series show now and then lower values than expected, see, e.g., Fig. 8. A procedure for discarding outliers only has to focus on outliers in the down side direction.

Differences are expected in the starting times of the half hour periods of the different data loggers, resulting in a maximum error of ± 0.25 hours in overlaying the time series of different systems. Maximum effect

of half an hour shift in the clear sky radiation (Eq. 13) is a difference of about 125 W/m^2. With some extra margin for measurement errors, a difference of 150 W/m^2 with the maximum value within that half an hour is used as the maximum difference before a measurement is classified as an outlier. Half hourly irradiance values that are representative for the area are calculated by taking the average of those values that differ less than 150 W/m^2 from the maximum. An example of how this procedure works out for four systems in the village of Polinggona is shown in Fig. 8. Two of the four systems do not contribute to the average value for Polinggona between 10.00 and 16.00, because they differ more than 150 W/m^2 from the maximum. From 12.30 and 13.30 the Polinggona average is based on one system only.

Results of the outlier removal procedure

The four systems in Polinggona show the longest uninterrupted series of data. With the help of this procedure, a two-and-a-half year time series of daily irradiation in Kolaka has been calculated that can be compared to other sources. The calculated insolation for 2002 is shown in Fig. 9.

3.5 Error estimates

A number of systematic errors affect the annual average of calculated irradiation figures:

a) Shading will decrease irradiance in the beginning and end of the day. The resulting systematic error in calculated daily irradiation is estimated to be around -2 to -3%.

b) To compensate for possible shading or a full battery at individual systems, only those insolation measurements are included that differ less than 150 W/m^2 from the maximum value. The lower this value, the higher the calculated daily irradiation figures.

c) Maximum clear sky irradiance was calculated to be 1045 W/m^2 based on two measurements. The estimated error is ± 5%.

d) The maximum light current during a year (based on figure 7) has an estimated error of about ±0.15 A, which is equal to about ±5%.

e) Maximum expected difference in starting times of the loggers is 30 minutes. This results in an overestimation of the annual average by about +3%.

f) Weather differences within the area will also lead to an overestimate of the annual average. In a flat area, with similar distances to the seashore, errors due to weather effects are estimated to be in the order of +1%

when systems are within a radius of 1 kilometre, as is the case for Polinggona. It is estimated to be in the order of +5% when systems are included at distances of 10 kilometres.

g) Furthermore, there is still a small chance that all included systems experience a full battery or shading at the same time, resulting in an underestimate of actual insolation.

Combining the systematic errors from the above sources, the total systematic error in the annual average irradiation is estimate to be in the range from 10 to 15%. When it is possible to check the calculated figures against direct measurements over a limited period of time (a few weeks to a few months), the systematic error is in the same range as that of the reference cell: 5 to 10%.

4. Validation

Three different data sets have been used to validate the proposed method. They are all three less than ideal for the purpose of direct comparison. Three days of horizontal insolation measurements have the disadvantage that they were obtained at a distance of 11 kilometres from Polinggona, where the four loggers are located on which the calculated insolation was based. Another series of two months of reference cell measurements was made at the right location: the centre of Polinggona village. But these measurements were made in a 10° tilted plane, requiring transformation to a horizontal plane first before a comparison can be made. Monthly averages of insolation based on historical climate data from satellites allow for identification of large systematic errors. But calculated monthly insolation averages can be outside ten-year climate extremes due to extreme weather conditions. However, all three combined, results in a sufficient level of validation of the proposed method.

4.1 Comparison with on site insolation measurements

In October 2003, horizontal insolation was measured continuously over a five-day period with a MacSolar at the new house of Toeng in Pewisoa Jaya. Table 2 shows for the three full days in the five-day measurement period that the calculated values are on average about 5% below the measured daily irradiation

values. Part of the differences can be attributed to the distance of 11 kilometres between the measurement site and Polinggona. To eliminate this distance effect, in the following section, another set of measurements were used, coming from Polinggona.

4.2 Comparison with reference cell in Polinggona

Two months of insolation measurements with a reference cell from a World Bank project data logger were used to validate the calculated insolation figures. With the same procedure as described in section 3.3, the measured insolation in the tilted plane of the World Bank logger was converted to horizontal insolation. First, the four systems in Polinggona were used to calculate daily global horizontal insolation. A comparison of calculated and measured values over a two-month period in 2001 is presented in Fig. 10. On average, the calculated values for Polinggona are only 0.07 kWh/m^2/d (1.3%) higher than the measured values. The standard error amounts to 0.24 kWh/m^2/d (5%), the RMSE = 0.26 kWh/m^2/d (5%), and R^2 amounts to 0.971. Three of the four loggers in Polinggona are only 100-200 meters from the World-Bank logger, and the fourth about 600 meters. It can be concluded that there is a very good correlation between measured and calculated values when the loggers are not too far apart (within about 1 km).

Data from 8 loggers in Polinggona, Pewisoa Jaya, and Popalia were combined to calculate a time series of insolation that is supposed to be representative for the Kolaka region, an area of about 10 by 10 kilometres. Figure 11 shows that the comparison with the measured data is not very well: the calculated values are on average 0.58 kWh/m^2/d (11%) higher than the measured values (R^2 = 0.942). The standard error is 0.31 kWh/m^2/d (6%), and the RMSE 0.66 kWh/m^2/d (13%). On top of the weather differences between the four villages, there is another effect that influences the calculated values. The more time series are included to calculate the insolation, the higher the average calculated value of the insolation becomes. The reason is that for calculation of the half-hourly insolation value, only those registrations are included, which differ less than 150 W/m^2 with the maximum of all loggers for that half-hour period. Adding data from an additional logger results in maximum values of half-hourly insolation that are either the same or higher.

