THE EFFECT OF A VARYING SOLAR SPECTRUM ON THE ENERGY PERFORMANCE OF SOLAR CELLS

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ABSTRACT: The annual performance of a multi-crystalline silicon cell (mc-Si) and an amorphous silicon cell (a-Si) is calculated using modelled spectra in combination with the well-known solar cell one-diode model. Two different sets of modelled minutely spectra are utilized for modelling cell performance: 1) Simulated spectral data, using measured irradiation data from KNMI (Royal Netherlands Meteorological Institute) and the SEDES2 spectral model, 2) Scaled AM1.5 spectra using global tilt irradiance. The modelled energy performance derived from each set of spectra is compared and a mismatch factor (MMF) is determined to quantify the amount of the spectral effects. Both the modelled solar cell performance and calculated MMF are then graphed against global irradiance, air mass, and sky clearness index for every month. The results show that spectral effects are larger for a-Si than for mc-Si, as was expected. Detailed minutely data shows MMF to vary between 0.66 and 1.77 for a-Si and between 0.74 and 1.11 for mc-Si solar cells. From the annual yield based on modelled and scaled AM1.5 spectra, it is concluded that a-Si is up to 8% more effective than mc-Si per installed Wp. The annual spectral effect was found to be −3% for a-Si and −1.7% for mc-Si. This indicates that in general models, which assume the AM1.5 spectrum, overestimate the energy yield.
Keywords: Modelling; Spectral effect; Mismatch factor (MMF); Solar cell; Energy performance

1 INTRODUCTION

The real energy performance of solar cells, i.e., the actual amount of produced electricity by a single solar cell, cannot be fully derived from data sheets as specified by manufacturers, as these are drawn up from measurements under standard test conditions (STC; 1000W/m^2 irradiation, air mass 1.5 spectrum and a cell temperature of 25 ^{o}C). The total irradiance and the actual operating temperature of the specific cell are often not known, but have a significant role in the specific performance. Therefore these parameters are widely used in performance models already. Nevertheless, the influence of the spectral distribution that also affects performance is often not accounted for. The aim of this research therefore is to investigate the effect of a varying solar spectrum on the energy performance of solar cells.

The spectral distribution of irradiation has a systematic influence on solar cell performance, and it depends on weather, geographical conditions and time-of-day [1]. Although many aspects of the effect of spectral distributions on solar cell performance are known, the influence is often neglected in modelling the energy yield of a solar system [2]. The magnitude of the spectral effect on cell performance of different PV technologies depends on the spectral response of the specific cell technology concerned, because it is related to the band gap of the semiconductor. Larger band gaps lead to a larger spectral effect [3]. Therefore a photovoltaic device with a narrower spectral response such as amorphous silicon (a-Si) is more sensitive to changes in the spectral composition of irradiation, compared to a wider spectral response device such as crystalline silicon (c-Si). Hence, a better understanding of the cell performance in different solar spectral regimes could lead to a better selection of more productive modules. Different types of solar cells could be developed for different geographical locations based on their prevalent solar spectral irradiance. Consequently modules with a larger annual energy output per installed Watt Peak power (kWh/W$_p$) can be distinguished and employed in different regions.

In this study a model to investigate the effects of spectral variation on solar cell performance is developed and validated. The cell performance was simulated using the well-known one-diode equation [4]. An amorphous silicon cell (a-Si) and a multi-crystalline silicon cell (mc-Si) were selected to be studied assuming a south facing 37^o tilted plane. Results throughout this study refer to a-Si and mc-Si cells and not modules. Moreover, in order to only model the spectral effect, the operating temperature was assumed to be constant at 25 ^{o}C. Therefore, any effect regarding the variation of operating temperature is not considered in this model.

In order to understand the spectral effect, cell performance results were studied and compared using two spectral data sets: Spectra generated by the SEDES2 spectral model were used versus scaled AM1.5 standard spectra. Since SEDES2 is supposed to simulate the natural prevailing spectra, the difference in cell performance was addressed as the spectral effect and quantified using the mismatch factor (MMF) approach.

2 MODEL STRUCTURE

Two independent models were involved in the modelling procedure of this study. First, the SEDES2 spectral model was utilized to generate minutely spectral data. Then, a performance model was developed and employed to simulate the energy performance of the cells.

In order to model annual performance, spectral resolved irradiation data for a complete year is required as data. Spectral response (SR) data of the solar cells are needed as well. The SR data was acquired from in-house measurements of various types of solar cells. As solar spectral data was not available for the Netherlands for a complete year, neither in the form of measured nor modelled data, we used the SEDES2[1] spectral model in order to generate spectral data from March 1st 2005 to February 28th 2006 on a minutely basis. As input to SEDES2, minutely measured irradiation data from the Cabauw meteorological site (51.971ºN, 4.927ºE) was used [5]. Cell performance parameters (i.e., I_{sc}, V_{oc}, FF, P_{peak}) were modelled on a minutely basis, and then assessed against global irradiance, air mass and sky clearness index. The spectral effect was calculated by comparing cell performance results and calculating a mismatch factor (MMF) using two sets of spectra: 1) Modelled spectra using the SEDES2 spectral model, 2) Scaled AM1.5 spectra based on global irradiance in the tilted plane. Finally, annual performance data including annual yield (kWh/W$_p$) are generated.

