**Heat Transfer and Renewable Sources of Energy 2012**
**A.A. Stachel and D. Mikielewicz (Editors)**

# CALCULATION OF SILICON CELL TEMPERATURE OF LOADED PHOTOVOLTAIC MODULE BASED ON THERMAL COEFFICIENTS FOR DIFFERENT WEATHER CONDITIONS OF NORTHERN POLAND

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ABSTRACT: The electrical performance of loaded photovoltaic module depends strongly on solar radiation intensity, ambient temperature, wind speed and on internal temperature of constituent photovoltaic cells. The operating cell temperature of loaded photovoltaic module depends on climatic variables as well but that relation is still not sufficiently described. Although the climatic variables are uncontrollable there is a necessity to reduce electrical losses of photovoltaic module as far as possible in different methods. One of the most achievable method of reducing temperature of photovoltaic cells may be obtained by reduction of excessive temperature of the module surface. In following paper the issue of impact of particular climatic variables on increase of module surface and photovoltaic cell temperatures was discussed. Photovoltaic module surface temperature dependency on solar radiation intensity and ambient temperature was presented. The relation between temperature of photovoltaic cell and photovoltaic module surface based on thermal coefficients of open circuit voltage was derived. General method that enables the calculation of operating temperature of photovoltaic cells was presented. The universality of proposed formula for determination of internal photovoltaic cell temperature based on specific variables in different weather conditions for commercially available photovoltaic modules was presented.

## NOMENCLATURE

$e$ – elementary charge, C,
$E_g$ – energy band gap, eV,
$FF$ – Fill Factor, -,
$G$ – solar radiation flux (irradiance) on module plane, W/m$^2$,
$I$ – current, A
$k$ – Boltzmann's constant, J/K,
$T$ – temperature, $^oC$,
$P$ – power, W,
$v$ – wind velocity, m/s,
$U_L$ – thermal loss coefficient, W/(m$^2$K),
$V$ – voltage, V.

**Greek symbols**

$\alpha$ – solar absorptance of PV layer, -,
$\tau$ – transmittance of glazing, -,
$\eta$ – cell/module efficiency, %.

**Subscripts**

*0* – values for the 25°C,
*amb* – ambient air,
*c* – cell,
*f* – front,
*mp* – maximum power,
*oc* – open circuit,
*sc* – short circuit.

## 1. INTRODUCTION

Photovoltaic module output parameters depend on environmental conditions, such as irradiance and temperature. PV modules perform best at cooler temperatures, and some lose less production as temperature rises than others, due to the materials and technologies used. As dark PV cells absorb radiant energy, their temperature increases and will be significantly higher than the ambient air temperature. Due to their light-absorbing properties, solar cells will average about 20ºC above ambient temperature. Increased temperature can decrease the efficiency of photovoltaic conversion. The physical aspects of deterioration of the output power and the conversion efficiency of solar cell and PV module with increasing temperature are: increase of the thermal lattice vibrations, leading to the electron-phonon scattering, decrease of the charge carriers mobility, reduction of the p-n junction built in voltage and junction ability to separate electrons from holes in the photogenerated pairs. The most significant is the temperature dependence of the voltage, which decreases with increasing temperature. Therefore it is very important to be able to determine the cell temperature during operation of the module.

Each module is tested at Standard Test Conditions (STC): an irradiance of 1000 W/m$^2$ and temperature of 25°C (it is important that STC references cell temperature - not ambient air temperature). The Nominal Operating Cell Temperature (NOCT) is the temperature reached by open circuited cells in a module, under the following conditions: irradiance on cell surface $G$=800 W/m$^2$, air temperature $T_{amb}$=20ºC, average wind velocity $v$=1 m/s, mounting - open back side, tilted normally to the solar noon sun.

