The Rating of Photovoltaic Performance

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Abstract—The electrical performance of photovoltaic (PV) cells, modules, and systems are rated in terms of their maximum electrical power with respect to a total irradiance, temperature, and spectral irradiance. The impact of the reference conditions, measurement procedures, and equipment on the performance rating is discussed.

Index Terms—Current, efficiency, photovoltaic, rating, voltage.

I. INTRODUCTION

PHOTOVOLTAIC (PV) devices that are to be rated range from small-area cells to modules to multi-megawatt systems. At the module level and smaller, the current versus voltage (I - V) characteristics and the quantum efficiency are measured, along with the maximum or peak electrical power used in the rating. PV cells are usually rated in terms of their efficiency with respect to standard reference conditions. Solar-concentrator and thermophotovoltaic (TPV) cells are rated in terms of their efficiency as a function of the total irradiance. PV modules typically have a nameplate rating, which gives the maximum electrical power under standard reference conditions, and other parameters such as the temperature coefficient. PV systems are rated in terms of their peak dc or ac power under reference conditions. A variety of energy rating methods being proposed by various researchers are designed to minimize the difference between what the customer expects and what the rating gives at the level of the module and system.

The procedures for determining the rating can dominate all other sources of discrepancy between various groups. The voltage and illumination history prior to the measurement, as well as how and where the current and voltage contacts are made, can be important.

II. REFERENCE CONDITIONS

The current internationally accepted standard reference conditions (SRC) for terrestrial nonconcentrating (flat-plate) PV devices were developed over a period of ten years. The conditions represent a compromise between the simple measurements that can be performed on a factory floor or small research facility and the accurate measurements that reflect the

TABLE I
STANDARD REFERENCE CONDITIONS FOR RATING
SOLAR PV CELLS, MODULES, AND SYSTEMS

Application	Irradiance (Wm^{-2})	Reference Spectrum	Temperature ($^{\circ}\text{C}$)
Terrestrial all	1000	Global ³⁻⁵	25
modules, systems	1000	Global ³⁻⁵	NOCT ⁸
concentration [†]	>1000	Direct ⁶	28
modules, systems	1000	prevailing [‡]	20° ambient
Extraterrestrial	1367	AM0 ⁷	25 or 28

[†] At present, no consensus standards exist, although ASTM is considering a draft standard. The value of 1000 Wm^{-2} actually corresponds to 1.3 times the integrated direct-normal reference spectrum. Most groups have adopted the value of 1000 Wm^{-2} as one-sun for terrestrial applications.

[‡] Linear regression of power to project test conditions, 850 Wm^{-2} , with a 5° field of view for concentrator systems.

performance under actual operating conditions. Manufacturers typically will assign a rating to a module's nameplate that is based on the power at SRC. Because this number is a typical value for a given model, there will be some differences between a module's nameplate rating and its actual performance under SRC. Amorphous silicon manufacturers often report a nameplate rating after an initial exposure period reflecting a "stabilized" rating. This exposure is typically 500 or 1000 h at 50°C and one-sun as measured with a reference cell.

Table I summarizes the accepted standard reference conditions for rating solar PV devices. Standards for infrared-sensitive TPV devices have not been adopted because of the wide range of operating environments [1]. The most serious compromise was to rate PV cells or modules at 25°C , even though modules typically operate at 40 – 70°C under clear-sky conditions. The PV community has arbitrarily taken the term "one sun" to mean a total irradiance of 1000 Wm^{-2} [2]. Consensus standards for space solar cells do not exist although a draft ISO standard is being developed. The national space laboratories have adopted standard procedures consistent with Table I. There are no standards for TPV cells or modules, primarily because the applications, light sources, and operating temperatures are varied and evolving. The term "direct" in

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Table I refers to the direct-normal (5° field of view) spectral irradiance distribution generated by a computer model [3], [4]. The term “global” in Table I refers to a modeled spectral irradiance distribution on a 37° -tilted south-facing surface with a solar zenith angle of 48.2° (AM1.5) [4]–[6]. The terms “AM1” or “AM1.5” are often used to refer to standard spectra, but the relative optical air-mass (AM) is a geometrical quantity and can be obtained by taking the secant of the zenith angle.

Nominal operating cell temperature (NOCT) is a rating designed to give information about the thermal qualities of a module. The NOCT of a module is a fixed temperature that the module would operate at if it were exposed to 20°C air temperature, 800 W/m^{-2} total irradiance, and a wind speed of 1 ms^{-1} [8]. Rating at NOCT benefits modules and systems that operate at lower temperatures and reduces the differences between power produced under field conditions and SRC.