Figure 1 shows an overview of the model structure used

[1] SEDES2 is an extension of SPCTRL2 to include cloudy skies and was developed by the Centre for Solar Energy and Hydrogen Research (ZSW) in Germany [3]. The source code of the model is written in FORTRAN and was recently updated and compiled by Daryl Myers (NREL).

in this study. The radiation data provided by the KNMI (Royal Netherlands Meteorological Institute) were used in order to derive the simulated spectral data for a one-year period to run the investigation. Modelled spectral data were used as input to the performance model.

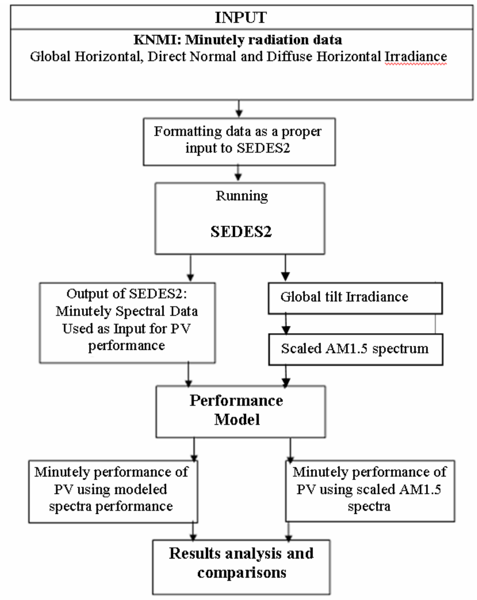


Figure 1: Principal structure of the model in this study

3 SCIENTIFIC BACKGROUND

3.1 Spectral modelling

Measured solar spectral data is not available for the Netherlands due to the lack of spectral measurement stations in the country. Therefore it is decided to use a modelling approach to derive required spectral data. For this purpose the SEDES2 spectral model was chosen to simulate minutely spectra for a one-year period. SEDES2 was developed by the Centre for Solar Energy and Hydrogen Research (ZSW) in Germany by Stefan Nann [3].

SEDES2 is an extension of SPCTRL2 to include cloudy skies. "*Within a three years effort one hundred thousand solar spectra were recorded*[2] *in the wavelength range from 300 to 1100 nm. These measured spectra were utilized to develop the semi-empirical model that calculates hemispherical solar spectra on a south tilted surface from three readily available meteorological data only: global and diffuse irradiance (alternatively direct irradiance), and dew point temperature (alternatively relative humidity and ambient temperature)*" [3] (see Fig. 2). The source code of the model is written in Fortran. SEDES2 was recently updated and compiled by NREL with the Lahey Fortran compiler for Fortran 90 version 4.501 [6].

Since March 2005, KNMI has established its own irradiance measurement station which continuously records the total, diffuse and direct irradiance every minute at a geographical location of 51.971ºN, 4.927ºE in Cabauw, which is close to the city of Utrecht.

Measured total, diffuse and direct irradiance provided by KNMI are used in order to derive minutely simulated solar spectrum for a one year period from March 1st 2005 to February 28th 2006. In addition to radiation information some other basic meteorological data (i.e. ambient temperature, relative humidity, and pressure) were needed to run SEDES2. These were also measured on site near to the irradiance measurement tools.

In Fig. 3, examples of SEDES2 output are shown for June 2nd and 19th 2005, which were distinguished as an overcast and clear sky day, respectively.

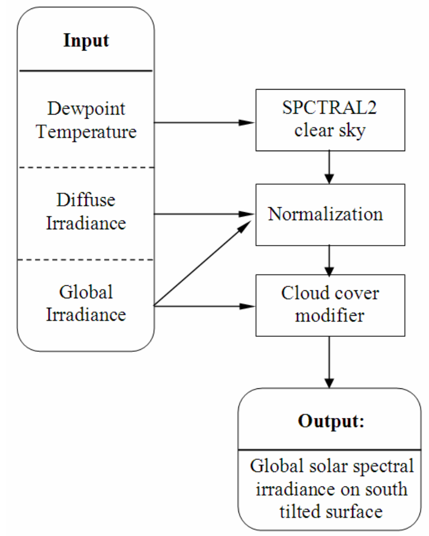


Figure 2: Structure used in SEDES2 spectral model [3]