4.3 Comparison with satellite data of monthly averages

There is no meteorological station near Kolaka that could provide a basis for comparison. Satellite cloud cover and radiation data over a 10-year period are the basis for the NASA Surface meteorology and Solar Energy (SSE) data base (NASA, 2003). The SSE data set represents the average climate in a 1° by 1° grid pattern. Average monthly irradiation figures are compared in Fig. 12. Annual average insolation of the satellite data is 4% higher than the average calculated using PV-module currents. When the monthly values in the Polinggona data are averaged over two or three years and compared on a monthly basis with the satellite data, the mean bias error is -3.9%, with a standard deviation of 6.4% and a maximum difference of -15.9%. Only in 3 of the 32 months, the SHS data were more than 0.1 kWh/m^2/day below the 10-year minima of the satellite data. Taking into account the NASA-reported +3% bias of the satellite data, it can be concluded that there is an excellent agreement between these two data sets.

5. Discussion

We have shown here that it is possible to calculate a time series of daily irradiation figures based on measured PV-module currents, that closely matches measured values of daily and monthly insolation. However, there are a number of remaining uncertainties. If distances are around 1 km, weather differences need not be regarded. But at 10 km distance, differences in weather at the different locations, results in an overestimation of insolation, especially on cloudy days. A more accurate determination of the distance over which weather differences can be omitted needs further investigation, which was not possible in the framework of our current monitoring work in Indonesia.

Validation of the methodology was only limited to a single area. Close to the equator, where PV-modules are placed almost horizontally, the required transformation from tilted to horizontal irradiance does not involve a large correction. Expected errors will become larger at higher latitudes. Future work is required to verify the procedure also for other locations, preferably further (>30°) from the equator.

The proposed method allows for determination of the absolute level of irradiation. However, the errors can be substantial, and are in the same order of magnitude as with the use of historical data based on satellite data (10-15%). Whenever the calculated irradiation figures can be compared or scaled with a short time series of

locally measured data, the error in the absolute level of irradiation will be at about the same level as direct insolation measurements with a reference cell (5-10%). The usefulness of this method depends on what is an acceptable error level. If an error of 15% is acceptable, and monthly averages are sufficient, then it is much easier to use historical satellite data. If the error has to be 10% or less, or if daily insolation values are required, then it is worth spending the effort in calculating insolation with this method.

Soiling of the PV-modules reduces output and affects the calculated insolation figures. In case of gradual accumulation of dust on the modules, calculated insolation is overestimated before the moment with the highest module current in a year, and underestimated afterwards. In practice, rain will often wash away part of the dust. If modules are not cleaned manually, part of the dust will stick and cause module output to decrease gradually over the years. One of the advantages of the presented method over direct measurements of insolation with a reference cell is that for a multi-year period our method is less affected by soiling of the reference cell or PV-modules and long term degradation of the solar cells. Each year a sort of calibration takes place, relating maximum module current to maximum clear sky irradiance. This renders our method insensitive for degradation of module output over the years.

Whenever a choice is possible, direct measurements of insolation are preferred over the presented method of constructing a time series of insolation based on PV-module currents. The above mentioned advantage of insensitivity for long-term degradation does not weigh as much as the disadvantage of having to use a complex calculation method with a number of uncertainties.

6. Summary and conclusions

A method to estimate daily irradiation data is presented here. It is based on the correlation of a number of measured PV-module currents and battery voltages of solar home systems that are located within small distances from each other. Such a method is a useful tool in evaluation of the performance of these systems, as often, local irradiation data are not available.

Three different ways to validate the methodology to use PV-module currents to calculate insolation all come up with consistent outcomes. Comparison with three days of reference cell measurements and with satellite data suggests that the module current approach underestimates the insolation by 5% and 4% respectively. On the other hand, the two months of reference cell measurements in Polinggona show an overestimate of insolation by 1 to 3%. These findings support an error estimate of 5-10% for the monthly averages in case there is time series

of a few weeks or months of actual measurement with which the calculations can be compared. If such measurement series is missing, the estimated systematic error is 10 to 15%, which is in the same order as the error in the monthly satellite data (10-17%). It can be concluded that using PV module currents of a number of nearby solar systems provides a means of obtaining reliable estimates of daily and monthly irradiation whenever actual measurements are absent or unreliable. Especially, when daily insolation data is required this method provides useful complementary information to the readily available satellite data that are limited to monthly averages.

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Table 1. Module parameters used in the IV-curve modelling

	Manufacturer's data sheet	Assumed
	BP-Solarex MSX-53	
Short circuit current I_{sc}	3.4 A	
Open-circuit voltage V_{oc}	20.6 V	
Diode quality factor n		1.3
$nV_{T,ref} = nkTN_s/q$		1.2 V
Series resistance R_s		0.48 Ω
Shunt resistance R_{sh}		200 Ω
Band gap silicon E_g		1.12 eV
Number of cells in series	36	

Table 2. Comparison of measured values of global horizontal insolation in Pewisoa Jaya with calculated

insolation based on four solar home systems in Polinggona at 11 km distance.