These values do not provide information about the real temperature which cells will reach in the irradiated and loaded module. The aim of this article was to propose empirical correlation for the operating temperature of commercial grade silicon photovoltaic cells and make a comparison with analogous relations in the literature. The temperature of the individual cells (actually, that of their *p–n* junctions) within a PV module, i.e. $T_c$, is the proper temperature to use in order to predict the electrical performance of the module.

The simplest explicit equation for the operating temperature of a PV cell links $T_c$ with the ambient temperature and the incident solar radiation flux [5]:

$$T_c = T_{amb} + k \cdot G \quad . \tag{1}$$

In this linear expression, which holds for no electrical load and no wind, the dimensional parameter $k$, known as the Ross coefficient, is given by the ratio

$\Delta(T_c - T_{amb})/\Delta G$, i.e. it is the slope in the ($T_c$-$T_{amb}$) versus $G$ plot. The main difficulty with this linear model lies in the estimation of $k$, which can be measured for an installed array but not easily estimated beforehand, especially when the wind effects are important [7].

A simple expression relating the cells within a PV module and the back-side temperatures is:

$$T_c = T_b + \frac{G}{G_{ref}} \Delta T, \tag{2}$$

in which $G_{ref}$ is a reference solar radiation flux on the module (1000 W/m$^2$), and ΔT is the temperature difference between the PV cells and the module back side, at this reference solar radiation flux [6]. The main difficulty with this model lies in the estimation of $T_b$.

The traditional steady-state energy balance which leads to the prediction of $T_c$ requires as input: thermal and physical properties of the cell/module, the solar resource and weather data, the wind heat transfer coefficient. An established procedure to formulate the PV cell operating temperature involves use of the Nominal Operating Cell Temperature (NOCT) [8]:

$$T_c = T_{amb} + \frac{G}{G_{NOCT}} \frac{U_{L,NOCT}}{U_L} \left(T_{NOCT} - T_{amb,NOCT}\right) \left[1 - \frac{\eta}{\tau\alpha}\right], \tag{3}$$

but since $\eta$ is itself a function of $T_c$, Eq. (3) is an implicit equation for the PV cell operating temperature. If the usual assumption of constant $U_L$ is made, then Eq. (3) can be written as [9]:

$$T_c = T_{amb} + \frac{G}{G_{NOCT}} \left(T_{NOCT} - T_{amb,NOCT}\right) \tag{4}$$

since the term $\left[1 - \frac{\eta}{\tau\alpha}\right]$ is small compared to unity.

Based on large set of numerical data, the effect of ambient temperature and solar radiation on solar cell temperature of PV system were studied. The results of the numerical studies were represented in terms of cell temperature correlation. In this correlation, the cell temperature is a function of both the ambient temperature and the solar radiation [10]:

$$T_c = 1.07\left(T_{amb}\right)^{0.57} G^{0.33}, \; 100 \leq G \leq 1000 \text{ W/m}^2. \tag{5}$$

## 2. METHOD

Temperature coefficients provide the rate of change with respect to temperature of different photovoltaic performance parameters. The derivatives can be determined for short-circuit current ($I_{sc}$), maximum power current ($I_{mp}$), open-circuit voltage ($V_{oc}$), maximum power voltage ($V_{mp}$), and maximum power ($P_{mp}$), as well as fill factor ($FF$) and efficiency ($\eta$).

Coefficients for modules can be measured either indoors with a solar simulator or outdoors under operational conditions. For indoor tests, the module is usually illuminated using a solar simulator and then heated from the rear surface in order to achieve a range of temperatures. For outdoor tests, the module can first be shaded to lower its temperature to near ambient temperature then unshaded with I-V curves measured as it heats up to operating temperature. In both cases, the average module temperature should be measured using multiple thermocouples attached to the rear surface [1].