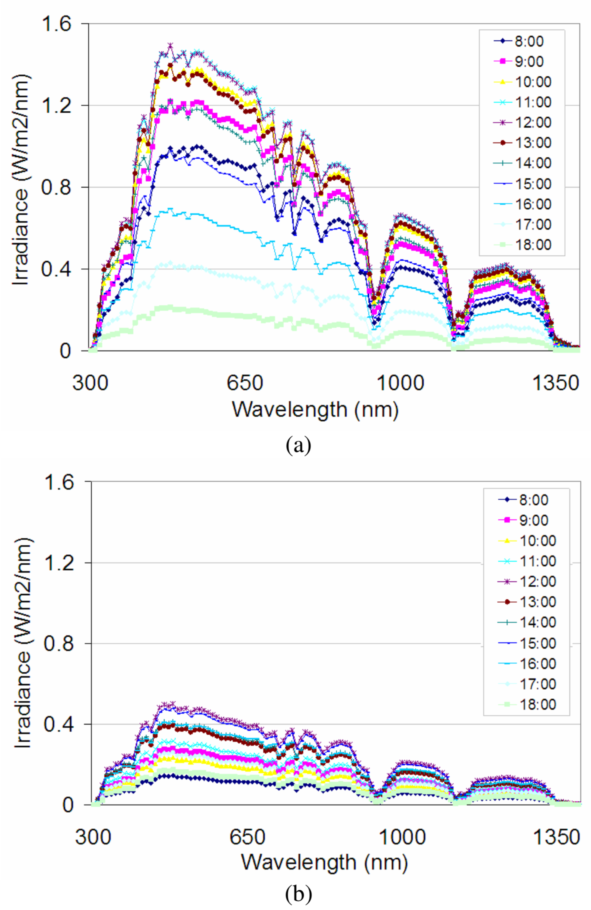


Figure 3: Example of hourly aggregated spectral resolved data for (a) a clear day and (b) an overcast day in June 2005 simulated by SEDES2

3.2 Cell performance model

One of they key device parameters of a solar cell is the short circuit current (I_{SC}). This parameter can be calculated

[2] At the Center of Solar Energy and Hydrogen Research (ZSW), Stuttgart, Germany, 49°N 9°E, a region with about 1800 sunshine hours a year, in a combined effort with the Solar Energy Research Institute, SERI, U.S, before it was renamed to NREL [3].

by convoluting the spectral response of the device and the incident solar spectrum using the following equation:

$$I_{SC} = A \int_{0}^{\lambda(E_g)} SR(\lambda) G(\lambda) d\lambda \qquad (1)$$

where I_{SC} is the short circuit current (A), A the cell area (m^2), $SR(\lambda)$ the spectral response of the device (A/W), $G(\lambda)$ the irradiance ($W/m^2/nm$) as a function of wavelength λ (nm) and E_g the energy band gap (eV) of the device.

The spectral response (SR) data was acquired from in-house measurements of various types of solar cells (Fig. 4).

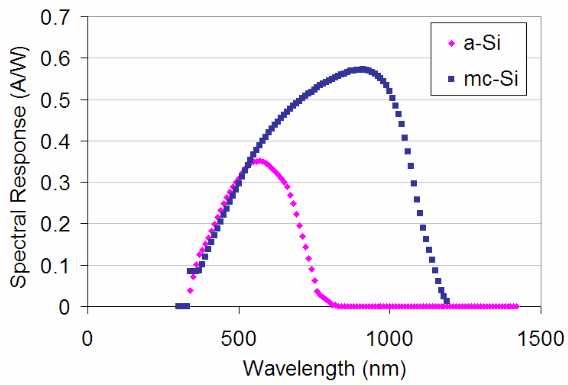


Figure 4: Spectral response of a-Si and mc-Si that were used in this study [10].

In order to calculate other performance parameters, the well known single-diode equation was employed [4]:

$$I = I_L - I_0 \left(\exp\left(\frac{qV}{nkT} \right) - 1 \right) \qquad (2)$$

with I the current in the device (A), I_L the light-induced current (A), I_0 the diode saturation current (A), V the voltage over the device (V), n the ideality factor, q the elementary charge (1.602×10^{-19} C), k the Boltzmann constant (1.38×10^{-23} J/K), and T the device temperature (K). Note that $n\approx1$ for an ideal p-n junction and $n\approx2$ for p-i-n junctions [7]. Here I_0 is given by

$$I_0 = I_{00} \exp\left(-\frac{E_g}{nkT} \right) \qquad (3)$$

where I_{00} is a constant (A) depending on the material and device characteristics and can be empirically determined. Some researchers have estimated the parameter I_{00}. Green suggests I_{00} to be 1.5×10^8 (mA/cm^2) for crystalline silicon cells [6]. According to studies done by Meillaud *et al.*, it is suggested that I_{00} would be equal to 5×10^4 (mA/cm^2) for state-of-the-art amorphous p-i-n diodes [7].