Day in 2003	Calculated	Measured (MacSolar)	Difference
	[kWh/m^2/day]	[kWh/m^2/day]	[%]
October 10th	5.69	5.59	+1.8
October 11th	6.15	6.63	-7.3
October 12th	4.48	4.92	-9.0
Average	5.44	5.71	-4.8
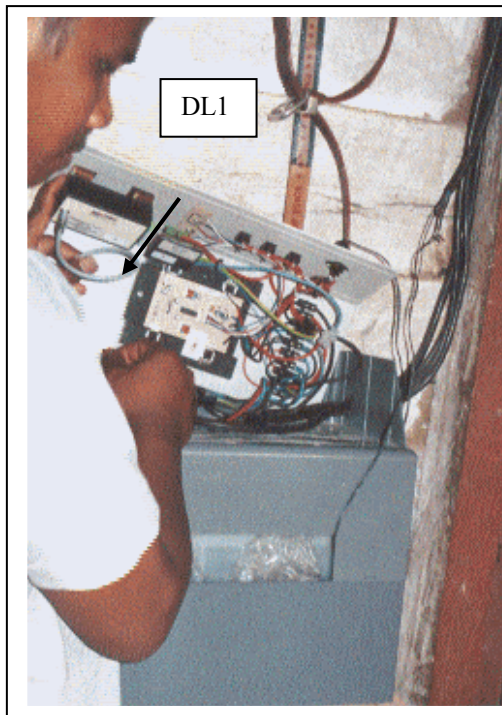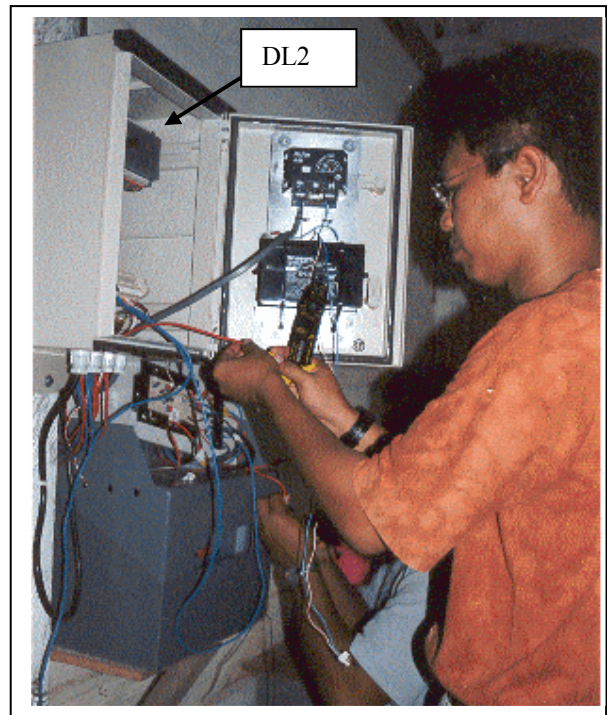
(a)   (b)

