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(54) Title: ENERGY YIELD ESTIMATION MEASUREMENT METHODOLOGY FOR SOLAR CELLS AND MODULES

(57) Abstract: A method for evaluating the energy yield of a solar energy generation unit is proposed. Operating conditions at a geographic location are measured at intervals, and the measured operating conditions are used to formulate representative measurement conditions, including a representative spectrum, an intensity and a representative temperature. These representative measurement conditions are simulated using an I-V tester including a solar simulator which is capable of generating a tuneable spectrum, such as an LED-based solar simulator. The energy generation of the solar energy generation unit is measured under these conditions. The energy yield of the solar energy generation unit during a year is obtained by combining the measured energy yields of all representative measurement conditions, weighted by an occurrence value indicating the duration during the year of conditions approximating the respective representative measurement condition.

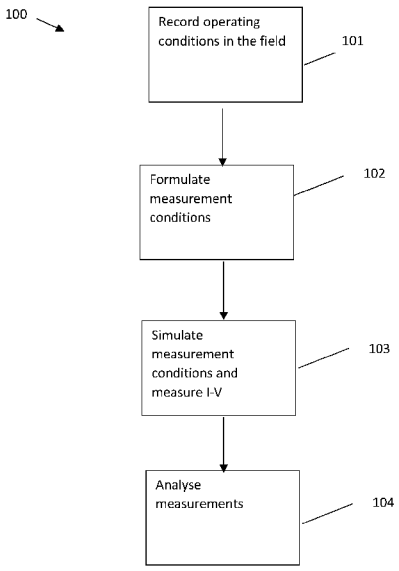


Fig. 1

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Energy Yield Estimation Measurement Methodology For Solar Cells And Modules

Field of the invention

The present disclosure relates to methods and apparatus for determining the energy yield of solar cells or modules.

Background

Solar modules are units which contain at least one array of solar cells. The energy yield of a solar module is usually quoted in terms of the energy which it generates during a year, and hence it is often called the "annual energy yield". Conventionally, the annual energy yield of the module is determined by placing the module outdoors and recording the electrical current and potential (I-V) generated by the solar module for a year. Due to variations in spectrum, irradiance and ambient temperature in outdoor operating conditions, the annual energy yield measured outdoors is usually lower than the expected energy yield which can be calculated from the efficiency determined under standard testing conditions (STC), which specify the solar cell temperature (25°C) and the illumination (AM1.5G spectrum at 1000 Wm^{-2}). Low irradiance conditions frequently occur during field operations and have a noticeable impact on the annual energy yield of solar modules.

This effect applies to all solar photovoltaic devices and is more severe in tandem modules (that is, solar modules in which each solar cell is a "tandem cell" having two or more (in general an integer n which is at least two) planar solar energy generation layers of stacked junctions (sub-cells), i.e. one lies above the other in the "vertical" direction in which solar light passes through the solar module). Note that the stacked junctions may be immediately above each other or separated. It is also possible for the junctions to be arranged in multiple solar energy generation layers but not necessarily stacked; that is, junctions in one of the layers may not necessarily be in register in directions in the plane of the energy generation layers with junctions in other(s) of the layers. In this case, incoming light may be split and directed towards each junction separately. Tandem modules are more sensitive to changes in operating conditions. Conventionally, tandem solar cells/modules have a two-terminal (2T) configuration, a three-terminal (3T) configuration or a four-terminal (4T) configuration, or even more (for example any integer up to $2n$).

Compared to efficiency determined under STC, the annual energy yield measured outdoors allows more accurate calculation of the levelized cost of electricity (LCOE). Hence, this measurement methodology is critical to determine the LCOE of photovoltaic (PV) generation, especially for tandem solar cells/modules.

However, typical procedures for optimizing a solar cell mainly rely on improving the PV efficiency under STC. To achieve current matching in 2T tandem solar cells, device and material properties, e.g. thicknesses of the absorbers in the sub-cells are usually designed according to the standard AM1.5G spectrum. Any variation in operating conditions affects the field performance of 2T tandem solar cells. Hence, it is sub-optimal to estimate the energy yield of tandem solar cells/modules in the field based on their STC efficiency.

The cost of electricity produced by a PV system is highly dependent on the annual energy yield of the system. Therefore, in addition to using STC efficiency as a performance indicator, it is valuable to evaluate the annual energy yield of a tandem solar cell/module using realistic outdoor operating conditions.

Liu et al., "The realistic energy yield potential of GaAs-on-Si tandem solar cells: a theoretical case study," Opt. Express, vol. 23, no. 7, p. A382, 2015, proposed determining the energy yield of tandem solar cells from the outdoor recorded operating conditions. M. Thway, et al., "Energy yield evaluation for field operation of solar cells in Singapore: GaAs/GaAs tandem vs. GaAs single-junction solar cells," in IEEE 44th Photovoltaic Specialist Conference (PVSC), 2017, pp. 284-289 (here “Thway et al.”) measured the effect of irradiance, spectrum and temperature on single junction (SJ) and tandem GaAs solar cells, and determined the importance of the individual factors (irradiance, spectrum and temperature) by considering these factors in a certain sequence. However, it did not propose a methodology for evaluating the energy yield of a solar cell or solar module.

Summary of the invention

The term ““solar energy generation unit” is used in this document to include both an individual solar cell and solar module, that is, a unit which is an assembly of electrically connected solar cells.

In general terms, the present invention proposes a method for evaluating the energy yield of a solar energy generation unit. The method may be performed within a few hours to estimate the annual energy yield of the module.

The method may be performed indoors (that is, substantially in the absence of real sunlight) to estimate the outdoor annual (or any other time period) energy yield of a solar energy generation unit which may be any type of solar cell or module. For example, the solar cell or module may be a mono-facial and bi-facial cell or module, as well as a single junction (SJ) or tandem cell or module.

In particular, the invention suggests using pre-recorded operating conditions in the field to formulate representative measurement conditions. These representative measurement

conditions are then simulated using an I-V tester including a solar simulator which is capable of generating a tuneable spectrum, such as an LED-based solar simulator. The energy generation of the solar energy generation unit is measured under these conditions. Multiplying the measured output power (W) of the solar energy generation unit for each of the representative measurement conditions by a respective occurrence value gives the energy yield for that representative measurement condition during a year. The occurrence value indicates the duration (h) during the year of that representative measurement condition (i.e. the length of time during the year at which actual conditions are equal to the representative measurement condition according to a similarity criterion), By combining the conditional energy yield of all representative measurement conditions, the energy yield of the sample in the outdoor field can be estimated.

The estimated energy yield (harvesting efficiency) is much more representative of the energy output of the sample in the field than the efficiency measured under STC. Experimentally, it was found that a method as disclosed here achieves an accuracy of 98.6% in predicting the energy yield of the solar energy generation unit in real outdoor measurements.