The open-circuit voltage V_{OC} and short-circuit current are related as follows:

$$V_{OC} = \frac{nkT_c}{e} \ln\left(\frac{I_{SC}}{I_0} + 1 \right) \qquad (4)$$

After the calculation of V_{OC} the initial fill factor (FF_0) can be calculated using the normalized open circuit voltage υ_{OC} [4]:

$$FF_0 = \frac{\upsilon_{OC} - \ln(\upsilon_{OC} + 0.72)}{\upsilon_{OC} + 1} \qquad (5)$$

$$\upsilon_{OC} = \frac{V_{OC}}{(nkT_c / e)} \qquad (6)$$

The above fill factor is not usually found in practice since there are series and shunt resistances in the circuit of the diodes and the cell itself. If the series resistance (R_s) would be very low and also the shunt resistance (R_{sh}) would be very high then the above fill factor could be used in calculations. However, in order to make the calculations more accurate both series and shunt resistances were taken into account and used in order to calculate the most realistic fill factor. For that purpose the parameter R_{ch} and normalized resistances r_s and r_{sh} are defined as follows:

$$R_{ch} = \frac{V_{OC}}{I_{SC}} \qquad (7)$$

$$r_s = \frac{R_s}{R_{ch}}, \quad r_{sh} = \frac{R_{sh}}{R_{ch}} \qquad (8)$$

The realistic fill factor FF was calculated using the following equation:

$$FF = FF_0(1 - r_s)\left\{ 1 - \frac{(\upsilon_{OC} + 0.7)}{\upsilon_{OC}} \frac{FF_0(1 - r_s)}{r_{sh}} \right\} \qquad (9)$$

where FF_0 is the ideal fill factor (Eq. (4)). With Eq. (9) the the realistic fill factor can be calculated with an accuracy of up to two significant digits as long as: $\upsilon_{OC} > 10$, $r_s<0.4$ and $r_{sh}>2.5$ [4].

Then peak power and cell efficiency was calculated:

$$FF = \frac{P_{peak}}{V_{OC} I_{SC}} \qquad (10)$$

$$\eta = \frac{P_{Peak}}{G} \qquad (11)$$

where P_{peak} is the peak power in W/m^2 and G is the global tilt irradiance in W/m^2.

The parameters used in this study are summarized in Table I.

Table I: Cell parameters used for amorphous and multi-crystalline silicon cells

at 1000W/m^2, AM1.5	a-Si	mc-Si
P_{peak} (W/m^2)	71	142
FF (%)	64	73
V_{OC} (V)	0.82	0.6
I_{SC} (mA/cm^2)	13.5	32
E_g (eV)	1.7	1.1
n	1.77	1.49
I_{oo} (mA/cm^2)	1.1×10^9	1.4×10^7
R_s ($ohm.cm^2$)	15.42	1
R_{sh} ($ohm.cm^2$)	1.2×10^4	2×10^4

3.3 Spectral effect and mismatch factor (MMF)

In order to understand the effect of spectral variation on cells performance, one should be able to measure the performance of the cell in two different conditions. In this study cell performance was modelled using two different spectra: 1) Modelled spectra by the SEDES2 spectral model, and 2) scaled AM1.5 standard spectra.

Scaled AM1.5 spectra were generated using the following relation:

$$G(\lambda)_G \Rightarrow [G(\lambda)_{AM1.5}/1000]\times G \qquad (12)$$

where $G(\lambda)_G$ is the scaled AM1.5 spectra, $G(\lambda)_{AM1.5}$ is the AM1.5 global spectrum at standard testing condition (STC), 1000 (W/m^2) is the total irradiance STC, and G is the total global irradiance measured on site (W/m^2).

Since SEDES2 is developed to simulate the natural prevailing spectra; the difference in cell performance was attributed to the effect of the spectral variation. This difference was defined as mismatch factor (MMF) which was represented by the following equation:

$$MMF = \frac{\int_{300nm}^{2500nm} SR(\lambda)G_{SEDES2}(\lambda)d\lambda}{\int_{300nm}^{2500nm} SR(\lambda)G_{AM1.5}(\lambda)d\lambda}\cdot\frac{\int_{300}^{2500nm} G_{AM1.5}(\lambda)d\lambda}{\int_{300}^{2500nm} G_{SEDES2}(\lambda)d\lambda} \qquad (13)$$

where $G_{SEDES2}(\lambda)$ and $G_{AM1.5}(\lambda)$ are the irradiance distributions on the tilted cell for SEDES2 and scaled AM1.5 spectra (W/m^2/nm).

Considering that the first integration is representing the short circuit current, which is calculated as described before, and also realizing that the second integration is equal to the global tilt irradiance, the above equation can be simplified as follows:

$$MMF = \frac{I_{SC,SEDES2}}{I_{SC,AM1.5}}\cdot\frac{G_{tilt,AM1.5}}{G_{tilt,SEDES2}} \qquad (14)$$

As global tilt irradiance calculated by SEDES2 is used in order to derive the scaled AM1.5 spectra for performance calculation, it holds that $G_{tilt,SEDES2}=G_{tilt,AM1.5}$ and the second division is equal to 1. Thus:

$$MMF = \frac{I_{SC,SEDES2}}{I_{SC,AM1.5}} \qquad (15)$$

The MMF determined according to Eq. (15) was then used to quantify the effect of spectral variation on solar cells performance, also denoted as 'the spectral effect'.