Efficiency measurements with respect to SRC do not distinguish between cells and modules. A variety of definitions for cells and modules have been proposed [9]. A module consists of several electrically interconnected cells. The area of a cell is taken to be the total area of the space-charge region, including grids and contacts. The definitions of standard cell area replace the term “space-charge region” with “frontal area,” but this term does not adequately account for more than one cell on a single substrate or superstrate. The PV efficiency (η) is the maximum electrical power density divided by the incident power density under standard reference conditions. Area definitions often account for the greatest differences in the reported efficiencies among various groups and values published in the literature. The largest differences occur when one uses the so-called “active area” (total device area minus all area that is shaded or not active). The use of active area in efficiency neglects the trade-off between lower resistance losses and increased shading. Several thin-film PV device structures do not have any shading losses, so the active and total areas are the same. At the module level, the total frame area is used. For prototype modules, where the frame design is less important than the encapsulation and cell interconnections, an aperture-area definition is used. This aperture-area definition is the minimum-sized rectangular aperture that can be placed over the module without affecting the performance. An easier-to-measure aperture-area definition is the total area minus the frame area. The national laboratories that provide the independent determination of PV efficiency have agreed on area definitions for reporting efficiency [10].

Unfortunately, performance measurements under natural sunlight differ substantially from the power or efficiency with respect to SRC [11]–[14]. The nameplate rating is a number that the manufacturer assigns to a typical module and is often higher than the measured power output in the field [11]–[14]. The nameplate rating often reflects the initial performance, rather than the long-term performance.

Rating the PV performance in terms of the energy produced over a given time period, where the air and module temperature and the irradiance are changing, is being investigated by several groups [15]–[17]. This effort will address the

discrepancy in module and system energy performance for different climates by referencing the PV module or system energy delivered to a set of reference days or climate zones. The standards organization committee is debating the specifics now.

III. PROCEDURES

The procedures for measuring the I – V characteristics affect the uncertainty of a PV rating. Procedures to measure the maximum electrical power and the effective irradiance have been described extensively in the literature [18]–[21]. Procedures include how the sample is measured, contacted, any treatment that the sample may undergo prior to the measurement, spectral corrections, and temperature. A summary of methods employed by the PV community to artificially enhance or reduce the maximum electrical power is given in [22].

The efficiency of Si, CdTe, Cu(Ga,In)(S,Se), and InP PV devices can be artificially enhanced or reduced depending on pre-measurement conditions, including light and voltage history [22]–[26]. Either sensing the voltage at a location different from where the current is collected or sensing the current at many locations on a device can mask power losses due to nonzero sheet resistance [18], [27]. If the voltage sense is far enough away from the current sense, then fill factors for the device can be larger than what would be achieved with a zero sheet resistance. PV cells deposited on insulating substrates often have a border of In around the cell or a thick layer of Ag epoxy to the metal contact to mitigate sheet resistance losses. At the submodule and module level, attaching separate voltage and current wires to the metal contacts eliminates losses in the efficiency due to external wiring. Unrealistically low fill factors are obtained when measuring the efficiency of cells that produce more than several hundred milliamperes, unless wires are attached. This is because probe contacts cannot adequately simulate the low-resistance contact that can be achieved by ribbons attached to the bond pads.

The spectral error is a common source of error and misunderstanding in rating PV devices. A spectral error will exist if a PV device is rated with respect to a reference spectral irradiance. This is because the sample is measured under natural or artificial light that only approximates the reference spectrum. If the device is rated with respect to the prevailing terrestrial or extraterrestrial spectral irradiance condition, then there is no spectral error by definition, as long as the total irradiance is measured with a spectrally flat detector such as an absolute cavity radiometer. The spectral error can be minimized by choosing a reference detector that has the same relative spectral responsivity as the device being tested. For rating with respect to the prevailing conditions, the reference detector should have a responsivity that is independent of wavelength. In any case, procedures have been developed to numerically correct for this spectral mismatch error for single- or multijunction devices [1], [18]–[21], [28]. The short-circuit current I_{sc} with respect to a reference spectral irradiance distribution $E_r(\lambda)$ under some source spectral irradiance distribution $E_s(\lambda)$ corrected for spectral error can be written as

[28]

$$I_{sc} = I_m \frac{\int_{\lambda_3}^{\lambda_4} E_s(\lambda) * S_r(\lambda) d\lambda \int_{\lambda_1}^{\lambda_2} E_{ref}(\lambda) * S_t(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_s(\lambda) * S_t(\lambda) d\lambda \int_{\lambda_3}^{\lambda_4} E_{ref}(\lambda) * S_r(\lambda) d\lambda} \quad (1)$$

where I_m is the measured short-circuit current of the device under test with a responsivity of $S_t(\lambda)$. The measured spectral responsivity of the photovoltaic or thermal reference detector used to measure the irradiance of the device under test is $S_r(\lambda)$.