Furthermore, the energy yield analysis of the proposed methodology gives better insight for optimization of processes compared to an I-V measurement under STC. This effect becomes even more apparent for 2T (bifacial) tandem solar cells, which are particularly sensitive to changes in operating conditions. Whereas fundamental and practical losses of SJ semiconductor solar cells limit the AM1.5G efficiency of such devices to about 30%, (bi-facial) tandem technology is expected to dominate the future of photovoltaic industry with efficiency more than 30%. Estimating the performance of such high efficiency solar cells in the field is critical to calculate the LCOE of such systems. The optimization of these solar cells becomes more complicated as they have more junctions and layers than SJ solar cells, so energy yield evaluation gives additional insights and assists the optimization process of high efficiency solar cells.

A method according to the present disclosure may include the following steps:

· Grouping measured operating conditions based on their respective average photon energy (AP)

· Formulation for each group of a representative spectrum — the representative spectrum is chosen by averaging all the spectrums for the operating conditions in the group,

· Formulation for a group of a representative temperature — the representative temperature is chosen by averaging all the temperature values inside a group.

· Formulation of one or more representative measurement conditions for each group. Each representative measurement condition includes the representative spectrum, a representative irradiance level and the representative temperature. Each representative measurement condition is associated with a respective occurrence value. The occurrence value for a given measurement condition may be proportional to the number of operating conditions in the group for which the corresponding irradiance data indicates a light intensity which is closest to the representative irradiance level for that representative measurement condition. Thus, the occurrence value for a given representative measurement condition is indicative of the proportion of the year for which that representative measurement condition is the one, out of all the representative measurement conditions, which the operating condition at the geographic location most closely resembles.

· Measurement — the current and voltage generated by the solar energy generation unit is measured when the unit is irradiated with light produced by a solar simulator (light generation unit) comprising LEDs and the ambient temperature (i.e. the temperature of an environment containing the solar energy generation unit) is maintained at the representative temperature. The LEDs emit light with different respective wavelength ranges, and different ones of the LEDs may have wavelength ranges of different spectral width. The LEDs are preferably controlled to simulate the representative spectrum using calibration algorithm which selects the outputs of the LEDs with broader emission first.

· Energy yield analysis — a computer-implemented algorithm is used to calculate the (annual) energy yield in addition to a performance ratio calculation.

· High resolution analysis — a high resolution energy yield analysis algorithm may be performed to provide insights concerning a detailed loss/gain analysis.

· Correction of measurement result — a fitting algorithm may be performed to correct any slight mismatch between the target representative spectrum and simulated spectrum, thereby minimizing systematic errors in the analysis.

Techniques are also proposed to apply the present energy yield estimation method to bi-facial cells/modules, two-terminal (2T), three-terminal (3T) & four-terminal (4T) tandem solar cells/modules, and cell-to-module energy yield analysis.

Brief description of the figures

Embodiments of the invention will now be described, for the sake of example only, with reference to the accompanying figures in which:

Fig. 1 shows steps of a method which is an embodiment of the invention;

Fig. 2 shows a respective representative spectrum for each APE value (from 1.80 eV to 2.07 eV) over the wavelength range of 300 nm to 1100 nm, with the standard AM1.5G spectrum added for comparison;

Fig. 3 shows the APE 1.80 target spectrum of Fig. 2, and a simulated spectrum produced by an LED I-V tester in an embodiment of the method;

Fig. 4 is a schematic view of performing a method which is an embodiment of the invention for mono-facial solar cell;

Fig. 5 is a schematic view of performing a method which is an embodiment of the invention for a mono-facial solar module;

Fig. 6 shows schematically a method of estimating operating conditions experienced by a bi-facial solar module;

Fig. 7 shows schematically an I-V measurement setup used in an embodiment of the method for bi-facial solar cells using two LEDs solar simulators;

Fig. 8 shows schematically an I-V measurement setup used in an embodiment of the method for bi-facial solar cells using one LEDs solar simulator; and

Fig. 9 shows schematically an I-V measurement setup used in an embodiment of the method for a mono-facial 4T tandem solar cell.

Detailed description of the embodiment

Referring firstly to Fig. 1, a flow chart is shown of a method 100 which is an embodiment of the invention. As shown in Fig.1, this method 100 has four main steps: recording 101, formulation 102, measurement 103 and analysis 104. The method 100 can be applied to any type of solar cell such as solar cells based on silicon, CIGS, GaAs, perovskite and so on, as well as, to solar modules. All these are referred to here as solar energy generation units.

The solar energy generation unit may have a mono-facial or bi-facial configuration, and single junction or tandem configuration, and steps 101-103 vary accordingly. However, the analysis 104 of the measured results and estimation of the energy yield may be the same for different structures of the solar cells/modules.

Furthermore, once steps 101 and 102 have been carried out, steps 103 and 104 may be carried out repeatedly using the results of steps 101 and 102 for different solar energy generation units. We will now explain various implementation of the method 100 for different types of solar energy generation unit.

1. Performance of steps 101-103 for mono-facial solar cells/modules

In the recording step 101, respective operating conditions in an outdoor location are recorded at a plurality of respective times spread out throughout a time period. The respective times are typically at regular intervals, e.g. at equally spaced apart times during daylight hours. The time period may be at least a month, and more preferably is a year. In fact, the time period is preferably as long as possible, since the longer it is the more representative will be the results obtained as explained below.

Each operating condition comprises at least three parameters, namely the intensity (irradiance) of the solar light, the shape of the spectrum (an item of spectral data, i.e. a measurement of solar light intensity at each of a plurality of different wavelengths within a wavelength range), and the ambient temperature. Note that the spectra referred to in this document may be normalised, such that each irradiance and spectrum are independent variables. The spectral data and irradiance data may be collected using a spectro-radiometer, while the ambient temperature data may be collected using a temperature sensor.

The spectrum (item of spectral data) at any time can be characterized by the average photon energy of the spectrum. The average photon energy (APE) is the average of the energy carried by all the photons in a certain wavelength range of a spectrum. The APE of a spectrum within a defined wavelength range can be calculated by dividing the integrated irradiance by the total number of photons within the same wavelength range:

$$APE = \frac{\int_{\lambda_1}^{\lambda_2} I(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} \phi(\lambda)d\lambda} == \frac{\int_{\lambda_1}^{\lambda_2} I(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{I(\lambda)}{hc/\lambda}d\lambda},$$

where $I(\lambda)$ is the intensity distribution for each wavelength of a spectrum, the wavelength range is from λ_1 to λ_2, $\phi(\lambda)$ is photon flux density for each wavelength of the same spectrum, and hc is the product of Planck's constant and the speed of light. APE is used as a metric to define the spectral composition of solar illumination.

For example, in an experiment performed in Singapore from 14-30 November 2018, items of spectral data were captured at intervals of one minute, and the corresponding APE values of these recorded spectra ranged from 1.70 to 2.20 eV. A time resolution of this order (e.g. measurements spaced apart during daylight hours by no more than about 1 to 3 minutes) is preferred for Singapore as its solar spectrum and illumination intensity vary rapidly due to the movement of clouds.