Figure 1. Solar home system battery box (grey box at bottom of (a) and (b)) with two different dataloggers in Kolaka, Indonesia. Fig. 1a shows the small Sentry datalogger (marked DL1), which is integrated in the battery box. The rest of the electronics is the battery charge regulator. Fig. 1b shows the more complex logger from another project (marked DL2) from which we expected to obtain insolation data.
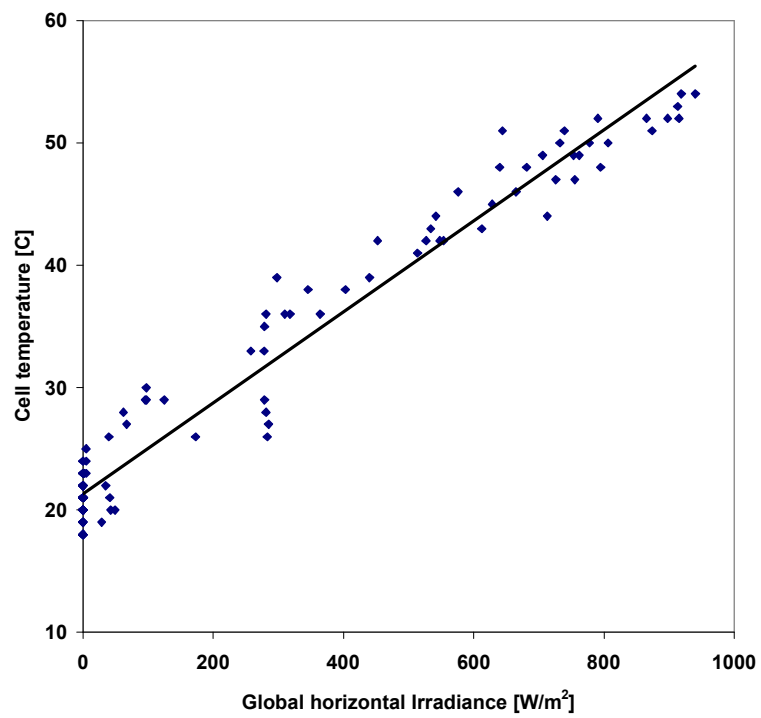
Figure 2. Relation between hourly averages of reference cell temperature and global horizontal irradiance in a five day measurement series in Pewisoa Jaya in October 2003. Measured with a MacSolar of (Solarc).
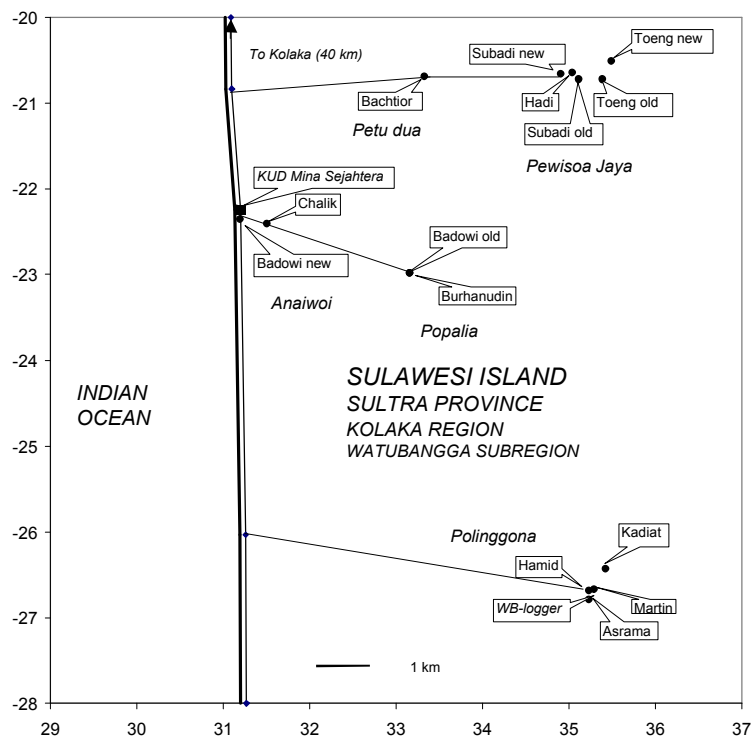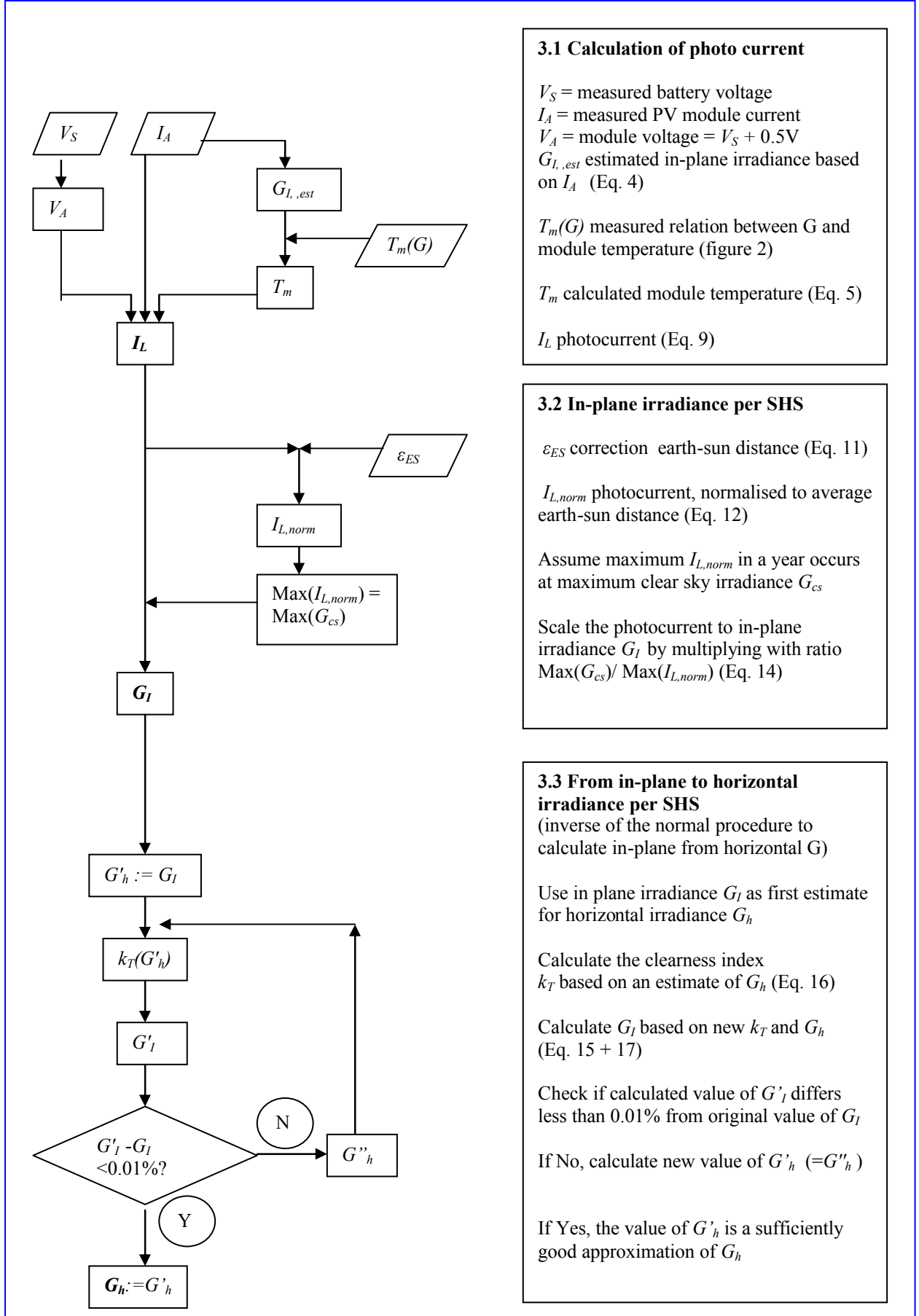
Figure 3. Map of Kolaka, Sulawesi, with the 9 BPPT-ECN dataloggers and the World Bank logger. Horizontal: longitude in minutes (+121° East), vertical: latitude in minutes (-4° South). KUD Mina Sejahtera is the co-operative responsible for installation and maintenance of the solar home systems.

