Calorimetric Measurement for Internal Conversion Efficiency of Photovoltaic Cells/Modules Based on Electrical Substitution Method

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Abstract. We have succeeded in the direct measurement for solar cell/module internal conversion efficiency based on a calorimetric method or electrical substitution method by which the absorbed radiant power is determined by replacing the heat absorbed in the cell/module with the electrical power. The technique is advantageous in that the reflectance and transmittance measurements, which are required in the conventional methods, are not necessary. Also, the internal quantum efficiency can be derived from conversion efficiencies by using the average photon energy. Agreements of the measured data with the values estimated from the nominal values support the validity of this technique.

1. Introduction
Among the characteristics on solar cells/modules, power conversion efficiency is essentially important. The external power conversion efficiency is defined as the ratio of the electrical power generated to the radiant power incident to the solar cell/module under the IEC Standard Test Conditions \cite{1}. While the evaluation for the output, the electrical power, can be conducted very easily, the evaluation for the input, the radiant power, typically needs defined measurements and corrections \cite{1} based on a standard cell using specialized instruments, and therefore it can be done only at limited laboratories \cite{2}.

From the viewpoint of material physics, the internal conversion efficiency, which is defined by the electrical power generated to the radiant power absorbed, is more important than the external one. In addition, there exists needs for efficiency measurement technique usable under spectrally and/or angularly diverted conditions (for instance, under oblique incidence condition) from the Standard Test Conditions.

To meet such needs, we aim to directly determine the internal conversion efficiency by utilizing the electrical substitution technique for solar cells/modules under test by applying forward bias current to the test cells/modules, and to evaluate if the technique is feasible. The technique to calorimetrically determine the internal quantum efficiency was developed by T. Inoue et al. for photodiodes receiving a laser beam \cite{3}. This is a first attempt to our knowledge to apply the technique to photovoltaic modules receiving non-monochromatic radiation to determine directly the internal conversion efficiency and derive the external one together with internal/external quantum efficiencies.

2. Principle of Operation
In our technique, the absorbed radiant power is determined by a calorimetric method in which the heat absorbed in the solar module is substituted by the electrical power applied to the solar cell as
illustrated in Figure 1. When the module is illuminated as shown on the left, a part of the incident radiant power, $P_i$, is reflected by (and transmitted through) the semiconductor substrate and the rest power is absorbed by the substrate. In the case when the module is open or shorted, all the absorbed power, $P_a$, is converted to the heat, $P_h$. In the case when the module is connected to a load, a part of the absorbed power is converted to the electricity, $P_m$, and the rest power generates the heat, $P_h$. When the incident radiation is shielded as shown on the right, the module temperature goes down. In this dark condition, the electrical power is applied from a power supply and is adjusted so that the module temperature becomes equal to the one in an illuminated condition. We can assume that the substituted electrical power is equal to the thermal power, or the absorbed radiant power in the case of an open- or short-circuit condition. When the load is connected, the absorbed radiant power is equal to $P_h+P_m$, the sum of the substituted electrical power and the power supplied to the load.

Since the maximum electrical power generated can be easily measured, the internal conversion efficiency is directly determined. External conversion efficiency and internal/external quantum efficiencies can also be obtained as we will see in the next section.

![Figure 1. Schematics to show the electrical substitution technique for solar modules.](image)

3. Analysis

3.1. Average photon energy

Figure 2 shows incident and absorbed spectra for (a) energy and (b) photons together with spectral absorbance curve. Average photon energy is necessary to convert between conversion efficiencies and quantum efficiencies. For radiation with the standard AM1.5 solar spectrum, the average incident photon energy is defined as the ratio of the spectral integration over wavelength, $\lambda$, of incident spectral irradiance, $E_i(\lambda)$ [W/(nm m²)], to that of incident spectral photon irradiance, $X_i(\lambda)$ [1/(s nm m²)], and derived as

$$\alpha_i = \frac{\int_{\lambda_1}^{\lambda_2} E_i(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} X_i(\lambda) d\lambda} = \frac{hc}{\int_{\lambda_1}^{\lambda_2} \lambda E_i(\lambda) d\lambda} \approx 1.45 \text{ eV},$$

where $\lambda_1=250$ nm, $\lambda_2=4000$ nm, $h$ the Planck constant, and $c$ the speed of light in vacuum.