In the formulation step 102, the operating conditions measured in step 101 are grouped based on the corresponding APE values of their respective items of spectral data. For each group, a respective range of APE values is defined (where the respective APE ranges for different groups preferably do not overlap, and preferably collectively span a range of APE values which

includes substantially all the measured APE values). Each operating condition, measured at a respective time, is allotted to the one of the groups for which the APE of the item of spectral data for the operation condition is within the corresponding APE range.

For each group, one or more representative measurement conditions are defined. Each representative measurement condition for the group includes a representative spectrum for the group which is the average of the items of spectral data for the operating conditions allotted to the group. The APE values of the spectral items of the operating condition allotted to each group are averaged to obtain a representative APE value of the representative spectra.

Optionally, if the number of operating conditions (times) allotted to any one or more of the APE ranges is below a threshold (e.g. less than 0.1% of the total number of measurement times), that group can be omitted, i.e. no representative spectrum is defined for that group.

Fig. 2 shows the standard AM1.5G spectrum (line 201). It also shows the representative spectra obtained experimentally corresponding to the representative APE values 1.80 (line 202), 1.86 (line 203), 191 (line 204), 1.95 (line 205), 2.01 (line 206), and 2.07 (line 207).

Typically, there are a plurality of representative measurement conditions for each group. These all share the same representative spectrum, but may differ in their representative illuminance level and representative temperature. The respective representative irradiance levels of the representative measurement conditions may be chosen with an interval of 0.1 suns (1 sun is equivalent to 1000 W/m2).

The number of representative measurement conditions may be chosen such that at least a threshold number of the operating conditions allotted to the group have irradiance data which is within 0.05 suns of the representative irradiance level of one of the representative measurement conditions.

For each representative measurement condition, a respective occurrence value is obtained. This may be done by considering in turn the operating conditions allotted to the group. For each these operating conditions, we find the respective measurement condition which has a representative irradiance level closest to the light intensity indicated by the irradiance data of the operating condition. The occurrence value of each representative measurement condition is proportional to the number of operating conditions of the group for which the light intensity indicated by the irradiance data of the operating condition is closest to the representative irradiance level of that measurement condition.

The representative temperature for each measurement condition may be obtained by (i) identifying the operating conditions of the group for which the light intensity indicated by the irradiance data of the operating condition is closest to the representative irradiance level of

that measurement condition, and (ii) averaging the recorded temperatures for the identified operating conditions.

Note that in a variation of the embodiment, multiple representative temperatures may be defined for a single representative irradiance level, and different ones of the measurement conditions for the group may have the same representative spectrum and the same representative irradiance level, but different ones of these representative temperatures. However, in the discussion below it is assumed that there is only a single representative temperature for each representative irradiance level.

An example of 35 formulated representative measurement conditions are shown in Table 1. Each box shows the representative temperature for the corresponding representative measurement condition. Blank boxes are irradiance values for which no representative measurement condition was defined because the corresponding group of operating conditions contained fewer operating conditions than a threshold having an intensity within 0.05 suns of that irradiance value. The threshold may be equal to one.

It should be noted that the interval chosen for each parameter (APE, irradiance and temperature) has an effect on the accuracy of the energy yield estimation. Hence, the value of the interval should be as small as possible, while keeping the total number of representative measurement conditions under a manageable value.

Temperature (°C)		APE (ev)					
		1.80	1.86	1.91	1.95	2.01	2.07
Irradiance value (suns)	0.1	27	29	28	28	26	26
	0.2		29	31	30	31	35
	0.3		27	32	33	37	
	0.4			32	34	39	
	0.5			32	36	41	
	0.6			33	37		
	0.7			36	39		
	0.8			37	40		
	0.9			38	41		
	1.0			40	42		
	1.1			42	44		
	1.2			40	43		

Table 1

In the measurement step 103, the representative spectra are simulated using a LED solar simulator. For each representative measurement condition, a sample solar energy generation unit is irradiated with a simulated spectrum simulating the corresponding representative spectrum, with an intensity based on the corresponding representative irradiance level, and in an ambient environment maintained at the representative temperature. Specifically, during the measurement step 103, the sample may be placed inside a temperature chamber with a temperature controlled air flow.

Figs. 4 shows schematically possible a measurement setup for a mono-facial cell. The cell is placed on a conductive copper chuck, and energy generated by the cell is measured using electrical probe bars. Fig. 5 shows a measurement setup for a mono-facial module.

In an example experiment, the simulated spectra were calibrated within a plurality of 100 nm intervals as mentioned in the international standard (IEC 60904-9). The LED solar simulator used in this experiment is a Sinus-220 (Wavelabs), which has 21 LED colours. In principle, a higher number of LEDs with different respective wavelengths (i.e. generating light with a wavelength range peaking at different respective wavelengths) would give better control over the simulated spectrum. In this experiment, the intensities of the LEDs were tuned manually to match with each target representative spectrum. It is expected that this process would be automated and incorporated into the LED solar simulator control software in the future. Firstly, the profile of each LEDs at 100% intensity (fully on mode) is recorded. The intensity percentage for each LED is calculated by matching its intensity with the target spectrum at respective wavelength ranges. The intensity percentages of LEDs with broader emissions are calculated prior to those of LEDs with narrower emissions. The intensity profiles of the LEDs are then saved for each target representative spectrum. The representative spectrum 301 for APE 1.80 is shown in Fig. 4, together with the simulated LED spectrum 302. Since the representative spectra are location specific, the calibration is repeated for each set of representative spectra at least once. The calibration can be automated by incorporating the calibration algorithm into the software used to control the LEDs as mentioned earlier. The measurement of energy yield was measured for each of the formulated representative measurement conditions listed in Table 1. Thus, the measurements included measuring the sample under 6 different spectra at 12 representative irradiance levels.

2. Performance of steps 101-103 for bi-facial solar cells/modules

Bi-facial solar cells/modules have having two differently-directed (oppositely facing) surfaces for receiving light. Typically, a first surface is directed skywards, and the second surface faces away. Thus, the cells/modules receive additional light from the rear onto the second surface

depending on the reflectance of the background. Hence, the data recording, formulation and measurement methodologies take more effort than in the case of mono-facial solar cells/modules.

In one option, during the data recording, there are at least two spectro-radiometers measuring respectively the sunlight and the reflected light from the background. The spectro-radiometers are placed back-to-back, and facing in opposite directions. The horizontal tilt angle of the recorders follows the tilt angle of the modules. The recorders are preferably placed near bi-facial solar modules to capture the shading effect of those modules on the background. In some applications, the bi-facial modules may be mounted vertically. In order to estimate the energy yield of the vertically mounted bi-facial modules, the spectro-radiometers are mounted vertically following the intended orientation of the bi-facial modules. Only one thermometer is needed to record the ambient temperature.

Thus, each operating condition comprises temperature data recorded by the thermometer, and data recorded by each of the two spectro-radiometers. The data recorded by the spectro-radiometer facing the sun will be referred to as direct (front) illumination and the data recorded by the other spectro-radiometer as reflected (rear) illumination. In case of vertically mounted spectra-radiometers, the data recorded by the spectro-radiometer that faces the rising sun in the morning will be referred to as direct illumination.