At open-circuit *I=0*, and the light plus thermally generated currents and recombination currents balance.The temperature dependence of the open-circuit voltage can be described in the form of [4]:

$$V_{oc}(T) = V_{oc}(T_0) - \left[\frac{E_{g0}}{e} - V_{oc}(T_0)\right]\left(\frac{T}{T_0} - 1\right) - \frac{3kT}{e}\ln\frac{T}{T_0} \tag{6}$$

Over a limited temperature range, $\frac{dV_{oc}}{dT}$ predicts an approximately linear temperature dependence of open-circuit voltage with temperature. Temperature coefficient of the open-circuit voltage is defined as:

$$\beta_{V_{oc}} = \frac{1}{V_{oc}}\frac{dV_{oc}}{dT} , \tag{7}$$

and allows to determine the temperature of photovoltaic cells by measuring the open cell voltage drop of the module in relation to the temperature of module's front glass cover:

$$T_c = T_f + \frac{V_{oc}(T) - V_{oc}(T_0)}{\beta_{V_{oc}} \cdot V_{oc}(T_0)} \Rightarrow T_c = T_f + \Delta T_\beta . \tag{8}$$

Formula (8) is a derivative of well-known but modified formula:

$$V_{oc}(T_f) = V_{oc}(T_o) - \beta_{v_{oc}}(T_f - T_o) \tag{9}$$

The temperature coefficients of the open-circuit voltage $\beta_{V_{oc}}$ for different crystalline silicon modules are within the range of 0.0029 $K^{-1}$ to 0.0042 $K^{-1}$ [1], [2], [3], with the mean value of 0.0036 $K^{-1}$ (Table 1).

Table 1. Temperature coefficients for crystalline silicon commercial modules.

| | $\frac{1}{V_{oc}}\frac{dV_{oc}}{dT}\left[\frac{1}{K}\right]$ | Reference |
|---|---|---|
| ASE-100-DGL-SM | -.0038 | [2] |
| ASE300, mc-Si | -.0036 | [1] |
| SQ-90, c-Si | -.0038 | [1] |
| MSX64, mc-Si | -.0042 | [1] |
| SP75, c-Si | -.0039 | [1] |
| M55, c-Si | -.0041 | [1] |
| BP Solarex BP 585 | -.0037 | [3] |
| Kyocera KC60 | -.0036 | [3] |
| Siemens S30 | -.0029 | [3] |
| Siemens SM-55 | -.0037 | [3] |
| Uni-Solar US-32 | -.0031 | [3] |
| ASE-100 | -.0034 | [3] |
| BP Solarex MST 43 | -.0033 | [3] |
| Shell RSM 75 | -.0033 | [3] |

Independently on the basis of long-term monitoring of photovoltaic system, which consists of mono- and multicrystalline modules, installed in Gdansk University of Technology, the values of $V_{oc}$ were related to the values of radiation intensity, ambient temperature and the number of the next day of the year, which clearly sets out the meteorological conditions. For computer system acquisition, storage and access to output data an application in Object Pascal was written and mounted on PC. Meteorological centre measures the ambient temperature, wind direction and speed. Also measured and recorded every 12 seconds are several temperatures (solar cell top temperature, solar cell under-surface temperature) and global solar irradiance on a horizontal surface. Apart from data collected from meteorological station, the PV data stations are continuously being monitored and stored: the photocell voltage with variable resistance of load and without load ($V_{oc}$), the photocell current with variable resistance of load and short circuit current ($I_{sc}$), the batteries voltage, the charge/discharge batteries current. Based on the above measured data, separately for both PV modules, the following values are calculated: module efficiency η, actual I(V) curve, instantaneous power.

The proposed correlation allows to determine the expected temperature of the cell for a specific time of year and weather conditions.