Figure 4. Flow chart for calculating one half-hourly value of global horizontal irradiance for a solar system based on measured battery voltage and module current, of a non-horizontal PV module.

3.1 Calculation of photo current

V_S = measured battery voltage
I_A = measured PV module current
V_A = module voltage = V_S + 0.5V
$G_{I,\,est}$ estimated in-plane irradiance based on I_A (Eq. 4)

$T_m(G)$ measured relation between G and module temperature (figure 2)

T_m calculated module temperature (Eq. 5)

I_L photocurrent (Eq. 9)

3.2 In-plane irradiance per SHS

ε_{ES} correction earth-sun distance (Eq. 11)

$I_{L,norm}$ photocurrent, normalised to average earth-sun distance (Eq. 12)

Assume maximum $I_{L,norm}$ in a year occurs at maximum clear sky irradiance G_{cs}

Scale the photocurrent to in-plane irradiance G_I by multiplying with ratio Max(G_{cs})/ Max($I_{L,norm}$) (Eq. 14)

3.3 From in-plane to horizontal irradiance per SHS
(inverse of the normal procedure to calculate in-plane from horizontal G)

Use in plane irradiance G_I as first estimate for horizontal irradiance G_h

Calculate the clearness index k_T based on an estimate of G_h (Eq. 16)

Calculate G_I based on new k_T and G_h (Eq. 15 + 17)

Check if calculated value of G'_I differs less than 0.01% from original value of G_I

If No, calculate new value of G'_h (=G''_h)

If Yes, the value of G'_h is a sufficiently good approximation of G_h
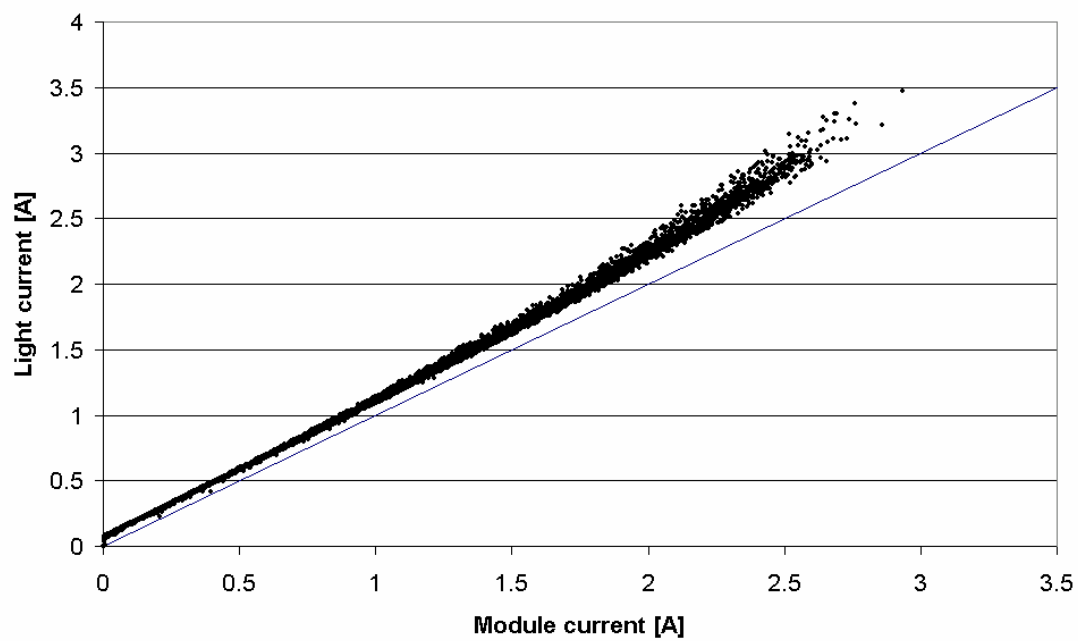
Figure 5. Calculated light current versus measured module current of Toeng's solar home system in 2002,