Representative measurement conditions for the front illumination can be formulated by following the same methodology for the mono-facial solar modules explained above. That is, the operating conditions are grouped based on the APE of the spectra for the direct illumination. Then, each group of operating conditions is further divided into subsets based on irradiance data for the front direction illumination.

However, in the bifacial case, each sub-set of the operating conditions may also include recorded data for the rear illumination. Each sub-set of operating conditions, is partitioned into a plurality of sub-sub-sets based on the measured data for the rear illumination, using similar methodology as grouping the front illuminations. A respective representative measurement condition (relating to both front and rear illumination) is defined for each of these sub-sub-sets. Hence, the total number of representative measurement conditions relating to both front and rear illumination, is equal to the number of rear representative measurement conditions (i.e. equal to the total number of sub-sub-sets of the operating conditions).

Each representative measurement condition includes a first (front) representative spectrum and (first) irradiance level derived by averaging the data generated by the front spectro-radiometer for the corresponding sub-group of operating conditions. It would further include a second (rear) representative spectrum and second irradiance level derived by averaging the

data generated by the rear spectro-radiometer for the corresponding sub-sub-group of operating conditions.

A representative temperature for each representative measurement condition is determined using the same method as for mono-facial modules mentioned earlier. That is, the representative temperature for a given representative measurement condition is the average of the temperature measurements for the corresponding sub-sub-set of operating conditions.

In a variation, only the illumination data for the front side is recorded/available for each measurement time. In this case, all the representative measurement conditions are defined using this illumination data for the front side, in the manner described above for mono-facial modules. Data describing the reflected (rear) illumination is calculated, for example using ray tracing or other appropriate modelling software. This can be done using a simple model, illustrated in Fig. 7, where the bi-facial solar energy generation unit (as shown in Fig. 7, a solar module) is considered as placed in front of a background. Firstly, the reflectance of the background and the transparency of the module are determined. There are two sources of reflected light from the background: the light that is transmitted through the module and the ambient stray light from the surrounding. Fig. 7 shows schematically the reflection of light from the background. The amount of reflected light reaching the module also depends on the tilt angle ϕ and the distance x shown in Fig. 7 between the rear surface of the bifacial module and the background. The data for the representative measurement conditions relating to the reflected light reaching the module can then be calculated by considering the reflectance of the background, the transparency of the module, the tilt angle and the distance.

Turning to measurement step 103 for a solar energy generation unit which is a bi-facial solar cells or module, it may be performed using two light sources. The setup in the case that the solar energy generation module is a solar cell is shown in Fig. 7. A setup for the measuring the bi-facial solar module would be similar but would omit the electrical probe bars.

For each measurement condition, the representative spectrum and first irradiance level for the front side of the solar cell is used to calibrate the output of a front LED solar simulator 71, while the representative spectrum and second irradiance level for the rear side of the solar cell is used to calibrate the output of a rear LED solar simulator 72. The calibration procedure is the same as that for mono-facial solar cells mentioned earlier. A temperature chamber is used to maintain the ambient temperature at the corresponding representative temperature.

Note that if the illumination of the rear of the solar energy generation unit depend only in a known way on the illumination of the front of the solar energy generation unit (with the dependence being the same for all the measurement conditions), instead of the setup of Fig.

8 a single LED solar simulator 81 can be used to illuminate the front of the solar energy generation unit to provide the front illumination, while a reflector 82 is used instead of a LED solar simulator 72 at the rear side. The reflector 82 is chosen to replicate the known dependence of the rear illumination on the front illumination,

3. Performance of steps 101-103 for tandem solar cells/modules

As noted above, conventionally tandem solar cells/modules can either be in two-terminal (2T), three-terminal (3T) or four-terminal (4T) configurations. A 2T tandem solar cell/module has two electrical terminals. Steps 101 and 102 for 2T tandem solar cells/modules are the same as for the respective (mono-facial and bi-facial) methodologies explained earlier, according to whether the 2T tandem cell/module is mono-facial or bi-facial. Furthermore, no modification to the setup is required to perform measurement step 103 for 2T tandem solar cells/modules. Analysis of 3T tandem devices is built upon 2T devices.

However, for 4T tandem solar cells, the luminescent coupling between the two sub cells is taken into consideration. Steps 101 and 102 should follow the respective methods according to the type of 4T tandem solar cells (i.e. mono-facial or bi-facial 4T tandem solar cells). However, in step 103, unlike SJ solar cells, the I-V measurement of 4T tandem solar cell is performed separately for each sub cell.

The setup of the LED solar simulator(s) is the same as when step 103 is performed as explained above, depending on the type of the 4T tandem solar cell (i.e. mono-facial or bi-facial 4T tandem solar cells).

First, the energy yield of the top sub cell is measured under all the representative measurement conditions. The maximum power point of the top sub cell under each representative measurement conditions is noted.

Subsequently, the energy yield of the bottom sub cell is measured for each of the representative measurement conditions. While this is done, the top cell is biased close to its maximum power point under that representative measurement condition. This is illustrated in Fig. 9, where the electrodes 91, 92 are used to apply this bias while the energy yield of the bottom sub-cell is measured. Note that the biasing procedure is the same for both mono-facial and bi-facial 4T tandem solar cells/modules.

The above procedure may be generalized for tandem cells with a number n of solar energy generation layers which is at least two, and a number of terminals which may be up to $2n$. In this case, the energy yield of the sub-cells under all the representative measurement conditions may optionally be measured separately for different ones of the sub-cells, for example layer by layer. The cell/modules are illuminated such that light passes first through a

"top" (first) one of the layers and then sequentially through the layers to a "bottom" (last) layer. When measuring the energy yield of sub-cells in each of the solar energy generation layers except the top layer, corresponding terminals for the higher layer(s) may be held at a predetermined relative voltages (bias).

Note that the present method is applicable to tandem cells of any form, including tandem cells/modules in which the sub-cells of different solar energy generation layers are not in register in directions lying in a plane of the solar energy generation layers.

4. Analysis step 104 for all types of solar energy generation unit

A programmed processor (optionally the same processor used to control the setup of the measurement step 103) can perform step 104 on the measured results from step 103, under the control of software. The software obtains the measured efficiency of the sample at each representative measurement condition (from the measured I-V for the measurement condition), and determines the power output of the sample. The processor multiplies the power output at each representative measurement condition with the corresponding occurrence value, and thereby obtains an individual power output (Wm^{-2}) contribution for each representative measurement condition.

The power output may be multiplied by the recorded interval (measurement period) to obtain the estimated energy yield (kWhm-2) due to the times that the operating conditions were closest to that representative measurement condition. If the recorded period is one year, the estimated energy yield can be regarded as annual energy yield ($kWhm^{-2}a^{-1}$), where a^{-1} denotes "per year". The annual energy yield depends on the annual insolation ($kWhm^{-2}a^{-1}$) and the annual insolation is dependent on time and location. Hence, the annual energy yield alone may not be sufficient to quantify the performance of solar cells. Accordingly, the "harvesting efficiency", a figure of merit, can be used instead of the annual energy yield. The harvesting efficiency can be calculated by dividing the energy yield by the insolation over the same period.

