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What is the Appropriate Reference Condition for Determining the Efficiency?

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What is the Appropriate Reference Condition for Determining the Efficiency?

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ABSTRACT

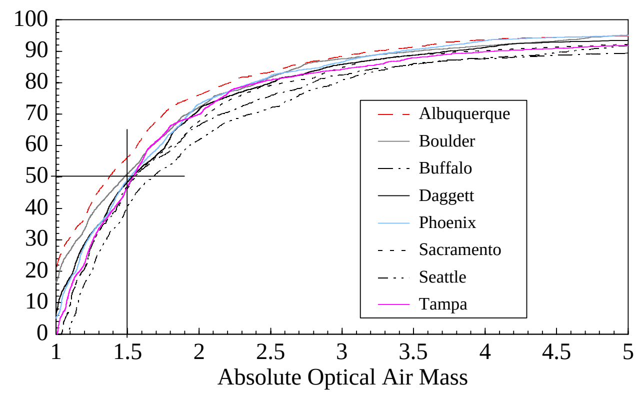
Historically the reference conditions for rating concentrator cells and modules have been informally agreed upon. These conditions for cells are 25°C cell temperature, ASTM E891 direct reference spectrum, and 1-sun is 1000 W/m^2 total irradiance. Concentrator modules have been rated in various ways, typically with respect to prevailing direct normal irradiance. This paper discusses the background of concentrator reference conditions, problems with the direct reference spectrum, and avenues to achieve a consensus for rating concentrator cells and modules.

1. Background

The only consensus standards related to concentrators is the direct-beam spectrum [1], a module qualification document [2], and the obsolete original cell and module standard [3]. The DOE High-Performance PV Project plans to develop a 33% concentrator module and a 40% concentrator cell to be developed. The reference conditions for these ambitious performance goals have been interpreted to mean the defacto concentrator reference conditions adopted by NREL, PVUSA, Sandia, and the Fraunhofer Institute in Germany, and the Progress in Photovoltaics Efficiency Tables [4-9]. These informally accepted conditions are 25°C cell temperature, 1-sun = 1000 Wm^{-2} total irradiance, and the direct-normal spectrum given in reference [1]. The area definition that is used for cells is the area that is designed to be illuminated, which is normally the total area minus any peripheral bus bars or contacts. For modules, the area is taken to be the area of the lens or mirror receiver. Rating procedures for concentrator modules vary from group to group.

Recent work has shown that the direct reference spectrum is not representative of sunny conditions in regions with a high direct-normal annual energy where concentrators might be deployed (the sun belt) [10,11]. A survey of 37 sites in the United States with 433,562 observations found that when the 2-axis hemispherical irradiance is 1001 W/m^2 (σ=1.3), the direct irradiance =834 W/m^2 (σ=22.8), air temperature =24.4°C (σ=4.0), wind speed=4.4 m/s (σ=1.1), and, most significantly, the turbidity @ 500 nm 0.08 (σ=0.02) and relative optical air mass=1.43 (σ=0.09) [10]. The direct reference spectrum integrates to 767 W/m^2 and has a turbidity of 0.27, which substantially reduces the amount of "blue" in the spectrum [1]. The orginal terrestrial reference spectrum for one-sun and concentrator cells and modules listed in reference [3] has turbidity of 0.12. The justification for AM 1.5 as the reference air mass for concentrators is justified by the following graph, showing that 50% of the annual energy is less than AM1.5.

Figure 1. Cumulative annual direct-beam energy from TMY2 data base [15]. Note that for Colorado and New Mexico, 20% of the energy is delivered below air mass 1.



At a given total irradiance and cell temperature under the direct or global reference spectra or under clear-sky natural sunlight, single junction concentrator PV cells or modules produced the same power within ±2%. This result makes moot the question of the applicability of the direct reference spectrum under which to optimize cells. The reason is because in the past, the only concentrators were single-junction Si, GaAs, or independently measured multijunction cells. The highest efficiency measured at NREL was 34.0±1.5% for a GaInP/GaAs/Ge cell at solar irradiances between about 130 and 630 suns under the global reference spectrum, and 30.7±1.5% under the direct reference spectrum [9]. Recent experience of ENTECH at the module level has shown that triple-junction GaInP/GaAs/Ge cells optimized for the extraterrestrial spectrum consistently outperformed cells optimized for the direct reference spectrum. The reason for this was that the direct-beam clear-sky spectra in Fort Worth, Texas and at NREL in Denver, Colorado, at direct beam irradiances above 850 W/m^2 are much closer to the tabular global or extraterrestrial spectra than the tabular direct-beam reference spectrum.

2. Concentrator Reference Spectrum

Changing standard reference conditions is problematic and should not be taken lightly. In the early 1980s, there were a wide range of "AM1.5" spectra that various groups around the world referred to, giving a spread in short-circuit currents of 3% to 9% depending on the spectra and PV technology. The world is now in agreement for the standard reference spectra for evaluating nonconcentrating cells and modules at the national (U.S., Japanese, and European

Commission standards) and international (IEC, ISO) level. This is not the case for concentrators.

At least one group in Japan reports the performance of concentrator cells only with respect to the global spectral irradiance. NREL has recently proposed 3 direct and global reference spectra as an ASTM draft standard [11]. These spectra represent the current reference conditions and two other meteorological conditions with a reduced turbidity. NREL has also proposed, in publications and through IEEE and IEC standards organizations, a set of spectra, irradiances and temperatures corresponding to 5 reference days in the Typical Meteorological Year Data Base [12]. These 5 days correspond to 'hot-sunny," "cold-sunny," "hot-cloudy,' "cold-cloudy," and "nice" days. It would be difficult, but in principle, concentrator cells or modules could be rated with respect to these reference days. Another option would be to rate a concentrator at a specific hour for one of these days such as noon on the hot-sunny day. This would ensure that optimal cells under reference conditions also produce a maximum amount of energy in the field. Concentrator modules and systems have been rated at PVUSA with respect to their performance at a direct-normal irradiance of 850 W/m^2, 1 m/s wind speed and an air temperature of 20°C [5]. This procedure has no provisions for correction to a given reference spectrum. This means that concentrator modules evaluated at direct irradiances greater than 850 W/m^2 are being rated under conditions more representative of the IEC global spectrum or the direct spectrum with a more representative turbidity. Consensus standards for concentrator measurements are currently under development in the United States [13] and Europe.

4. Recommendations

This unfortunate but temporary confusion in rating PV concentrator cells can be rapidly resolved. At NREL, concentrator modules will be evaluated outdoors under prevailing clear-sky conditions without a correction to the existing direct reference spectrum following PVUSA procedures [5]. A first-order spectral correction of outdoor concentrator module data to AM1.5 following the procedure developed at Sandia will be investigated [2]. The Sandia procedure also allows for a single set of procedures to be followed for flat-plate, non tracking low-concentration, and high-concentration modules [2]. Cells for concentrator modules should be optimized for the global spectrum for maximum module efficiency because the global spectrum is much closer than the direct [1] spectrum to conditions where concentrator modules will be evaluated [14].

Until a consensus can be reached, concentrator cell efficiencies measured at NREL will be measured under the global and direct reference spectrum, with the direct spectrum counting for targets. The standards labs must meet in person or via email to make a decision to change the direct reference spectrum to reflect a more realistic turbidity. Interest at present is driven by NREL researchers. The U.S. concentrator industry and the national labs (Sandia and NREL) must reach a consensus on what set of reference conditions should be used in evaluating concentrators.

5. Acknowledgements

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