For two-terminal multijunction devices, the light source must be adjusted so that the photocurrent for each junction is correct. This is accomplished by separately adjusting the spectrum and intensity of the light source using a reference cell and spectral mismatch correction for each junction, using (1) [29]–[32].

The assumption is typically made that the short-circuit current is linear with irradiance and that the quantum efficiency is independent of light and voltage bias. Thus, the one-sun I_{sc} is accurately measured, and the total irradiance is assumed to be the product of the one-sun total irradiance and the measured I_{sc} divided by the one-sun I_{sc} . These assumptions can introduce errors, either small or substantial, depending on the device [18], [33]. These assumptions can be relaxed by using calibrated neutral density filters or a calibrated concentrator reference cell. The temperature and irradiance dependence of the quantum efficiency will result in the spectral error changing with irradiance and temperature. Quantum efficiency measurements with bias levels above one-sun are problematic because of trying to measure a low-level ac signal with a large dc signal whose noise is larger than the ac signal. Bücher and coworkers have solved this issue for bias levels approaching 200 suns [33].

IV. STATE-OF-THE-ART

The state of the art in PV cell and module performance has been summarized in efficiency tables [34]–[36]. These tables contain results from national laboratories around the world, rather than the usually higher efficiencies reported by researchers. Section III details many of the reasons that differences between various groups can occur. There are numerous reviews of the various PV technologies under consideration, including chapters in books in the *Advances in Solar Energy* series published by the American Solar Energy Society or the *Current Topics in Photovoltaics* series published by Academic Press. Reviews of the national PV programs in the various technology areas are presented at the major PV conferences. Reviews of various technologies, including space cells [37], CuInSe₂ [38], and amorphous silicon [39], have also been published.

Record cell efficiencies are constantly increasing. The trade-off that manufacturers make between high efficiency and reduced cost per watt of power are not reflected in efficiency tables. The highest independently confirmed efficiency is 32.6 % $\pm$ 1.7% at 100 suns for the Boeing GaAs/GaSb

mechanically stacked concentrator cell [34]. Several groups have exceeded 30% efficiency under concentration and at one-sun for the GaInP/GaAs dual-junction monolithic cell [34]. The highest independently measured efficiencies for modules greater than 700 cm² in area are; 10.4% for a triple-junction amorphous silicon fabricated at United Solar Systems Corporation, 9.2% for CdTe manufactured by Golden Photon, 11.8% for a Cu(Ga,In)(S,Se) manufactured by Siemens Solar Industries, 15.3% for multicrystalline Si manufactured at Sandia, and 22.7% for monocrystalline Si manufactured at the University of New South Wales [34]. Solar Cells, Inc. has produced a 61.8-W module with an efficiency of 9.1% [40]. Recently, an 18.8% efficiency was achieved for a Cu(Ga,In)(S,Se) cell manufactured at NREL [41]. The performance of all PV technologies is continuing to increase, while the cost is decreasing. As technologies continue to improve and be mass produced, compromises between performance and cost will continue to be made for large-area flat-plate modules. Accurate rating of the PV performance under standard reference conditions and under field conditions is required to compare various technologies.

V. SUMMARY

The performance of PV cells and modules are rated in terms of their maximum electrical power produced under illumination by the reference spectral irradiance at a given total irradiance and temperature. This rating serves as the basis for comparisons of the efficiency between various technologies. The PV community is attempting to standardize a rating based on the PV energy produced over a given period of time divided by the total irradiance over that same time. The specifics of the time interval (daily, seasonal, or annual) and the air temperature and the total and spectral irradiance versus time are an active area of research.

A variety of artifacts and procedural differences can cause substantial differences in the efficiency. For this reason, the PV community has relied on national laboratories to serve as an independent efficiency verification agency and to be aware of and minimize artifacts and procedural ambiguities.

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