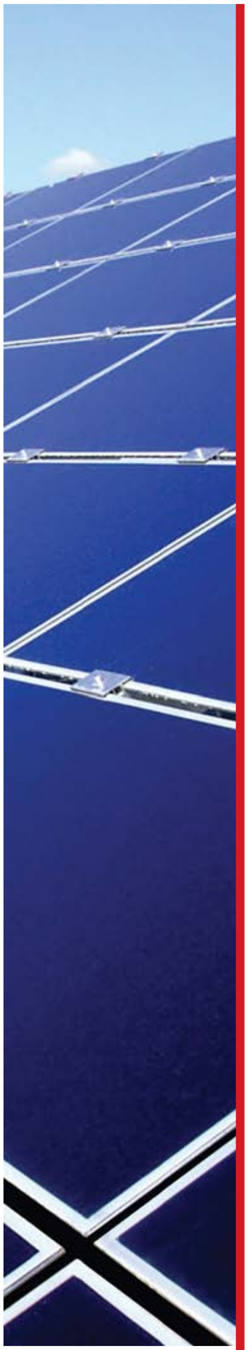

Module Characterization
Spectral Response of FS Series PV Modules

Purpose

The information presented in this document provides supplemental information about the response of First Solar FS Series PV Modules to different wavelengths of light. The data is intended to support the proper design of systems using the FS Series modules as well as the development of more accurate models for energy prediction. All data reported in this document is representative of First Solar FS Series cadmium telluride (CdTe) PV Modules, although some variation of performance between modules is normal and to be expected.

FS Series PV Module Spectral Response

The spectral responses of different FS Series CdTe PV Module types, provided in the form of external quantum efficiency (EQE), are shown in Figure 1. The EQE is limited in the short wavelength region by absorption of photons in the soda-lime glass superstrate material, transparent conducting oxide (TCO) layer, and window layer of the CdTe heterojunction. Photons of wavelength greater than 570nm easily pass though these layers and are absorbed near the PN junction of the structure. These longer wavelength photons create most of the electron-hole pairs which comprise the electrical current produced by the PV module. At wavelengths greater than 830nm, the EQE rapidly drops. This behavior is associated with the bandgap of the CdTe absorber layer. Photons of wavelength greater than 870nm have energies less than the bandgap energy (approximately 1.44eV), and therefore are unable to create electron-hole pairs. Such photons do not contribute to the current produced by a CdTe PV module.

Spectral Response Comparison

In order to make a comparison with the conventional silicon PV module quantum efficiency characteristic, Figure 2 provides overlaid EQE curves for First Solar FS Series CdTe PV Module types, along with the curve of a monocrystalline silicon (Si) PV module. All of the EQE curves have been normalized with respect to the peak response value to highlight the difference in EQE response from one PV module type to the next.

In the wavelength region from 430nm to 550nm, the EQE of the Si PV module shows greater response than the FS Series 3 and FS Series 4 CdTe PV modules for several reasons. The Si module's cover glass is thinner and has less iron content than the soda-lime glass used in FS Series 3 and Series 4 CdTe PV modules. In addition, the Si module has no transparent conducting oxide layer, nor window layer (as is used in a heterojunction CdTe type solar cell), so more of the short wavelength photons are able to get to the PN junction region and contribute to the Si module's photo-generated current.

The FS Series 4V2/Series 4V3 EQE shows significantly better response in the 350nm to 550nm wavelength range than both the earlier FS Series CdTe PV module types and the Si PV module. This improvement in EQE is made possible by changing the design of the transparent layers in front of the CdTe absorver layer in the CdTe PV module. The net result is an increase in the photocurrent delivered by the PV module, when compared to the photocurrent of FS Series 3 and FS Series 4 CdTe PV module types.

Figure 2 also shows that for photons of greater than 870nm, the Si module produces electron-hole pairs, since the bandgap of Si is lower than that of CdTe. The Si response approaches zero at about 1100nm, which corresponds to the bandgap of Si (approximately 1.12eV). The gradual decrease of the Si module's response from 900-1100nm is due the the fact that Si has an indirect bandgap, whereas CdTe is a semiconductor of the direct bandgap type. This property of First Solar CdTe PV modules yields a sharp cutoff in EQE response at the bandgap energy, with good response evident at wavelengths just shorter than the critical wavelength. Photons with energy slightly higher than the bandgap are strongly absorbed in CdTe, whereas the absorption coefficient for similar photons in the Si case is less, and becomes smaller still as photon energies approach the bandgap energy.