For the absorbed radiation, the average photon energy becomes a function of the absorption coefficient, $\alpha(\lambda)$, and of the substrate thickness, $t$. If the reflectance is neglected, it is defined as

$$\alpha_a = \frac{\int_{\lambda_1}^{\lambda_2} E_i(\lambda)[1-\exp(-\alpha(\lambda)t)] d\lambda}{\int_{\lambda_1}^{\lambda_2} X_i(\lambda)[1-\exp(-\alpha(\lambda)t)] d\lambda} = \frac{hc}{\int_{\lambda_1}^{\lambda_2} \lambda E_i(\lambda)[1-\exp(-\alpha(\lambda)t)] d\lambda}.$$

For the standard AM1.5 solar spectrum and 0.4 mm-thick crystalline Si, it is evaluated by using the published optical constants [4] to be

$$\alpha_a \approx 1.89 \text{ eV}.$$

Spectrally integrated energy absorbance is defined and calculated as,

$$A_a = \frac{\int_{\lambda_1}^{\lambda_2} E_i(\lambda)[1-\exp(-\alpha(\lambda)t)] d\lambda}{\int_{\lambda_1}^{\lambda_2} E_i(\lambda) d\lambda} \approx 0.773,$$
while spectrally integrated photon absorptance is defined and calculated as,

\[ A_p = \int_{\lambda_1}^{\lambda_2} x_2(\lambda)[1 - \exp(-\alpha(\lambda) t)]d\lambda = \frac{\int_{\lambda_1}^{\lambda_2} E_i(\lambda)[1 - \exp(-\alpha(\lambda) t)]d\lambda}{\int_{\lambda_1}^{\lambda_2} E_i(\lambda)d\lambda} \approx 0.592. \]

Among the four values, the following relationship holds.

\[ a_i A_e = a_a A_p \]

3.2. Experimental efficiencies derivation
Definitions \[5,6\] for power conversion efficiencies and quantum efficiencies are tabulated in Table 1.

| Table 1. Definitions for power conversion efficiencies and quantum efficiencies |
|-----------------------------------------------|
| **Conversion efficiency** | **Quantum efficiency** |
| External | \( C_{\text{ext}} = \frac{P_m}{P_i} = A_e C_{\text{int}} \) | \( n_{\text{ext}} = \frac{n I_{\text{sc}}}{e \Phi_a} = A_p l_{\text{int}} \) |
| Internal | \( C_{\text{int}} = \frac{P_m}{P_a} \) | \( n_{\text{int}} = \frac{n I_{\text{sc}}}{e \Phi_a} = \frac{n a_a I_{\text{sc}}}{P_a} \) |

Here, notations are as follows. \( P_a \) [W]: absorbed radiant power, \( \Phi_a \) [1/s]: absorbed photon flux, \( n \): number of solar cells in the module, \( P_m \) [W]: maximum electrical power generated, \( I_{\text{sc}} \) [A]: short circuit current, \( e \) [C]: elementary electronic charge.

In our technique, the absorbed radiant power can be directly determined as explained. Therefore, the internal conversion efficiency is, in the first place, determined based on the definition. Secondly, the external power conversion efficiency was derived from the internal power conversion efficiency using the calculated absorptance. Lastly, the internal/external quantum efficiencies were converted from the internal/external power conversion efficiencies by using the short circuit current and the average photon energy as shown in Table 1.