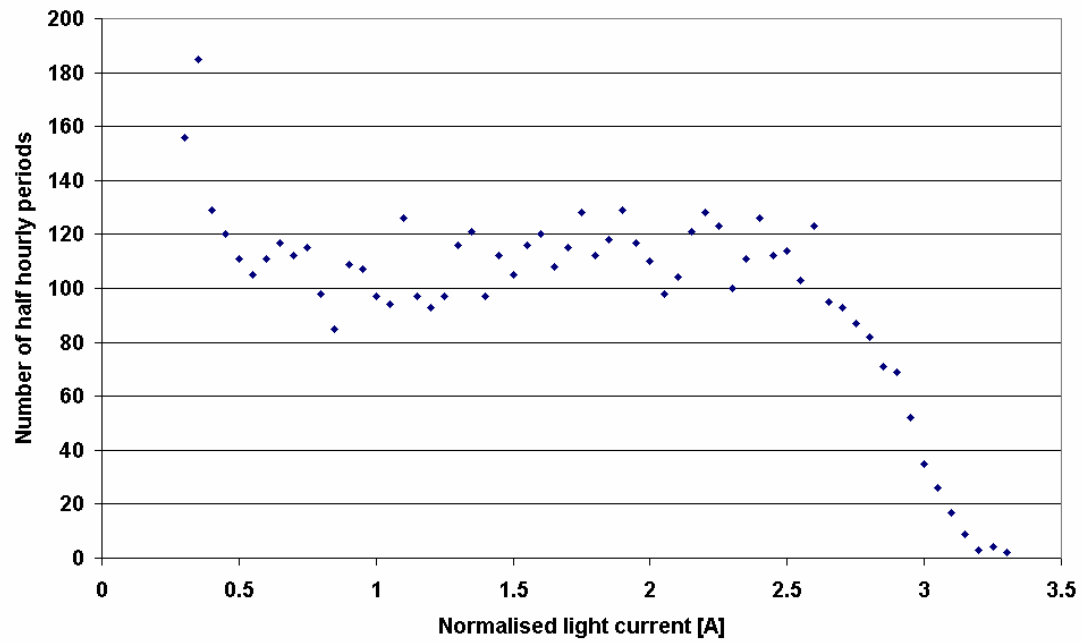showing that the light current is 20% higher than the module current at the high insolation end.