The energy yield analysis can be further broken down into the energy yield component under each representative measurement conditions. The resolution of this analysis depends on the interval chosen to formulate the representative measurement conditions. The interval can be chosen to be small enough so that a high-resolution insight can be generated. The advantage of high-resolution matrix is that it can be shown in a colour scale map to provide additional insight. This matrix may be generated by extrapolating. However, in principle, a small interval can be chosen to generate a high-resolution energy yield matrix. The higher energy yield region covers from mid- to high-irradiance ranges. This information assists the optimization of solar cells, as well as, the cross comparison of different solar cells under different operating conditions.

In addition to performing calculation of the energy yield, the software is designed to correct the results for any small mismatch in measurement step 103 between the representative spectra and the simulated spectra, as well as any discrepancy between the representative irradiance level and the intensity of the artificial light. In step 103, the actual illumination conditions such as APE and irradiance during I-V measurement are recorded for each measurement. In step 104, the software reads the actual illumination data (APE and irradiance), and modifies the efficiency for the corresponding measurement condition based any discrepancy between these values and the targeted representative spectrum and irradiance level. The fitting algorithm used may be a piecewise cubic Hermite interpolating polynomial (PCHIP) if the curve has more than three data points; otherwise, it may employ linear fitting. As the mismatch between the targeted and the actual measured conditions is usually small, the fit usually corrects the measured efficiency value by less than 1%. This correction reduces any systematic error introduced by the mismatch in the targeted and simulated illumination.

Optionally, the software may have a number of additional features. As noted above, method 100 can be applied to solar energy generation units which are both cells and modules. By consistently comparing the energy yield of cells and modules, this measurement methodology may be used to estimate the energy yield of the modules by measuring the cells. The cell to module loss/gain is affected by many parameters such as the back sheet, the ribbon, the gap between cells and the edge spaces. Optionally, using the energy yield of a cell obtained by method 100, there may be a step of predicting the energy yield of a module comprising multiple cells. This step may consider all these parameters (the back sheet, the ribbon, the gap between cells and the edge spaces) as providing a constant gain or loss. The process may be performed repeatedly for different types of cells and modules, and the results used to perform a learning and correcting process, which may involve the use of artificial intelligence (AI).

Claims

1. A method of determining the energy yield of a solar energy generation unit at a geographic location, the method comprising:

obtaining a plurality of operating conditions, each operating condition being a dataset characterizing the geographic location at a respective one of a plurality of times during a measurement period, each operating condition comprising an item of spectral data characterizing the wavelength distribution of solar light incident at the geographic location at the respective time, irradiance data characterizing the level of light intensity of the geographic location at the respective time, and thermal data characterizing the temperature of the geographic location at the respective time;

grouping the operating conditions into groups based on a respective average photon energy of the respective items of spectral data, and for each group using the items of spectral data of the corresponding operating conditions to derive spectral data characterizing a representative spectrum;

for each group, using the irradiance data and thermal data of the corresponding operating conditions to derive at least one corresponding representative measurement condition, each representative measurement condition comprising the spectral data characterizing the corresponding representative spectrum, a representative irradiance level and a representative temperature, and each measurement condition being associated with a respective occurrence value;

successively for each group, and for each corresponding representative measurement condition:

(i) maintaining an environment containing the solar energy generation unit to be at the corresponding representative temperature, and irradiating the solar energy generation unit with artificially generated light, the artificially generated light having a wavelength distribution based on the corresponding representative spectrum and having an intensity based on the corresponding representative irradiance level, and

(ii) measuring an energy yield of the solar energy generation unit; and

calculating the energy yield of the solar energy generation unit as a sum of the measured energy yields weighted by corresponding occurrence values indicative of the proportion of the year for which the operating condition at the geographic location most closely resembles the respective representative measurement condition.

2. A method according to claim 1 in which, for each group, there are a plurality of representative measurement conditions which each have different representative irradiance levels.

3. A method according to claim 1 or claim 2, in which the solar energy generation unit is a bi-facial solar energy generation unit having two differently directed surfaces for receiving solar light, said irradiating the solar energy generating unit with artificially generated light comprising:

irradiating a first of the surfaces of the solar energy generation unit with artificially generated light having a wavelength distribution based on the corresponding representative spectrum and having an intensity based on the corresponding representative irradiance level, and

irradiating a second of the surfaces of the solar energy generation unit with the artificially generated light after it has passed through the solar energy generation unit and been reflected towards the second surface of the solar energy generation unit.

4. A method according to claim 1 or claim 2, in which the solar energy generation unit is a bi-facial solar energy generation unit having two differently directed surfaces for receiving solar light, said irradiance data characterizing the intensity of solar light propagating in a first direction, and each operating condition comprising secondary data characterizing the intensity of solar light at the geographic location propagating in a second direction different from the first direction,

each said representative measurement condition further comprising a second representative irradiance level based on the secondary data of the corresponding group of operating conditions,

said irradiating the solar energy generating unit with artificially generated light comprising irradiating a first of the surfaces of the solar energy generation unit with artificially generated light having a wavelength distribution based on the corresponding representative spectrum and having an intensity based on the corresponding representative irradiance level, and irradiating the other surface of the solar energy generation unit with artificially generated light having an intensity based on the corresponding second representative irradiance level.

5. A method according to claim 4 in which each group, the representative measurement conditions comprise a plurality of representative measurement conditions having the same representative irradiance level and representative temperature, and which differ in their second representative irradiance level.

6. A method according to any preceding claim in which the solar energy generation unit comprises at least two solar energy generation layers, the artificially generated light being directed to pass successively through the two solar energy generation layers.

7. A method according to claim 6 in which the solar energy generation unit comprises, for each of the solar energy generation layers, respective electrodes for applying voltages to the solar energy generation layer.

8. A method according to claim 7 comprising, during said irradiating of the solar energy generation unit with artificially generated light, applying a voltage bias to the electrodes of the solar energy generation layer through which the artificial generated light first passes.

9. A method according to claim 8 in which the voltage bias is substantially equal to a maximum power point of the solar energy generation layer through which the artificial generated light first passes.

10. A method according to any preceding claim comprising generating the items of spectral data and irradiance data at the respective times using a photodetector, and generating the temperature data at the respective times using a thermometer.

11. A method according to claim 10 when dependent upon claim 4 further comprising generating the irradiance data by measuring the intensity of light propagating in the first direction, and generating the second irradiance data by measuring the intensity of light propagating in the second direction following a reflection.

12. A method according to claim 10 when dependent upon claim 4 further comprising generating the irradiance data by measuring the intensity of light propagating in the first direction, and generating the second irradiance data by multiplying the irradiance data by a reflectance factor.