## 3. RESULTS

In order to determine the correct working temperatures of solar cells on the basis of novel formula (8), we carried out a long-term examination of two commercially available photovoltaic modules based on monocrystalline (AstroPower AP-7105) and polycrystalline (Photowatt PWX850) silicon wafers with output specifications as follows (Table 2):

Table 2. Electrical/mechanical parameters of modules defined in STC.

| | AP-7105 (mono-Si) | PWX850 (multi-Si) |
|---|---|---|
| Peak power $P_{peak}$, $W_p$ | 75.0 | 75.0 |
| Open Circuit Voltage $V_{oc}$, V | 21.0 | 21.5 |
| Max. Power Voltage $V_{mpp}$, V | 17.0 | 17.0 |
| Short Circuit Current $I_{sc}$, A | 4.8 | 4.7 |
| Max. Power Current $I_{mpp}$, A | 4.4 | 4.4 |
| $V_{oc}$ coefficient $\beta_{V_{oc}}$, V/K | -.08 | -.079 |

To compare results credibly apart from consisting materials, both photovoltaic modules possess the same mechanical and electrical parameters. They were installed in unperturbed location at the same tilt and azimuth angles and were equipped with one type of MOSFET temperature sensors on specific location on front glass cover.

Open circuit voltage depends particularly on solar radiation intensity $E$, type of radiation (direct or diffused), ambient temperature $T_{amb}$ and working temperature of solar cell $T_c$ i.e. internal temperature of silicon wafers in our case. Solar cell working temperature $T_c$ influences open circuit voltage and that impact may be depicted mathematicaly as:

$$V_{oc} = f\left(E, T_{amb}, T_f\right) \tag{10}$$

Due to that dependency there is a particular requirement to eliminate both the impact of radiation intensity and ambient temperature on open circuit voltage values. In order to determine the impact of internal wafer temperature i.e. Schottky *p-n* junction temperature on values of open circuit voltage there is a specific need to transform the equation (10) into target relation as follows:

$$V_{oc} = f(T_f) \tag{11}$$

It may be done provided that experimental (meteorological) data analysis will be uniformed as far as constant radiation intensity is taken into account in working temperature calculation. Because values of open circuit voltage depend much more on intensity radiation and ambient temperature than on working temperature there is a necessity to eliminate the impact of mentioned factors on open circuit voltage according to following algorithm:

$$V_{oc} = f(E, T_{amb}, T_f) \Rightarrow \frac{T_{amb} = f(E)}{T_f = f(E)} \Rightarrow V_{oc} = f(T_f) \tag{12}$$

To calculate the working temperature of silicon cells of loaded photovoltaic modules based on thermal coefficients for different weather conditions of northern Poland appropriate meteorological data set was analysed. We obtained average ambient temperatures (Figure 1a) and front cover glass temperatures (Figure 1b) of modules under defined values of direct solar radiation intensities from 400 W/m$^2$ to 800 W/m$^2$ for 6 summer months characterized by high degree of clear blue sky occurrence.

