Experimental study of solar spectrum impact on solar cells

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ABSTRACT

Variations in solar spectrum can lead to changes in the performance of solar cells which operate at peak efficiency over a relatively narrow band of the spectrum. In this work, the variations of the solar spectrum were measured at different times during the day under different sunlight and weather conditions using a spectroradiometer. The spectroradiometer output was used to generate plots of the solar spectral irradiance versus wavelength. The insolation levels were derived from the irradiance and the corresponding wavelength. The measured insolation levels were approximately 0.5kW/m^2 for a typical cloudy noon in Hawai`i. Longer wavelengths were more attenuated than shorter wavelengths (by up to 10%) by cloud cover. The effects of different cloud cover during the day were observed. This information may eventually lead to tailoring of the materials used in photovoltaic panels based on the weather conditions of the local region, especially for building installations where the location is fixed.

Keywords: solar spectrum, solar cell, insolation level, light wavelength, semiconductor materials

1 INTRODUCTION

The solar insolation level and incident solar spectrum impact the performance of solar panels which usually have a narrow band over which they operate at peak performance. Atmospheric elements like cloud cover, pollution, aerosols, and volcanic gasses can alter this incident solar spectrum and reduce the solar insolation. It is therefore important to study spectral changes as a function of weather conditions throughout the day. Places like Hawai`i have unique environmental characteristics where some locations rain often throughout the year.

The term "spectral irradiance" describes the amount of solar power available in a certain area at a certain wavelength ($W \cdot m^{-2} \cdot nm^{-1}$) and "solar insolation" describes the integrated radiation over all wavelengths of light (W/m^2)[1]. The spectroradiometer is the sensor used to measure the irradiance. Typical solar spectra taken by the spectroradiometer are shown in Figure 1 and Figure 2.

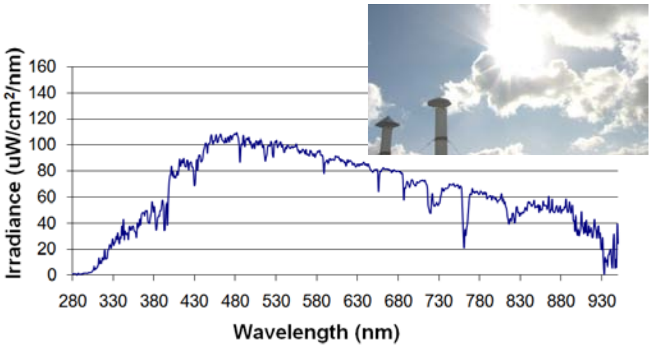

Figure 1: The spectra with corresponding sky pictures on a partly cloudy day.

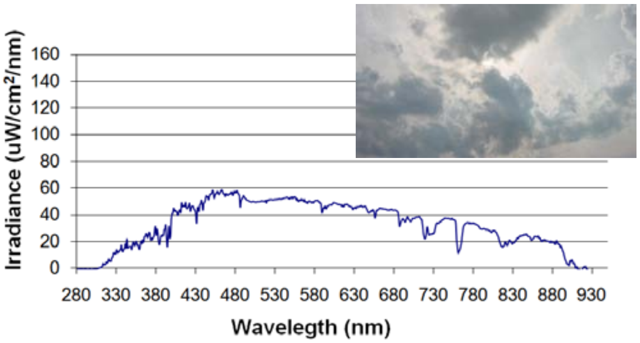

Figure 2: The spectra with the corresponding sky pictures on a cloudy day.

Different weather conditions can lead to a significant change in the solar spectrum affecting some parts of the spectrum more than others and potentially shifting peak wavelengths. If the intensity of the peaks changes throughout the day or under various atmospheric conditions like clouds, haze, smog, volcanic fog, then there may be a preference to install one type of panel versus another to harness the most energy-available portion of the spectrum. Also spectral changes may be an indicator of future weather conditions throughout the day.

Figure 3 shows a relative change of the values revealing that longer wavelengths are affected more than shorter wavelengths.

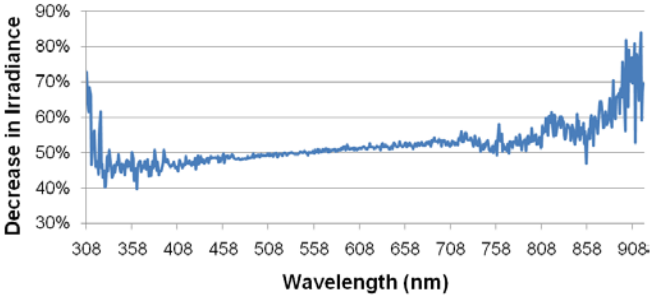

Figure 3: Relative decrease in irradiance due to cloud cover (computed from Fig. 1 and 2).