4 MODEL VALIDITY

4.1 SEDES2 spectral model

The key parameter used for the solar cell performance modelling is the short circuit current (I_{SC}), which is calculated based on the spectral data and the spectral response of the cell. Solar cell spectral response data are assumed to be precise due to the high quality measurements done at the Utrecht Solar Energy Laboratory and the Energy research Centre of the Netherlands (ECN). Hence it is believed that the accuracy of SEDES2 is the largest source of uncertainty in the performance model. In order to determine how accurate the spectral data produced by SEDES2 are, we investigated the quality of the SEDES2 model in more detail. In order to understand the effect of a SEDES2 error on cell performance calculation, four different sky conditions were chosen in different seasons. Fig. 5 shows selected sky conditions ranging from a full cloudy to a full sunny day, with respective clearness sky indexes of 0.03 and 0.78.

The corresponding solar spectral irradiance for each condition could be found via the NREL online spectral database [8]. Simultaneously, global and diffuse irradiance along with other necessary meteorological data was available in order to model spectral data using SEDES2. The short circuit currents corresponding to each condition were calculated using measured and modelled spectra for each cell. Fig. 6 shows the result As shown, SEDES2 provides acceptable accuracy in terms of cell performance simulation. A maximum error was found in very overcast condition (k_t=0.03) and equalled –2.6% and 0.7% for a-Si and mc-Si, respectively. The Root Mean Square Error (RMSE) was found to be 7%, 5%, 4% and 3.5% for sky clearness indexes of 0.03, 0.13, 0.28 and 0.78, respectively

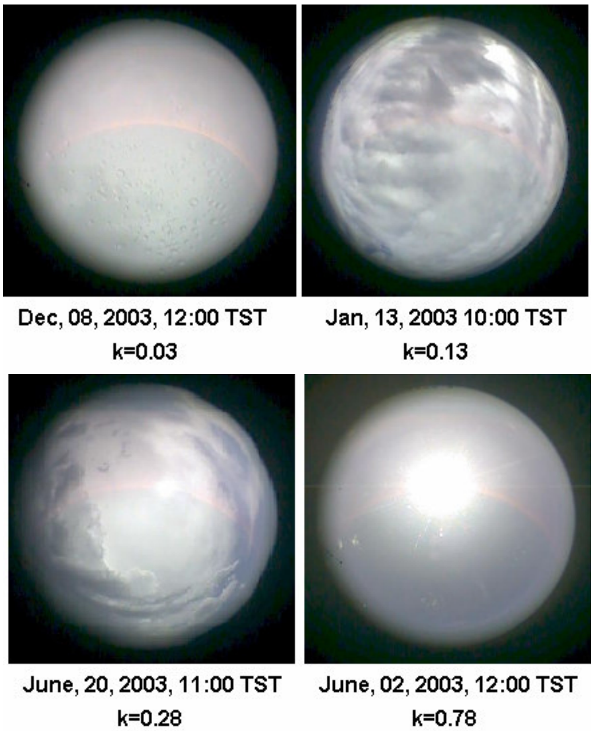


Figure 5: *Sky Images* show four selected sky conditions with clearness sky index ranging from 0.03 (cloudy) to 0.79 (clear) respectively from top left to bottom right.

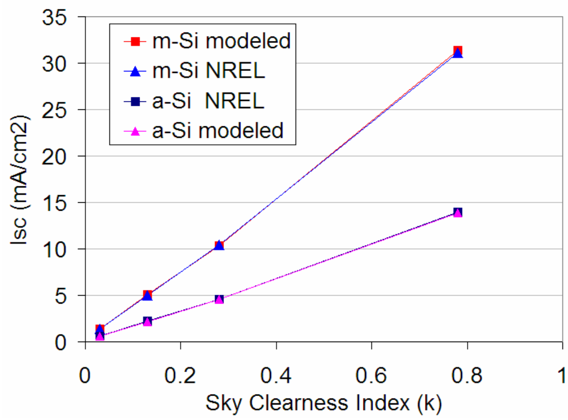


Figure 6: Calculated I_{SC} using modelled and measured spectral data for different sky clearness index values

4.2 Cell performance model

Since the aim of this study is to investigate the spectral effect on energy yields of solar cells, the performance model, which plays the main role for deriving the results, should be validated against any inconsistency. This will prevent us to harvest erratic results which then can cause vagueness in our final conclusion. Evaluation of the performance model can be achieved by using a dataset of measured performance of a solar cell under standard testing condition (STC). Subsequently, these values can be compared with modelled performance using the standard AM1.5 spectrum. For this aim an amorphous silicon cell is chosen and its performance was modelled using the scheme explained in Section 3.

As can be seen in Fig. 7, the energy performance model shows a very good estimate of the cell efficiency compared to the measured data. Other performance parameters such as *FF*, V_{OC}, I_{SC} and P_{max} were also checked and their modelled values were close to what was expected (i.e., measured values).