While the Si module's response in the 900-1100nm region enables it to make use of more near infrared (NIR) light in the solar spectrum than FS Series CdTe PV Modules can, the amount of energy available in this wavelength region is limited, and decreases with increasing photon wavelength (see the Figure 3 for the spectral irradiance distribution of a typical reference solar spectrum). In addition, atmospheric water vapor strongly absorbs in this region (seen as a notch in the standard spectrum around 950nm in Figure 3). The overall contribution of NIR radiation to the total energy produced by a PV system is limited by these characteristics of the solar spectrum, and thus the value of NIR quantum efficiency in PV modules may not be the most important consideration when evaluating the energy yield of a PV system.

First Solar's Solar Simulator

Figure 3 illustrates both the ASTM G173-03 standard spectrum for hemispherical (global) solar radiation on a 37° tilted surface, and the output of xenon arc solar simulators used at First Solar. As can be seen in the figure, there is close agreement between the standard spectrum and the solar simulator output over much of the wavelength range to which FS Series PV Modules respond (approximately 350nm to 850nm). The simulator shows a higher output in the 300-500nm range and a large spike in output around 823nm. Such spikes occur at wavelengths of characteristic emission lines of xenon and other gases used in the arc lamp source. Since FS Series PV Module EQE falls to zero at around 870nm, disagreement between the spectra shown in Figure 3 at wavelengths greater than 870nm has no impact on the electrical output of the module. First Solar's calibration procedure takes the impact of the higher short wavelength output and the 823nm spike into account, so results of measurements made on PV modules correspond to the output of the modules under the standard spectrum.

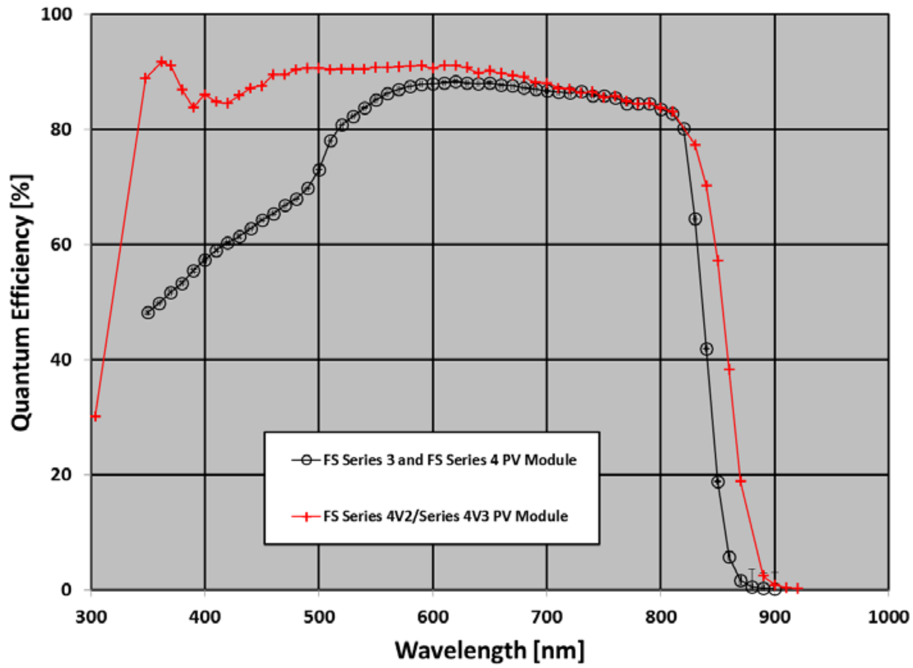

Figure 1. External quantum efficiency of a First Solar FS Series 3, FS Series 4, and FS Series 4V2/Series 4V3 PV Module types.