With the spectroradiometer, the insolation level (*in*cident *sol*ar radi*ation*) of the sun is given by the integration over the spectral irradiance curve. An alternative measuring the insolation level directly is to use a silicon-cell pyranometer which is lower cost than a spectroradiometer, but gives only a single-valued output.

The solar spectrum is affected by many factors including the solar elevation angle. An important term is air mass abbreviated AM. The air mass ratio[2], *m*, is the length of the path h_1 taken by the sun's rays as they pass through the atmosphere divided by the minimum possible path length h_2 (Fig. 4).

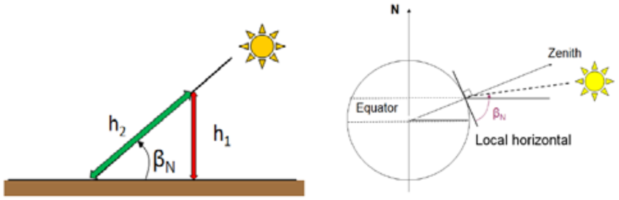

Figure 4: The elevation angle of the sun.

The air mass ratio can be expressed as

Air mass ratio: $$m = \frac{h_2}{h_1} = \frac{1}{\sin \beta_N} \qquad (1)$$

where β_N is the elevation angle of the sun. AM1 means that the sun is directly overhead. AM1.5 is assumed for an average solar spectrum at the earth's surface[3]. The solar spectra for various air mass ratios are shown as Figure 5.

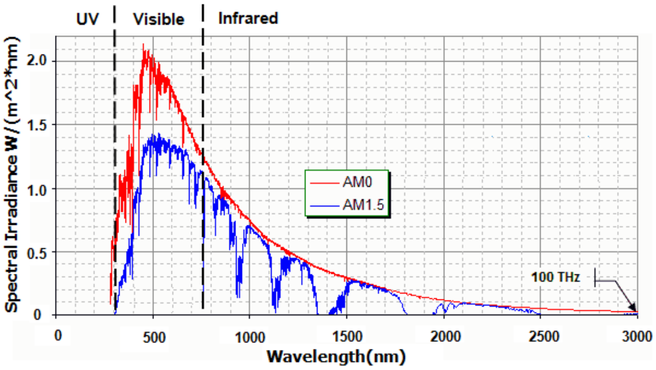

Figure 5: Solar spectrum of AM0 and AM1.5.

The portion of incoming solar radiation is also shown in Figure 5. With AM1.5, 2% of the incoming solar energy is in the spectrum of Ultra Violet (UV), 54% is in visible light, and 44% is in infrared. However, the largest portion of energy is in the visible range, from 380nm to 780nm [3]. The visible range only accounts for 20% of the whole wavelength range.

2 EXPERIMENTAL ARRANGEMENT

2.1 Motivation and Consideration

A motivation for this experiment is to help the UHM Green Holmes Hall Initiative (GHHI) which aims to install photovoltaic panels on the roof to produce power for the engineering building. But before the panels are installed, measurement and analysis of the solar energy is necessary to gain a clear idea on the best panels to use and the best places to install those panels[4].

The measurement should consider several aspects such as weather conditions, ambient temperature, and the various atmospheric conditions. Due to a limitation of the spectroradiometer, the solar spectrum cannot be recorded as continuous data, but several time points to take the measurements can be chosen according to the weather forecast. The spectroradiometer used in the experiment is shown in Figure 6.

Figure 6: The whole set of the spectroradiometer and comparison with the pyranometer on the right.

To calibrate the spectroradiometer, the reference AM1.5 spectrum from the American Society for Testing and Materials (ASTM) was used [5]. The AM1.5 spectrum, occurring at solar noon, corresponds to an insolation of approximately 1.0kW/m^2. But at different times during the day and due to weather conditions, the real insolation is always less than this value.

2.2 Experimental procedure

According to the weather forecast, we chose several representative time points. The solar positions expressed as air mass ratio are given in Table 1. Air mass ratio can be calculated by measuring the shadow s or altitude angle β_N. Assume that the object of shadow length is h_1.