13. A method according to any preceding claim further comprising measuring at least one discrepancy between the measurement conditions and at least one of the irradiance level and spectrum during said irradiating of the solar energy generation unit with the artificially generated light, and correcting the corresponding measured energy yield based on the measured discrepancy.

14. A system for determining the energy yield of a solar energy generation unit at a geographic location, the system comprising:

a light generation unit for irradiating a solar energy generation unit with artificial light;

a temperature control unit configured to control the temperature of the solar energy generation unit;

a memory storing a plurality of representative spectra, and for each representative spectrum data defining one or more representative measurement conditions, each representative measurement condition comprising a respective one of the plurality of respective representative spectra, a respective representative irradiance level and a respective representative temperature, and each measurement condition being associated with a respective occurrence value;

a power measurement unit for measuring electrical power generated by the solar energy generation unit; and

a processor arranged, successively for each corresponding representative measurement condition, to:

(i) control the temperature control unit to maintain an environment containing the solar energy generation unit to be at the corresponding temperature;

(ii) control the light generation unit to irradiate the solar energy generation unit with artificially generated light, the artificially generated light having a wavelength distribution based on the corresponding representative spectrum and having an intensity based on the corresponding representative irradiance level;

(iii) receive from the power measurement unit data indicating the electrical power generated by the solar energy generation unit for the representative measurement condition;

(iv) calculate the energy yield of the solar energy generation unit as a sum of the measured energy yields weighted by corresponding occurrence values indicative of the proportion of the year for which the operating condition at the geographic location most closely resembles the respective representative measurement condition.

15. A system according to claim 14 further including a reflector for reflecting light which has passed through the solar energy generation unit back towards the solar energy generation unit.

16. A system according to claim 14 further including a second light generation unit for irradiating the solar energy generation unit with artificial light from a direction different from the direction in which the first light generation unit irradiates the solar energy generation unit, the processor being configured during the irradiation of the solar energy generation unit by the light generation unit to control the second light generation unit to irradiate the solar energy generation unit with artificial light having a wavelength distribution based on the corresponding

representative spectrum and having an intensity based on a second representative irradiance level comprised in the corresponding measurement condition.

17. A system according to any of claims 14 to 16 which is operative to supply a bias to electrodes of a first solar energy generation layer of the solar energy generation unit while the power measurement unit generates data indicating the electrical power generated by a second solar energy generation layer of the solar energy generation unit.

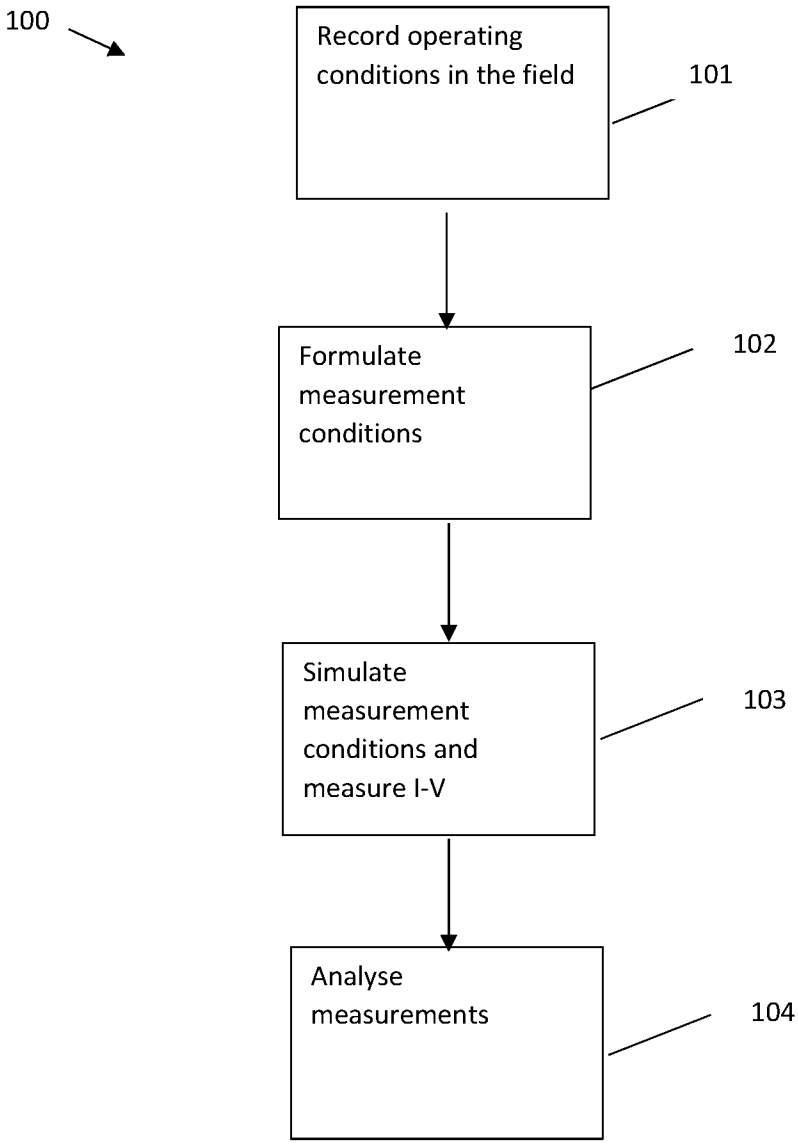

100
Record operating conditions in the field
101
Formulate measurement conditions
102
Simulate measurement conditions and measure I-V
103
Analyse measurements
104

Fig. 1

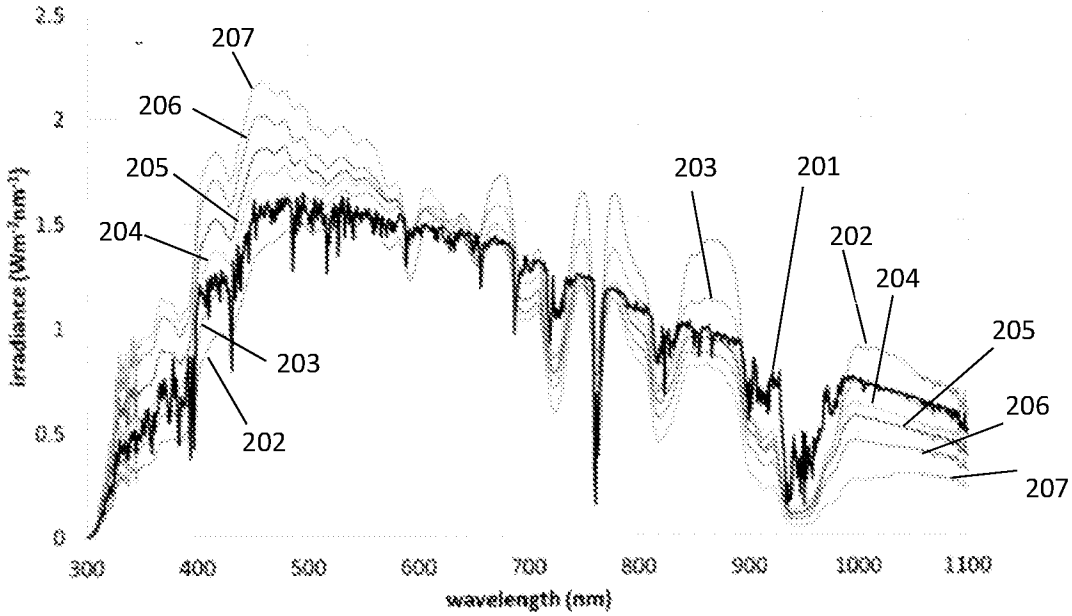

2.5
2
1.5
1
0.5
0
irradiance (Wm⁻²nm⁻¹)
300
400
500
600
700
800
900
1000
1100
wavelength (nm)
207
206
205
204
203
202
201
203
202
204
205
206
207