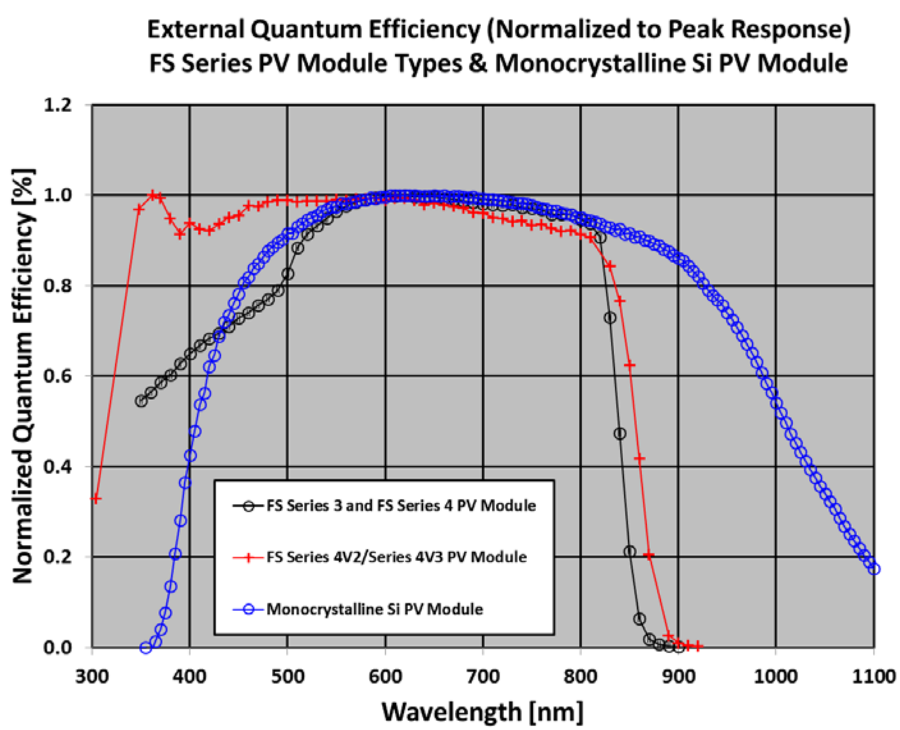

Figure 2. Normalized external quantum efficiency of First Solar FS Series 3, FS Series 4, and FS Series 4V2/Series 4V3 CdTe PV Module types, compared with that of a monocrystalline Si PV module.

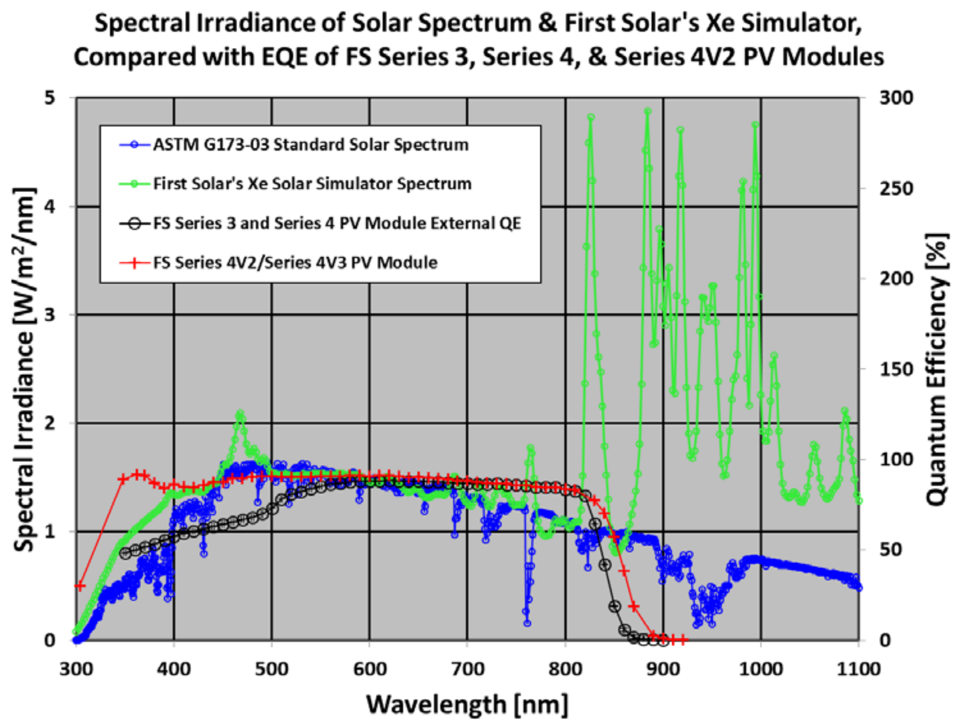

Figure 3. Comparison of the ASTM G173-03 standard solar spectrum and First Solar's continuous xenon arc solar simulator spectral output. The external QE data from Figure 1 are included for reference, and indicate that good agreement exists between spectral irradiance distributions over the response range of First Solar PV modules.