Incident light length: $h_2 = \sqrt{s^2 + h_1^2}$ (2)

Altitude angle: $\beta_N = \arcsin\sqrt{\frac{h_1^2}{s^2} + 1}$ (3)

Air mass ratio: $m = \sqrt{\frac{s^2}{h_1^2} + 1}$ (4)

Time	Shadow length $\times h_1$	Elevation angle β_N °C	Air mass ratio AM
8:30	3.05	18.16	3.2
9:30	1.80	29.02	2.1
10:30	1.28	38.00	1.6
11:30	1.04	44.01	1.4
12:00	0.97	45.85	1.4
13:00	0.99	45.15	1.4
14:00	1.19	39.99	1.5
15:00	1.63	31.54	1.9
16:00	2.61	21.00	2.8

Table 1: Air mass ratio measured in Dec. at Hawai`i.

The measurement was taken over several days and because of the sun position changes every day, the measurement time was shifted two minutes behind to make the solar position constant. The comparison is shown in Figure 7.

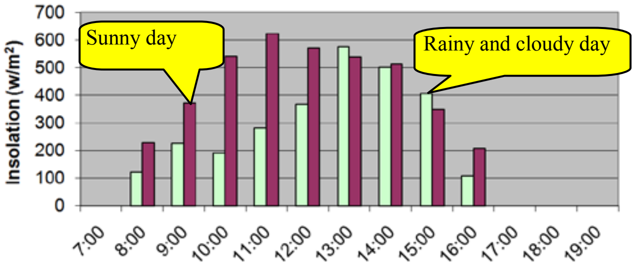

Figure 7: Two days of different weather conditions.

Another set of spectroradiometry measurements were taken over a short period of time to examine the unpredictable nature of the Hawaiian weather, which often changes without warning. This significantly affects the spectral irradiance as shown in Figure 8. Again, the relative decrease in irradiance was calculated from the data to show the spectral impact of the weather. In most cases, the cloud cover impacts the shorter wavelengths less than the longer wavelengths. It is interesting to note the curvature of this decrease which shows that under some conditions (11:00) the longer wavelengths are uniformly decreased while under other conditions (11:03) the longer wavelengths (>700nm) begin to be affected less by the cloud cover.

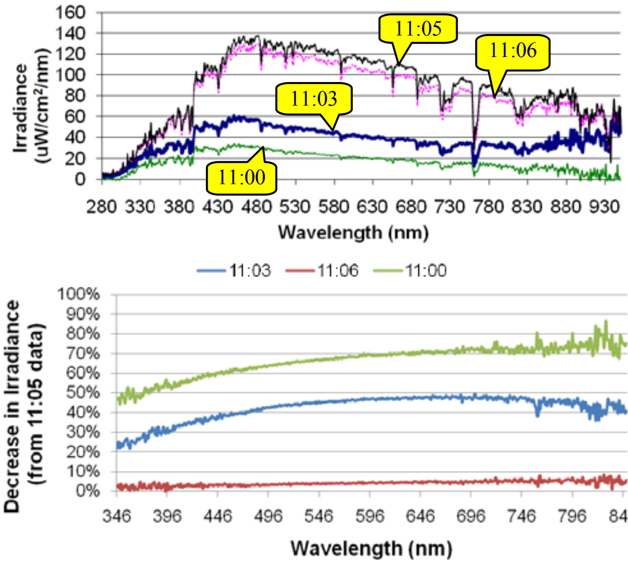

Figure 8: The solar spectrum changed in a short period of time depending on the weather conditions. Clouds blocked the sun at 11:00 and 11:05, and it was partly cloudy from 11:03 to 11:06.

As shown in Figures 7 and 8, the solar spectra have the greatest variability in a short period of time and different weather conditions. These significant changes of solar spectra will play an important role in producing the electricity of solar cells. After the detailed measurements of the solar insolation are collected at the site of the installation, then we can combine those measurements with the weather forecast to predict the intensity and to further estimate the output electricity of the solar cell.

3 RESULTS AND ANALYSIS

In this study, the measured insolation levels were approximately 0.5kW/m^2 for a typical cloudy noon in Hawai`i. These lower measured insolation levels mean the photovoltaic panels will produce less power output.