3.3. Efficiencies estimated from nominal values
To compare the measured efficiencies, conversion efficiencies and quantum efficiencies for a module and a cell estimated from the nominal values were calculated as shown in Table 2. Here, \( E=1000 \) [W/m²]: the irradiance of STC, \( S \) [m²]: module area, \( S_c \) [m²]: cell area, \( n \): number of cells per module,
Table 2. Equations to derive various efficiencies from nominal values

| Conversion efficiency | Quantum efficiency |
|-----------------------|--------------------|
| module                | cell               | module               | cell               |
| External              | $C_{\text{ext,m}} = \frac{P_m}{ES}$ | $C_{\text{ext,c}} = \frac{P_m}{nES_c}$ | $\eta_{\text{ext,m}} = \frac{n\eta_{\text{sc}}}{ES}$ | $\eta_{\text{ext,c}} = \frac{a\eta_{\text{sc}}}{ES_c}$ |
| Internal              | $C_{\text{int,m}} = \frac{C_{\text{ext,m}}}{A_{\text{e}}}$ | $C_{\text{int,c}} = \frac{C_{\text{ext,c}}}{A_{\text{e}}}$ | $\eta_{\text{int,m}} = \frac{\eta_{\text{ext}}}{A_p}$ | $\eta_{\text{int,c}} = \frac{\eta_{\text{ext,c}}}{A_p}$ |

4. Experiments

Measurements were carried out on two types of crystalline silicon solar modules, specifications of which are tabulated in Table 3. Two sets of identical solar modules were set in the same outdoor conditions with the appropriate load (5.29 Ω for HIP-63S1, 46.6 Ω for GT-833S-TF) to attract maximum power. In addition, the electrical substitution experiments were conducted also for the modules (GT-833S-TF) in an open- and short-circuit conditions. Module temperatures were monitored by thermocouples attached to the center of the rear side of the modules and also by a thermographic camera set behind the modules.

Experiment procedures are as follows.
1. Align the modules to the sun and wait until the thermal equilibrium is established.
2. Shade one (test module) of the two modules completely with a sun shield.
3. Apply electrical power (in constant current mode) to the test module and adjust it so that its temperature becomes equal to the temperature of the other module (reference module).
4. Take the substituted electrical power plus the electrical power generated when the sun is not shielded as the absorbed power. Analyze the data.

Absorptance of the substrate is evaluated by the calculation using the literature absorption coefficient of crystalline silicon as described in section 3.1.

Table 3. Nominal values and specifications of photovoltaic modules tested.

| Manufacturer | SANYO | KIS |
|--------------|-------|-----|
| Model        | HIP-63S1 | GT-833S-TF |
| Type         | HIT      | c-Si    |
| Nominal maximum power /W | 63      | 7     |
| Nominal short circuit current /A | 3.75    | 0.45  |
| Nominal open circuit voltage /V | 22.6    | 21.1  |
| Number of cells | 32      | 34     |
| Module area /m² | 0.465    | 0.0466 |
| Cell area /m² | 0.011    | 0.00123 |

5. Results

Figure 3 shows one of the measurement results (done in the campus on 2014/10/25) for the HIT type modules (Sanyo HIP-63S1) as a function of time. The test module was sun-shielded from 11:55 until the end of the graph. Even in the sunny condition, the temperatures of both modules fluctuated mainly due to the wind. The small difference in temperature between the modules at the same condition is also likely to be attributed to the difference in the wind condition.

Electrical power (97 W) started to be applied to the test module at 12:11. The applied power was increased to around 200 W at 12:20. With this power, both temperatures of the test module and the reference one agree. In this duration, the average substituted power was 203 W while the averaged maximum electrical power generated from the reference module was 61.3 W. It means that the sum, 264.3 W, is equal to the absorbed power. Therefore, the internal conversion efficiency is simply given by the ratio of 61.3 W to 264.3 W resulting in 0.232 as shown in Table 4 together with other
efficiencies and comparison with the estimations from nominal values. For all the measured efficiencies, spectral mismatch corrections \[7\], which are required for rigorous evaluation to take account of the difference between the actual spectrum and the standard one were not applied.

In Table 4, separate measurement results on a different day (2014/10/29) are also shown to check the reproducibility. All the second measurement results are smaller than the first one by 2.2%, 2.2%, 1.9% and 1.8% for ICE, ECE, IQE and EQE, respectively. Reproducibilities \((k=2)\) obtained are 3.1%, 3.2%, 2.7% and 2.6% for each.