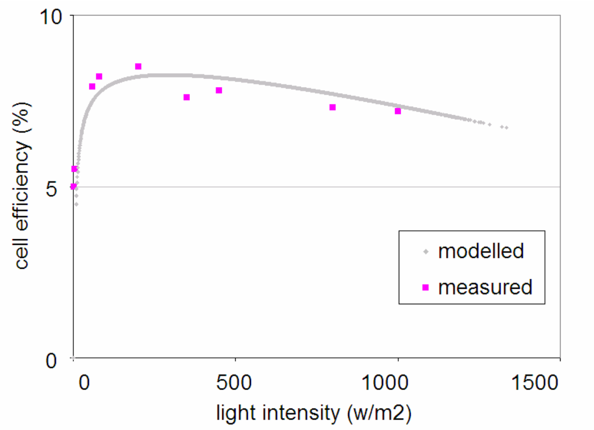


Figure 7: Comparison of measured and modelled performance of an a-Si cell

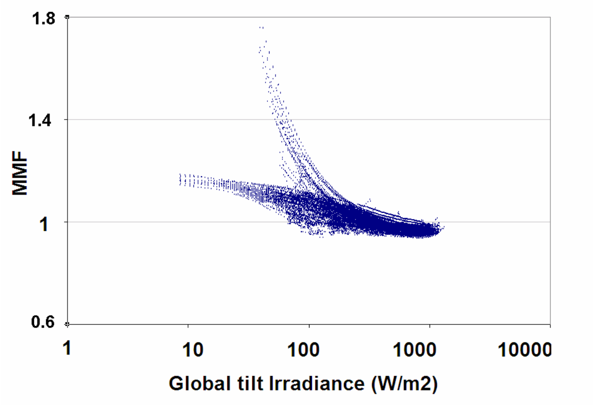
5 RESULTS

The cell performance was modelled for a complete year starting from March 1st 2005 until February 28th 2006 using the minutely generated spectral data in the performance model as described above. Minutely modelled performance parameters and calculated MMF together with global irradiance, air mass and sky clearness index enabled us to assess the cell performance at any time during the mentioned period. As an impression of the results, the months of December (as representative of the winter season) and June (as representative of summer) were selected and the mismatch factor in these months was plotted against the global irradiance for both a-Si (Figs. 8 a/b) and mc-Si (Figs. 9 a/b).

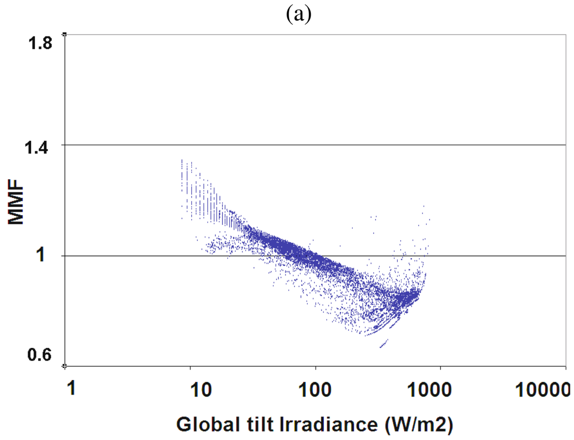
In general a-Si is more sensitive to spectral changes, as is clear from the larger variations in MMF compared to mc-Si, in particular in the winter (Fig. 8b). The situation for mc-Si however is different; since mc-Si has a wider spectral response (see Fig. 4). Figs. 9 a/b show that mc-Si is less vulnerable to spectral changes and MMF fluctuates close to the unity line. Minutely data shows that the MMF varies between 0.66 and 1.77 for a-Si and 0.74 and 1.11 for mc-Si.

5.1 Amorphous silicon performance

The modelled a-Si annual performance for a complete year, averaged to monthly values, is shown in Fig. 10. It reveals that the maximum difference between the two spectra is in winter, while the minimum difference is in the summer. This can be explained by the fact that in the winter irradiance is generally redder of colour than in summer for the elevation of the sun is lower in the winter (high air mass). Thus modelled spectra (SEDES2) contain less blue than scaled AM1.5, which results in a better performance of the cells than for scaled AM1.5 spectra. In the summer the characteristics of modelled spectra are closer to scaled AM1.5, which leads to smaller differences in performance. The maximum monthly difference in a-Si energy output related to spectral changes was found at −13% in the winter. The total annual energy output per square meter for a-Si is 94.63 and 97.52 (kWh/m^2), for modelled (SEDES2) and scaled AM1.5 spectra, respectively, see also Table II. In other words, using scaled AM1.5 spectra leads to an overestimation of the a-Si annual energy output by 3%. Since the nominal peak power of the cell is supposed to be 73.5 Wp/m^2 (at

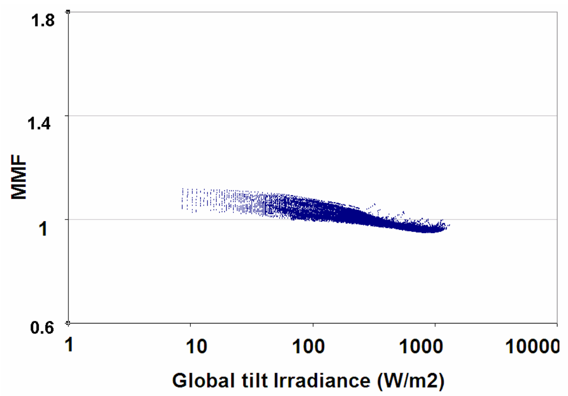


(a)