More specifically, from studies of the semiconductor material properties, it is known that different solar cell materials will respond to different ranges of light wavelength [6]. This certain wavelength range is the effective spectral range for the solar cell materials. Any energy of the solar spectrum with a wavelength longer than the band gap of the material will not be converted to electricity effectively by the device. The traditional standard crystalline silicon devices (c-Si) can respond up to 1100nm. In recent years, thin film devices have developed allowing for absorption on a different spectral range.

Recently, solar cell companies are paying more attention to research done on light transmittance in various air masses and weather conditions. Solar cells are normally tested under the Standard Test Conditions (STC), which specifies the AM1.5 at a temperature of 25°C. The standard AM1.5 spectrum and corresponding spectral response of different solar cell materials is shown in Figure 9.

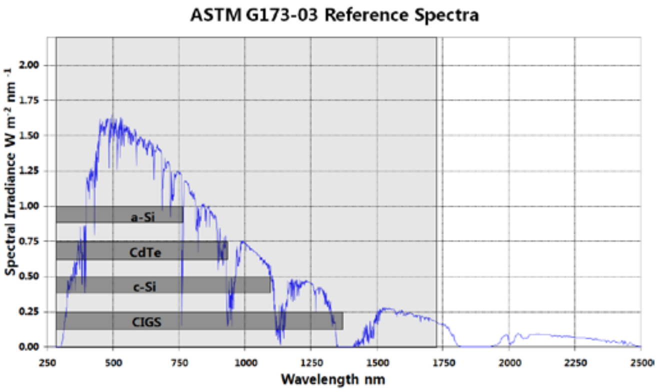

Figure 9: AM1.5 spectrum and corresponding spectral response of different solar cell materials.

For example, amorphous-silicon (a-Si) only responds to wavelengths of 280nm to 780nm while copper-indium, gallium-diselenide (CIGS) thin film can respond up to 1360nm. For other normally-used materials, cadmium telluride (CdTe) can respond from 280nm to 900nm, which is still less than c-Si.

Recall that the larger spectrum ranges the solar cell materials can absorb, the more electricity they can produce. However, the expense of solar cell materials and technical demand must also be considered. The high efficiency materials such as CIGS still cannot widely be used.

To compare with the efficiency of these solar cell materials between several manufactures, the average efficiency is approximately 10%. The highest efficiency is 18.5% using multi-semiconductors. However, all of this statistical data is under Standard Test Conditions (STC). Since the solar spectrum has contributions from direct and diffuse sunlight. The diffusive component can account for about 20% of the total radiation in a clear sky [7]. But the percentage will increase with the cloudy coverage, position of the sun, and other structural effect. So there exists a great variability in the incident solar spectrum at the different locations on the earth's surface.

4 FURTHER STUDY

By using a data acquisition system, we can remote-control a server and download spectroradiometer and pyranometer data to a local computer enabling these instruments to capture continuous insolation data before and during the installation and operation of the rooftop solar panels. It is meaningful for both the solar cell companies and the solar cell researchers to establish this kind of solar data station. For the companies, the data support is a crucial determination on choosing the solar cell materials and installation locations. For solar cell researchers, as seen from the recent research of power-output simulations, most of the PV models use uniform insolation levels as the input and do not consider the specifics of the solar spectrum or the PV materials [8]. If the real-time insolation levels can be used in the models and the spectral response of the specific materials can be considered, then more accuracy on the performance and efficiency of solar cell technologies can be obtained. The simulation result will become a crucial determinant in PV panel installation.

5 CONCLUSION

It is clear that the solar spectrum has a crucial impact on the performance of solar cells. In this experimental study, the spectral irradiance was measured over various weather conditions during the day. The measurement is quite different from the theoretical value. Cloud cover, location of the sun, and other factors like wall reflections directly impact the spectrum. For our project, the solar irradiance measurement is an essential determination of the choice of the solar panel installation site and the solar panel material. If long-term measurements can be sustained at different locations, the collected solar spectra, location, measurement conditions, and correlated weather conditions could become a reference database used in multiple domains of research such as solar energy optimization, building-integrated photovoltaics, and weather prediction.

ACKNOWLEDGMENTS

This study was supported in part by Dr. Anthony Kuh of the Renewable Energy and Island Sustainability (REIS) project. The authors wish to thank Mitch Ewan for technical assistance, graduate student, Robert Brewer, for proofreading and discussion, and undergraduates, Angela Meninghi, Timothy Kutara, and Jordan Torres.

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