Figure 6. Frequency distribution of the photocurrent I_{Lnorm}, normalised to the average earth-sun distance, of Burhanudin's solar home system in 2002.
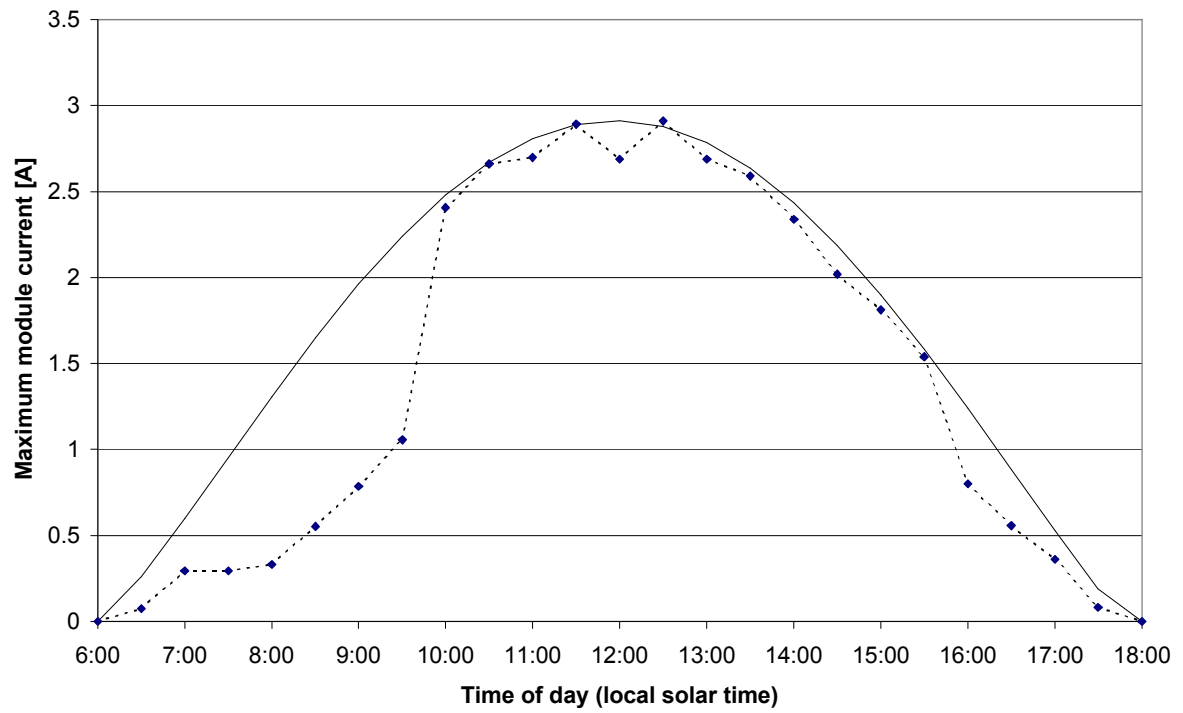
Figure 7. Measured monthly maximum module current of SHS of Hamid in Polinggona (dots), and calculated clear sky irradiance, during May, 2001. Before 10 A.M. there is substantial shading.
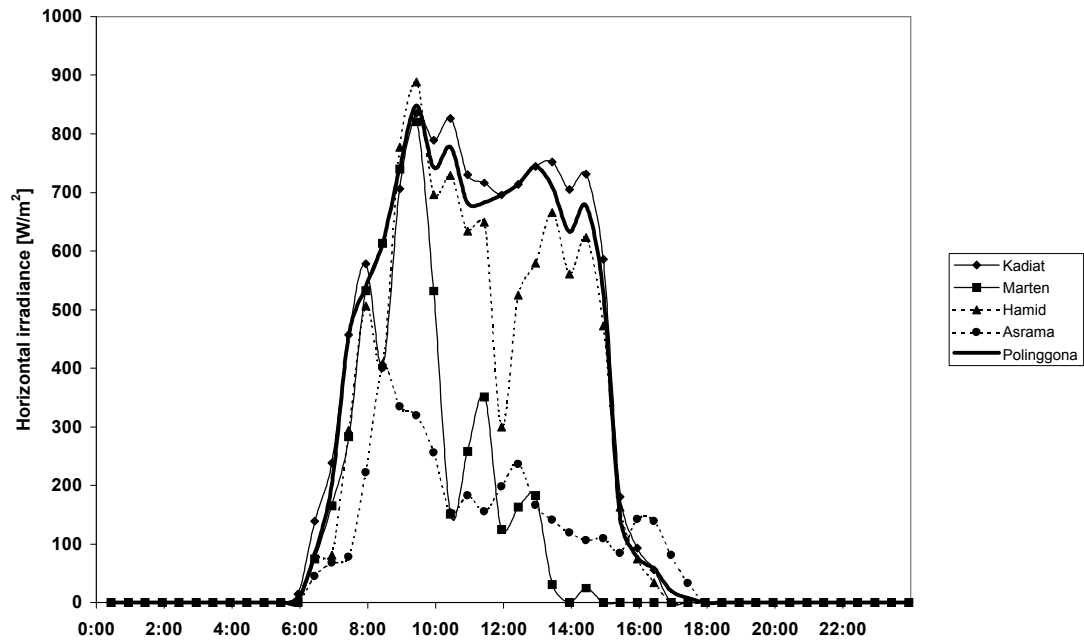
Figure 8. Calculated global horizontal irradiance of four individual systems (Kadiat, Marten, Hamid, Asrama) in Polinggona village and their combined value (Polinggona) on 10 October 2003.
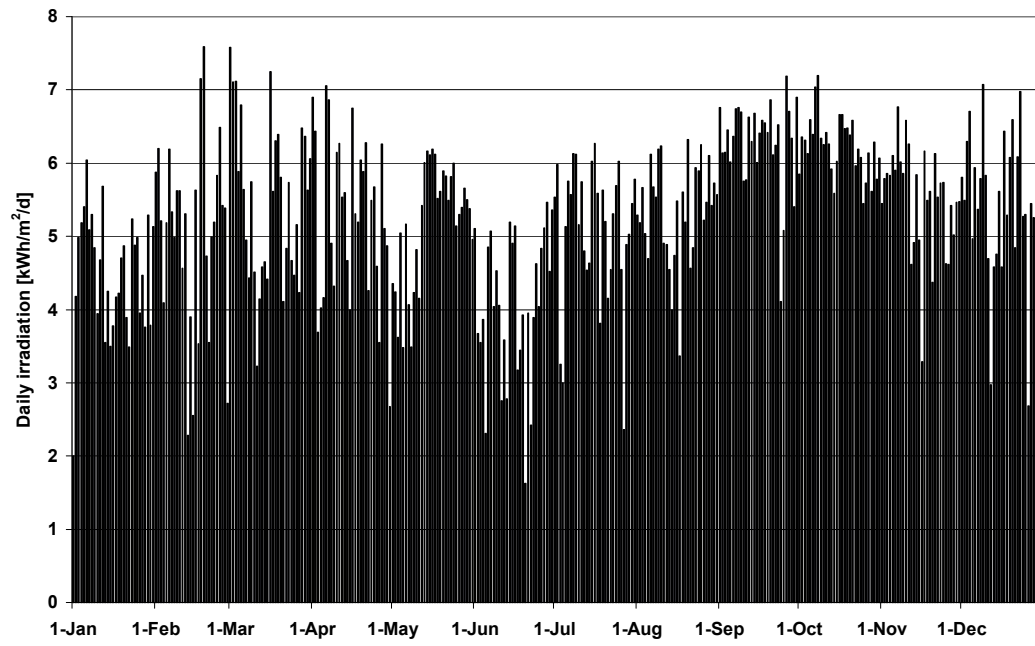
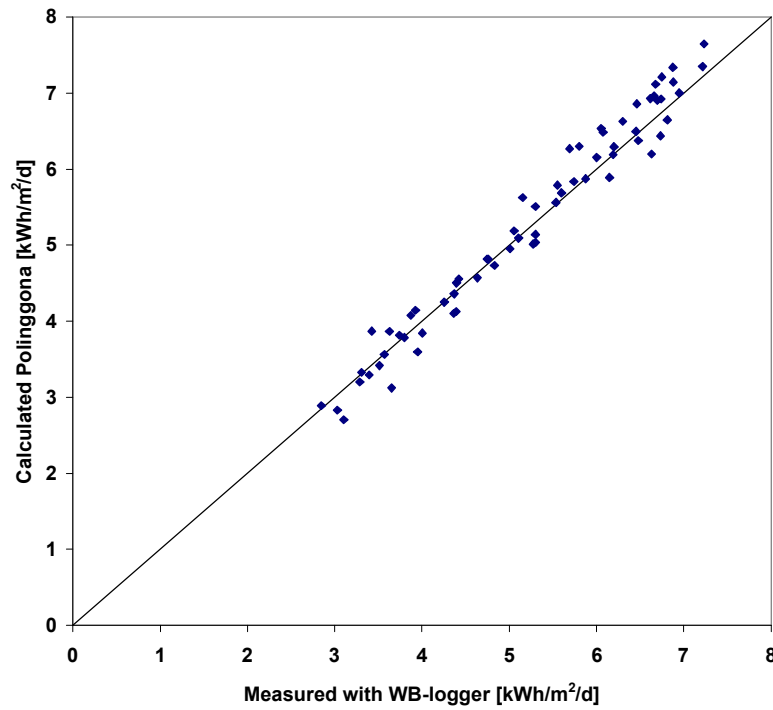Figure 9. Calculated daily irradiation in 2002 in Polinggona in kWh/m^2/day