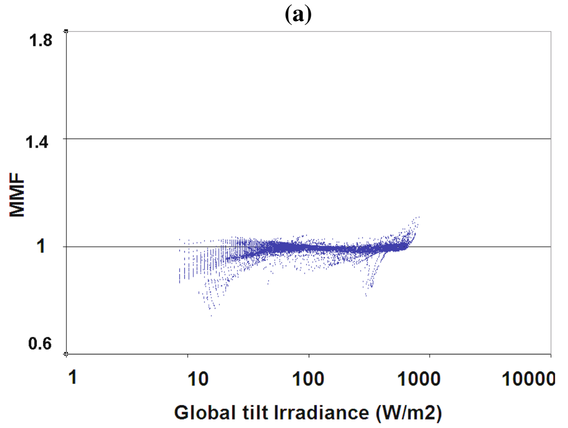


(b)

Figure 8: Mismatch factor as a function of Global tilt irradiance for a-Si in June 2005 (a) and December 2005 (b)



(a)



(b)

Figure 9: Mismatch factor as a function of Global tilt irradiance for mc-Si in June 2005 (a) and December 2005 (b)

standard testing condition), the annual energy yield of the cell was calculated to be 1.28 and 1.32 (kWh/W_P) for modelled and scaled AM1.5 spectra. The annually averaged efficiencies, also denoted as effective efficiency [9], are larger than the STC efficiency of 7.1% (Table I).

Table II: Modelled annual performance of a-Si. Note that the total irradiation energy is 1242 kWh/m^2/yr for the period March 1st 2005 until February 28th 2006

Spectral data	SEDES2	Scaled AM1.5
Energy Output (kWh/m^2/yr)	94.63	97.52
Effective efficiency (%)	7.62	7.85
Yield (kWh/Wp)	1.28	1.32

5.2 Multicrystalline silicon performance

Fig. 11 shows mc-Si annual performance for both modelled (SEDES2) and scaled AM1.5 spectra. During the whole year, the energy output for scaled AM1.5 is shown to be higher than modelled spectra. In contrast to the a-Si performance results, the difference in performance is higher in summer than in winter. The reason is that in winter light is generally redder because of high air mass (lower sun elevation) thus SEDES2 simulates a relatively redder spectrum which results a closer performance to scaled AM1.5. On the other hand in the summer, because of more blue light (clear sky conditions) SEDES2 simulates less red irradiance resulting in lower performance (considering mc-Si spectral response). The maximum monthly difference in energy output caused by spectral changes was found to be less serious in mc-Si and equal to −3% in the summer comparing to a-Si (−13% in winter, see Fig. 10). This indicates that using the AM1.5 scaled spectrum leads to overestimating the mc-Si maximum monthly energy output by 3%.

Table III shows that total annual energy output per square meter modelled for mc-Si cell is 167.6 and 170.5 (kWh/m^2) for modelled and scaled AM1.5 spectra, respectively. Annual energy output of mc-Si is overestimated using the scaled AM1.5 spectrum up to 1.7%. Since the nominal peak power of the cell is supposed to be 142W_P/m^2 (at standard testing condition), the annual energy yield of the cell was calculated at 1.18 and 1.20 (kWh/W_P) for modelled (SEDES2) and scaled AM1.5 spectra, respectively. The annually averaged efficiencies (effective efficiencies) are lower than the STC efficiency of 14.2% (Table I).

Table III: Modelled Annual performance of mc-Si

Spectral data	SEDES2	Scaled AM1.5
Energy Output (kWh/m^2/yr)	167.6	170.5
Effective fficiency (%)	13.49	13.73
Yield (kWh/Wp)	1.18	1.20

5.3 Performance comparison

The variation of energy output (kWh) produced in each month per installed watt peak power (Wp) is compared in Fig. 12 for the a-Si and mc-Si cell. The relative yield shows that in the winter the yield of a-Si is quite close to the one of mc-Si, while their maximum difference in yield is occurring in the summer. On a yearly basis, a-Si is thus more productive than mc-Si, which means that for the same amount of installed peak watts, amorphous silicon cells produce more energy than multi crystalline silicon cells for the location of Cabauw (51.971ºN, 4.927ºE). Interestingly, the effective efficiency is larger than the one at STC for a-Si, while it is smaller for mc-Si.