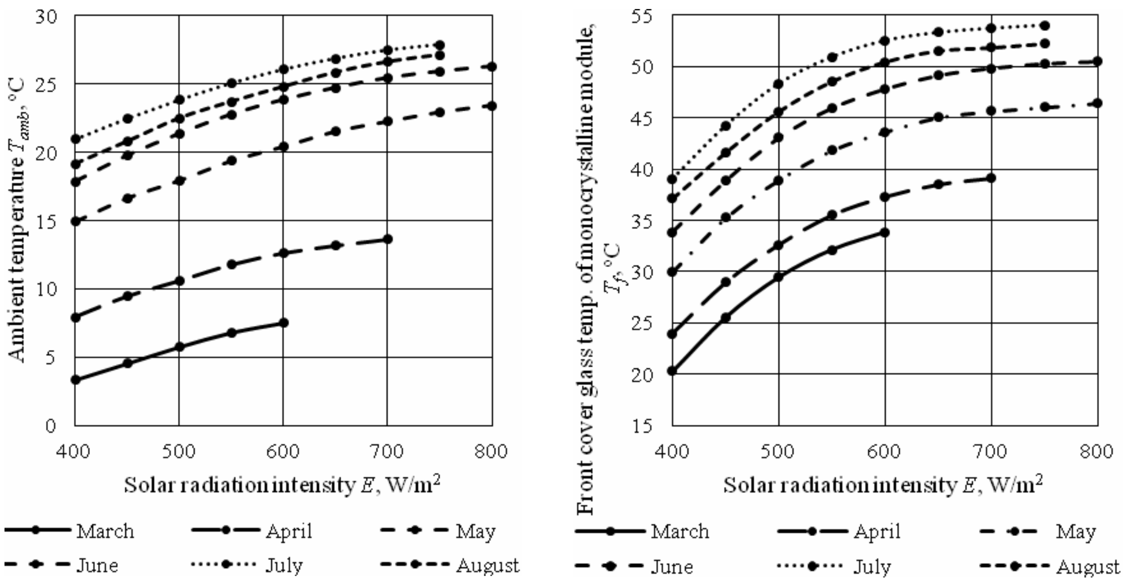


Fig. 1. Determined experimentally a) mean monthly air temperature for specific intervals ($\Delta E$ = 50 W/m$^2$) of solar radiation intensity in 6 months of summer. For cooler months such as March and April we did not detect the values of intensity of radiation greater than 600 W/m$^2$ and 700 W/m$^2$ respectively b) mean monthly temperature of monocrystalline module's front cover glass determined for specific intervals ($\Delta E$ = 50 W/m$^2$) of solar radiation intensity for 6 months of summer.

To determine the working temperature we separated the open circuit voltage values $V_{oc}$ and voltages under optimal resistances $V_L$ for front cover glass temperatures of monocrystalline photovoltaic module. The values were measured for certain undisturbed intensities of radiation from 400 W/m$^2$ to 800 W/m$^2$ with interval $\Delta E$ = 50 W/m$^2$. We selected 30 points of ($T_f$, $V_{oc}$) and 30 points of ($T_f$, $V_L$) determined from uniform solar radiation intensity values as mentioned beforehand. The open circuit and load voltage values versus front cover glass temperature of module in the form of $V_{oc}(T_f) = \beta \cdot T_f + V_{oc}(0°C)$ and $V_L(T_f) = \beta \cdot T_f + V_L(0°C)$ was presented in Figure 2.

We determined the internal operating temperature of photovoltaic silicon wafers $T_c$ by calculation of excessive temperature $\Delta T_\beta$ based on values of $V_{oc}$ and $V_L$ according to equation (8). The eccessive temperature of wafers $\Delta T_\beta$ obtained on the basis of $V_{oc}$ and $V_L$ values in relation to the temperature of external glass $T_f$ was presented in Figure 3.

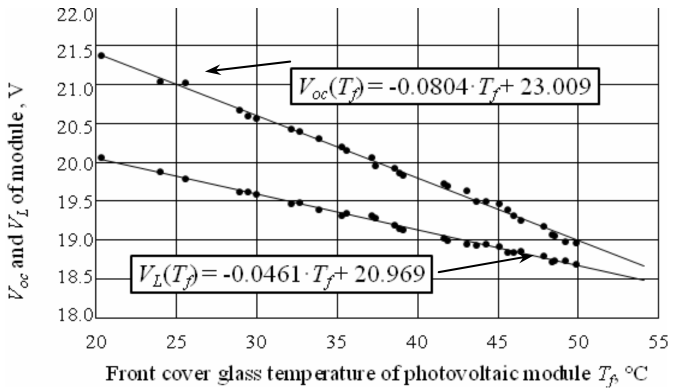


Fig. 2 Dependency between values of open circuit voltage $V_{oc}$/voltage under optimal load $V_L$ of photovoltaic module and the front cover glass temperature $T_f$, determined based on experimental data set and algorithm (12). The values of $V_{oc}$ and $V_L$ for standart test conditions temperature (25ºC) are 21 V and 19.8 V, respectively