Fig. 2

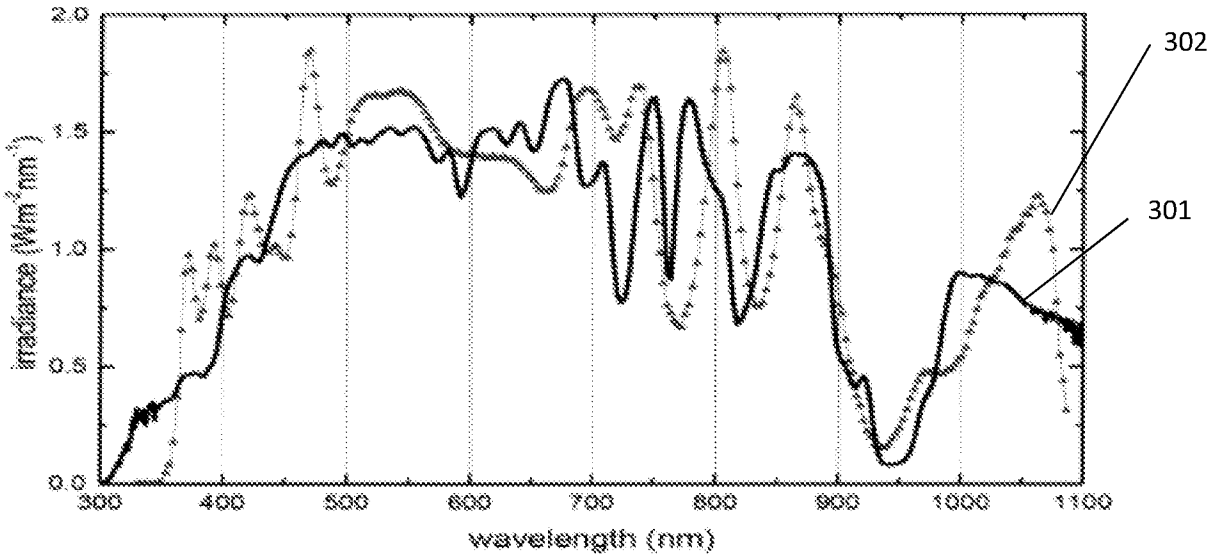


Fig. 3

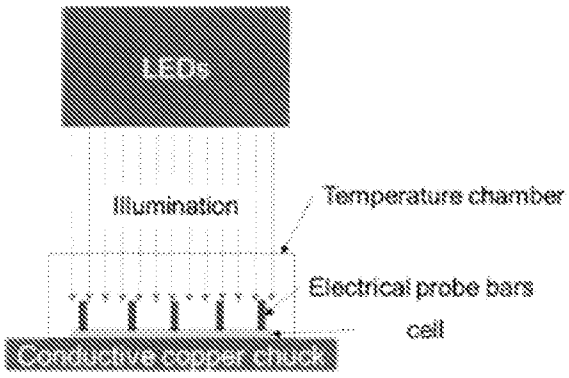


Fig. 4

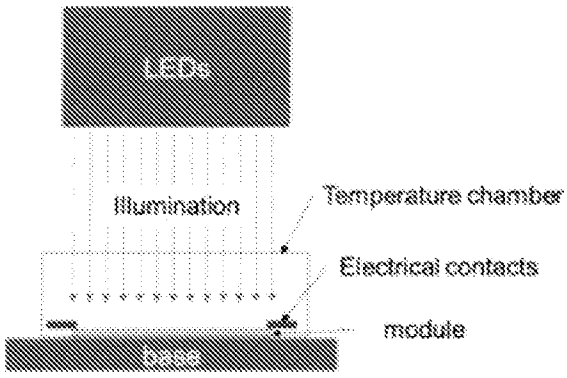


Fig. 5

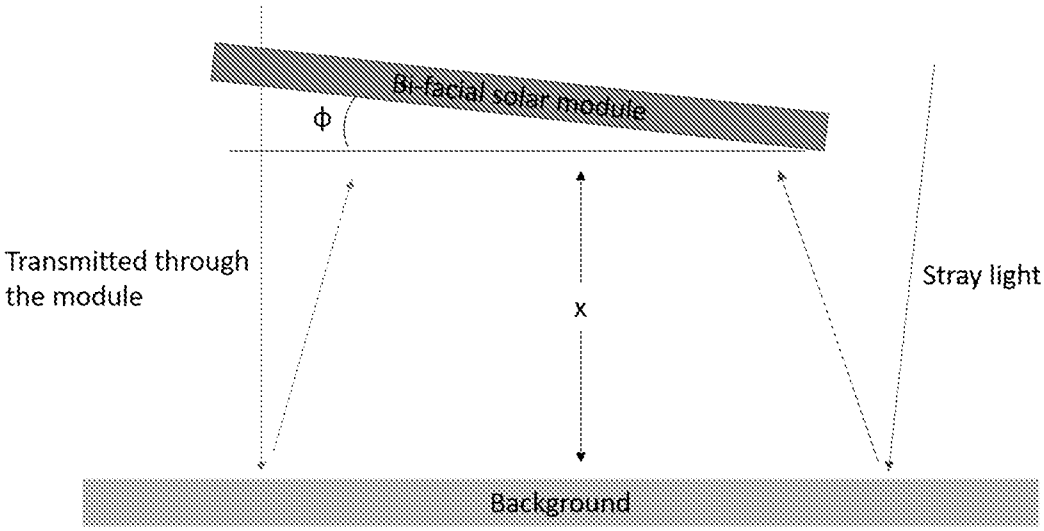


Fig. 6

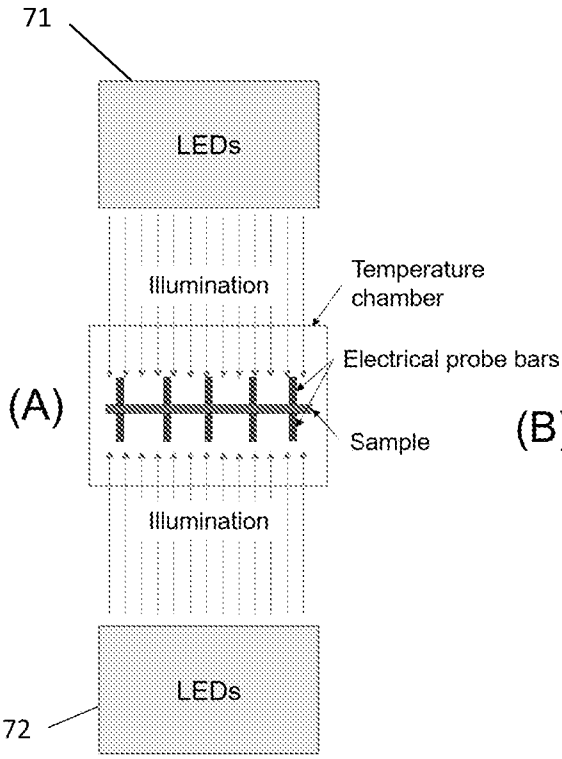


Fig. 7

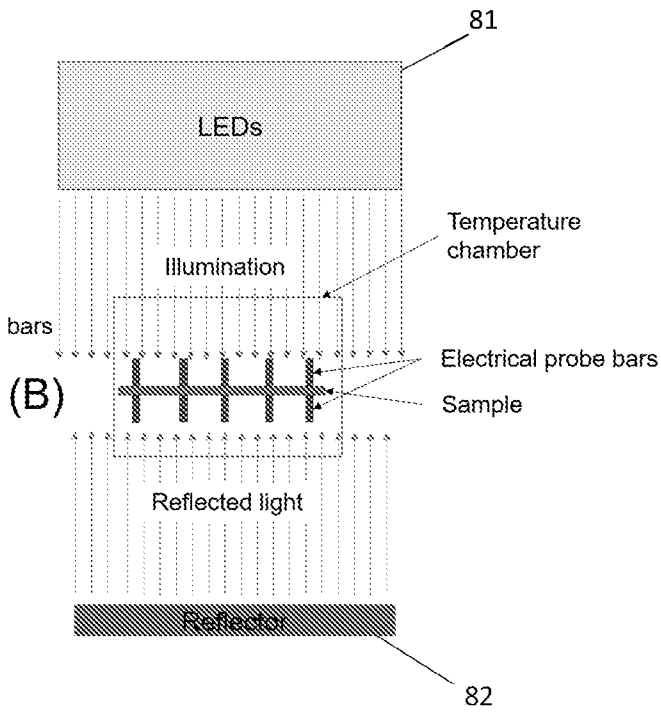


Fig. 8

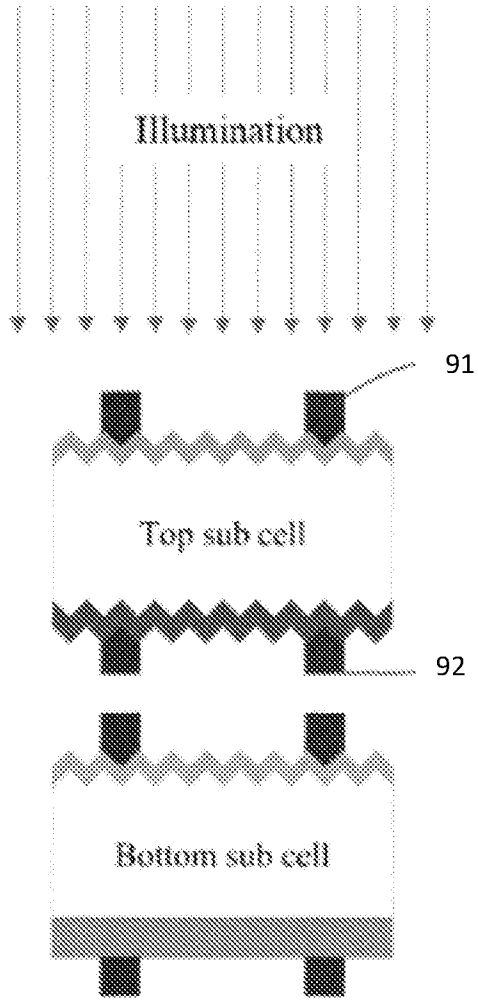


Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2021/050140

A. CLASSIFICATION OF SUBJECT MATTER

H02S 50/10 (2014.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H02S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FAMPAT: solar, photovoltaic, cell, module, efficiency, yield, conversion, performance, power output, test, measure, check, irradiation, spectra, spectrum, irradiance, temperature, geographic, location, place, field, simulate, reproduce, occurrence, ratio, percentage, weightage, reflector, mirror, bi-facial, double side, tandem, multi-junction, 太阳, 光伏, 电池, 组件, 效率, 转化率, 功率, 表现, 性能, 检测, 监测, 测试, 量, 测, 光谱, 谱, 辐照, 辐射, 温度, 地理, 地点, 位置, 模拟, 模仿, 仿真, 几率, 比例, 比率, 比重, 反射, 反光, 镜面, 双面, 双玻, 双面, 双玻, 叠层, 多层 and similar relevant terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	MAUNG T. ET AL., Energy yield evaluation for field operation of solar cells in Singapore: GaAs/GaAs tandem vs. GaAs single-junction solar cells. *IEEE 44th Photovoltaic Specialist Conference (PVSC)*, 30 June 2017, Vol. 2017, pages 284-289 [Retrieved on 2021-05-12] <DOI: 