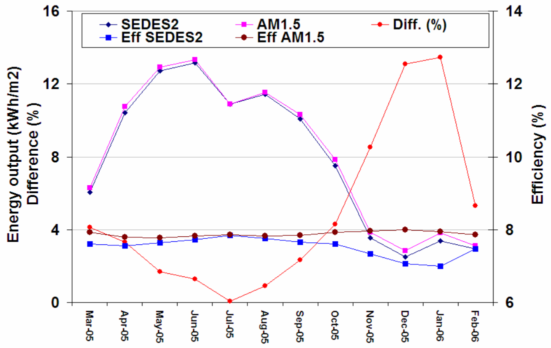


Figure 10: Modelled annual performance of a-Si

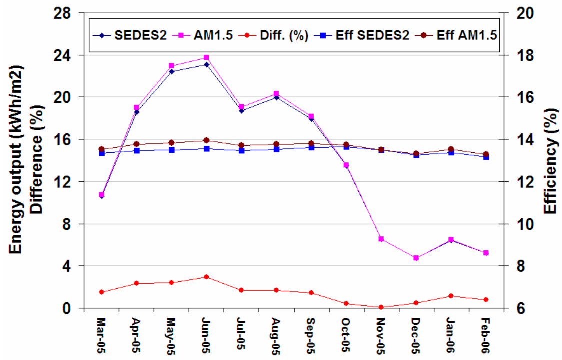


Figure 11: Modelled annual performance of mc-Si

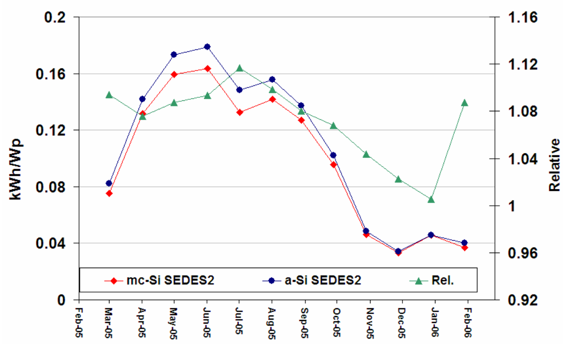


Figure 12: Yield (kWh/W_P) distribution for a-Si and mc-Si during a year

6 DISCUSSION

The model validity study was undertaken for one clear and three different cloudy conditions in the winter and summer (Fig. 5). For these selected weather conditions, the validity study showed that the model is capable of simulating the spectra with a good accuracy. The spectra were modelled and compared to measured values. The Root Mean Square Errors (RMSE) were found to be 7%, 5%, 4% and 3.5% for sky cleanness indexes of 0.03, 0.13, 0.28 and 0.78, respectively. The inaccuracy effect of the model on the output of the cells was also studies and found to be below 2.8% and 1% for a-Si and mc-Si, respectively. The outcome is quite satisfactory since the main goal of this study is to find the spectral effect of solar cell by comparing cells performance using two sets of spectra (modelled and scaled AM1.5 spectra).

However, if SEDES2 is going to be used to simulate prevailing spectra in order to predict precise performance of solar cells, a thorough study on SEDES2 will definitely be needed. The validity study in this report was limited to four different weather conditions in order to see if the model is capable enough to be utilized for the purpose of this research. Therefore, results obtained in the present study should be treated with care for absolute estimation or prediction of energy output of any type of solar cell.

The performance model shows a good agreement with both measured and nominal performance parameters in standard testing condition (STC). However there are still some uncertainties associated with the performance model. One of these uncertainties regards the cell's technical parameters and uncertainties associating with their measurements. This includes the efficiency, spectral response and resistance properties of the cells. Another uncertainty is associated with the model results for conditions other than STC. Since the only available performance data of the cells were measured under STC condition, it was not possible to check its reliability under other conditions. However, since the model is based on the well-known one diode equation, and since it shows good results at STC conditions, the performance model can be utilized safely for a comparison study to assess the effect of spectral variation on the performance of solar cells.

It should be mentioned that the performance model cannot be generalized for other types of mc-Si or a-Si cells. The reason is that the model is using two sets of technical parameters including SR data which belong to these specific cells. Thus the performance model is only valid for these specific cells. Of course, the model itself is generic.

A draw back of the performance model is that the cell temperature is assumed to be always equal to 25°C throughout the whole year. This was explicitly chosen so as to be able to perform the study, while only focusing on spectral effects.

7 CONCLUSION

We have developed a model for the study of the effect of spectral variation on the performance of solar cells. This model is based on experimental irradiance data for one year that are used for the modelling of spectra throughout that year on a minutely basis, by employing the SEDES2 model. A performance model is developed using the well-known one-diode equation [4], and using experimental spectral response and performance data of two specific solar cells: one amorphous silicon cell and one multicrystalline silicon solar cell.

The result shows that the spectral effect is larger for a-Si than mc-Si, as was expected on the basis of the differences in their spectral response curves. From detailed minutely data we show that the mismatch factor (MMF) varies between 0.66 and 1.77 for a-Si and 0.74 and 1.11 for mc-Si.

From the annual yield based on modelled and scaled AM1.5 spectra, it is concluded that a-Si is up to 8% more productive than mc-Si per installed Wp. The annual spectral effect was found to be −3% for a-Si and −1.7% for mc-Si. This indicates that general models, which assume the AM1.5 spectrum, overestimate the energy yield by those amounts.

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