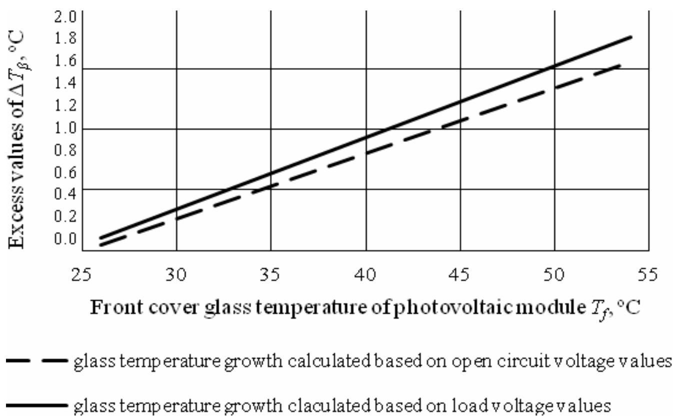


Fig. 3 Excessive values of front glass cover temperature of external module surface $\Delta T_f$ over $T_f$ temperature for two modes of work: without external load (dashed line) and with external load connected (solid line)

## 4. CONCLUSIONS

In following paper we presented a novel formula based on thermal coefficients for determination of actual operating temperature of silicon cells in encapsulated, commercially available photovoltaic modules. Till that time calculations of these temperatures were made on the basis of highly inaccurate formula of (1). We proved that interior temperature of cells is higher than temperature of front glass coating as they can be regarded as an internal heat source. We demonstrated that thermal coefficients of open circuit voltage may be transformed into thermal coefficients of output voltage for loaded photovoltaic module. The value of thermal coefficient of loaded voltage is significantly smaller than the one for open circuit.

Introduced formula has the essential meaning of estimations of photovoltaic arrays performance and will be developed in the nearest future.

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## TEMPERATURBESTIMMUNG DER SOLARZELLEN EINES BELASTETEN PHOTOVOLTAIK-MODULS AUF GRUNDLAGE DER TEMPERATURKOEFFIZIENTEN DER SPANNUNG DES OFFENEN KREISES IN KLIMABEDINGUNGEN NORDPOLENS.

ZUSAMMENFASSUNG: Die elektrischen Parameter des belasteten Photovoltaik-Moduls hängen stark von der Intensität der Sonneneinstrahlung, der Umgebungstemperatur, der Windgeschwindigkeit und der Temperatur der Solarzellen-Komponenten ab. Die Temperatur der Zellen im Solarmodul ist streng von den Klimabedingungen abhängig, diese Abhängigkeit wurde jedoch noch nicht ausreichend beschrieben. Obwohl die Klimabedingungen nicht kontrolliert werden können, existiert die Notwendigkeit, die elektrischen Verluste des Photovoltaik-Moduls unter Anwendung – wenn möglich – verschiedener Methoden soweit wie möglich zu begrenzen. Eines der am leichtesten umzusetzenden Verfahren, die Temperatur der Solarzellen zu reduzieren, ist die Begrenzung der übermäßigen Erwärmung der Moduloberfläche. Im folgenden Artikel wurde der Einfluss der einzelnen klimatischen Variablen auf die Erwärmung der Moduloberfläche und der einzelnen Zellen besprochen. Es wurde die Abhängigkeit der Temperaturwerte der Modul-Oberfläche von der Umgebungstemperatur und der Intensität der Sonneneinstrahlung dargestellt. Es wurde die Abhängigkeit zwischen der Temperatur der Solarzelle und der Temperatur der Moduloberfläche auf Grundlage der Temperatur-Koeffizienten der Spannung des offenen Kreises bestimmt. Es wurde eine allgemeine Methode vorgestellt, die die Berechnung der Arbeitstemperatur der Solarzellen erlaubt. Es wurde die Vielseitigkeit der vorgeschlagenen Formel aufgezeigt, die es erlaubt, für auf dem Markt verfügbaren Photovoltaik-Module, die Temperatur der Solarzellen bei verschiedenen Wetterbedingungen zu bestimmen.