Concerning the comparison with the efficiencies from nominal values, all the measured results are closer to the corresponding cell efficiency than the module efficiency; the measured efficiencies are smaller by 4-6% than the cell efficiencies while they are larger by 30-33% than the module efficiencies. Although the uncertainty is in the process to be analyzed, a tentative uncertainty is estimated to be 5-6\%(k=2). The result that the measured efficiencies are closer to the cell efficiencies can be understood reasonable considering that radiation heating is rather confined to the area of the cell substrate because of the whiteness of the back-sheet, which is similar to the electric joule heating.

Table 4. Comparison on Sanyo HIP-63S1 between experimentally determined efficiencies and estimated ones from nominal values. ICE / ECE: Internal / External Conversion Efficiency, IQE / EQE: Internal / External Quantum Efficiency.

| Sanyo HIP-63S1 | ICE  | ECE  | IQE  | EQE  |
|----------------|------|------|------|------|
| Estimated from nominal values | Module | 0.175 | 0.135 | 0.632 | 0.374 |
|                             | Cell  | 0.242 | 0.187 | 0.874 | 0.517 |
| Measured (Loaded)           | 2014/10/25 | **0.232** | **0.179** | **0.837** | **0.495** |
|                             | 2014/10/29 | **0.227** | **0.175** | **0.821** | **0.486** |

Table 5 shows additional results on different smaller crystalline silicon modules (KIS GT833-TF) to compare efficiencies under loaded, open, and shorted conditions together with estimated ones efficiencies from nominal values. Regardless of the load conditions, the conversion efficiencies agree within ±4.8\%(k=2) and the quantum efficiencies agree within ±2.5\%(k=2). However, contrary to the results in Table 4, most of the measured efficiencies are closer to the module efficiencies. It is highly likely for this type of small modules that the nominal values such as maximum power etc. are not reliable enough but has high uncertainties.
6. Conclusions
It has been proven that internal power conversion efficiencies can be successfully determined by a calorimetric method by which the absorbed radiant power can be determined by replacing the heat absorbed in the solar module with the electrical power. The technique is advantageous in that the reflectance and transmittance measurements, which are required in the conventional methods, are not necessary. The internal power conversion efficiencies are converted to external one by using the average photon energy. Agreements of the measured data with the values estimated from the nominal values support the validity of this technique.

ECEs and EQEs obtained by this technique are compared with those derived from nominal values for module and cell efficiencies. All the reliable measured efficiencies lie between the estimated cell efficiency and the module one and are closer to the former. This is reasonable considering the white back-sheet reflects most of the incident radiation and therefore generates little heat outside of the substrate, which is similar to the joule heating by electricity.

The disagreement are considered to be caused by the following factors: temperature fluctuation due to wind, inequivalence between radiation heating and electrical heating, uncertainty in nominal values of the solar modules, deviation from the standard test conditions and so on. Further study is being performed to investigate the details and to improve the performance, for instance, by introducing the automatic substitution method.

References
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Table 5. Comparison on KIS GT833-TF between experimentally determined efficiencies under loaded, open, shorted and estimated ones from nominal values.

|                      | KIS GT833-TF | ICE   | ECE   | IQE   | EQE   |
|----------------------|--------------|-------|-------|-------|-------|
| Estimated from       | Module       | 0.194 | 0.150 | 0.804 | 0.476 |
| nominal values       | Cell         | 0.216 | 0.167 | 0.894 | 0.530 |
| Measured             | Loaded       | 0.188 | 0.145 | 0.731 | 0.433 |
|                      | Opened       | 0.195 | 0.151 | 0.722 | 0.428 |
|                      | Shorted      | 0.207 | 0.160 | 0.758 | 0.449 |

To automatize the electrical substitution, we have also conducted experiments with negative feedback control system, which automatically adjusts the applied electrical power to maintain a constant temperature. The automatic substitution system also has been proved to work successfully and is to be published somewhere.