10.1109/PVSC.2017.8366059> Section II, figs. 2 and 7, pg. 2, left col. 2nd para ll. 1-3, 5-8, right col. 1st para. ll. 7-9, 2nd para. ll. 2-9, pg. 4, left col., 1st para. l. 1-3, pg. 5, left col. 2nd para.ll. 1-3, 10-15.	1-2, 6-10, 13-14, 17 3-5, 11-12, 15-16
Y	CN 106972829 A (GUANGDONG AIKO SOLAR ENERGY TECHNOLOGY) 21 July 2017 Fig. 1, para. [0029], [0032] of the original non-English language document (a machine translation is enclosed **only** for your reference)	3-5, 11-12, 15-16

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12/05/2021 *(day/month/year)*	*17/06/2021* *(day/month/year)*

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2021/050140

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	LIU H. ET AL., The realistic energy yield potential of GaAs-on-Si tandem solar cells: a theoretical case study. *Optics Express*, 20 March 2015, Vol. 23, No. 7, pages A382 [Retrieved on 2021-05-12] <DOI: 10.1364/0E.23.00A382> Fig. 1	
A	KR 101472782 B1 (MCSCIENCE) 15 December 2014 Abstract of the machine translation	
A	CN 109756188 A (SHAANXI GSOLAR POWER) 14 May 2019 Whole document of the original non-English language document (a machine translation is enclosed **only** for your reference)	

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/SG2021/050140

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 106972829 A	21/07/2017	NONE	
KR 101472782 B1	15/12/2014	NONE	
CN 109756188 A	14/05/2019	NONE	