Figure 10. Comparison of calculated daily irradiation figures based on the four dataloggers in Polinggona with World Bank datalogger measurements in Polinggona over the period of September 17th to November 22nd 2001.
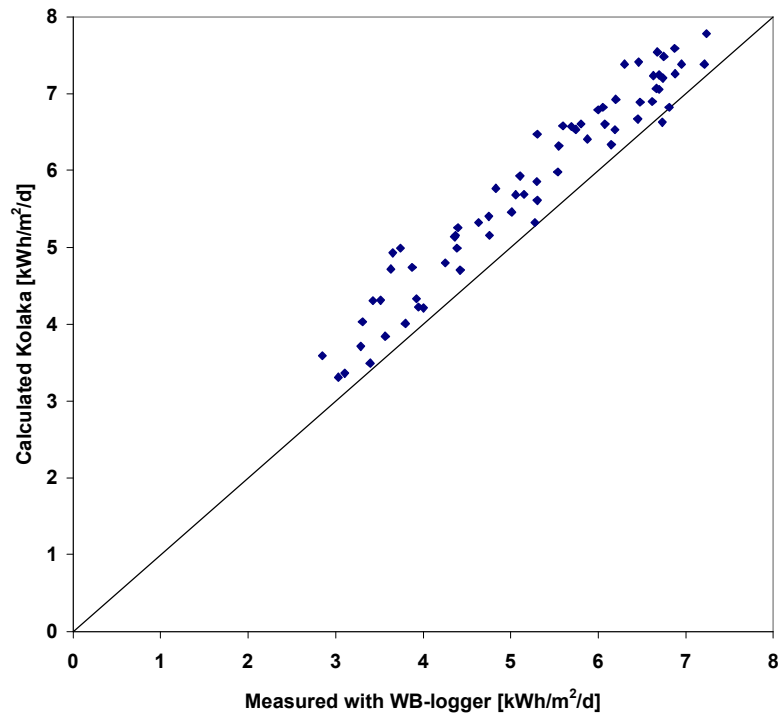
Figure 11. Calculated daily irradiation figures for Kolaka based on all 8 data loggers compared with World Bank data logger measurements in Polinggona over the period of September 17th to November 22nd 2001.
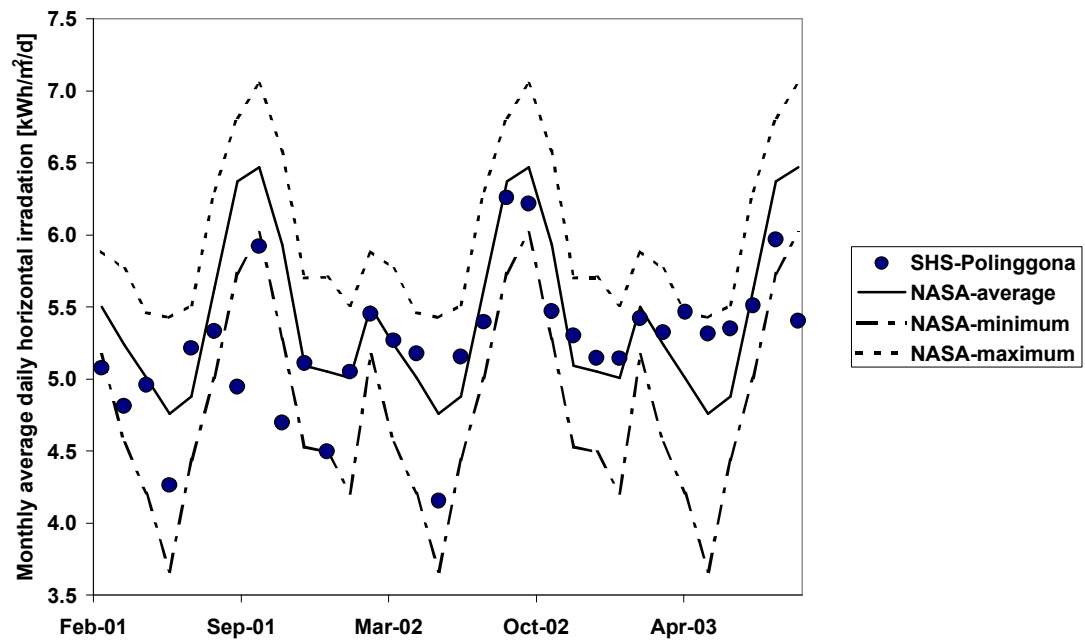
Figure 12. Calculated monthly average irradiation in Polinggona over the period March 2001 to October 2003, compared with NASA satellite-based climate data. For the satellite data, 10-year averages, and 10-year extremes are presented.