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Reflective Efficiencies of Materials for Applications of Bifacial Solar Cells

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Reflective Efficiencies of Materials for Applications of Bifacial Solar Cells

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Thesis Acceptance

LINFIELD COLLEGE

Thesis Title: Reflective Efficiencies of Materials for Applications of Bifacial Solar Cells

Submitted by: Michael A. Metter Date Submitted: May, 2016

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ABSTRACT

Reflective Efficiencies of Materials for Applications of Bifacial Solar Cells

The bifacial solar cell is superior to its monofacial predecessor due to its ability to convert both incident light on top and reflected light from below into energy. The scattering of the reflected light is affected by the property of the material on which it is interacting. To date, little work has been contributed to studying the properties of these materials to determine optimal quantities for bifacial solar cells. In the first experiment, reflective efficiencies compared to the angle of reflection were explored for different grit of sandpaper in order to develop an understanding of how surface texture impacts reflectivity. Then material that would typically be used in construction are explored using the same techniques. As the world becomes more energy efficient, it is important to understand what building materials should be used to increase solar cell efficiencies.

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I: Background

Understanding of solar cell technology and their applications has greatly improved since its invention by French physicist Edmond Becquerel in 1839 [1]. Engineers are constantly exploring new methods and techniques to improve the efficiency of these devices; such as, tandem cells that absorb light more efficiently, cells that absorb incident light better because of anti-reflective films, cells made of improved materials, and bifacial cells that absorb light on both sides [2]. The research described in this paper focuses primarily on the energy collected at the rear surfaces of the cell; in particular, the efficiencies of the surfaces that reflect the light into the back of the solar cell.

In modern day construction, solar cells are used to produce energy for homes, businesses, and cities [3]. It is a clean energy that harnesses the light produced by the sun and converts it into usable electricity. Silicon based solar cells are the most popular and cheapest to produce [4]. As stated above, there are a wide variety of solar cells and they come with varying cost. The benefit of bifacial solar cells compared to the monofacial is that they exceed in efficiency due to the fact it converts both incident and reflected light. Figure 1.1 shows a schematic representation of how light is reflected and absorbed by a bifacial solar cell.

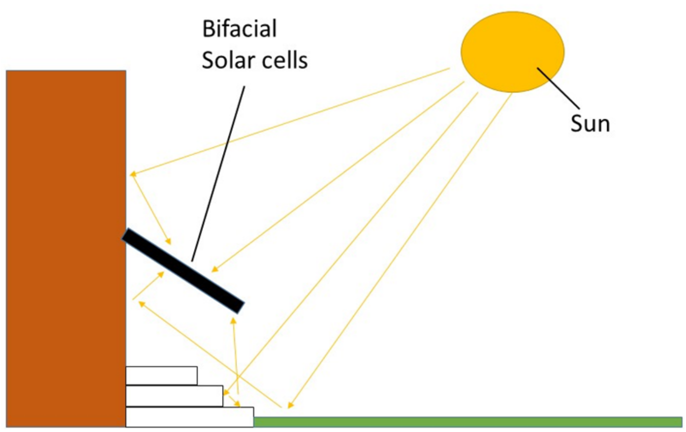

Fig. 1.1. Bifacial solar cell absorbs the incident light from the sun and light reflected off surfaces.

The material that the rear reflective surface is made out of impacts how much energy the cell will produce. The reflective nature of a material is determined by its roughness, which was explored by M. P. Schultz and A. Myers [5]. They compared the three roughness function determination methods of different sandpapers. They decided to use sandpaper because of its already built in roughness system known as grit. Since sandpaper provides a prime sample set of easily varying roughnesses, this experiment will use a similar set of sandpaper to explore the efficiency of reflection for the sandpapers at different angles. The analysis from the sandpaper will be used to understand the characteristic of the construction material being observed.

II: Theory

2.1: Solar Radiation

The goal of the experiment is to explore materials that optimize the output of bifacial solar cells. Solar cells create a more efficient clean energy through converting solar radiation into usable energy. The sun emits electromagnetic radiation of various wavelengths, ranging from ultraviolet to infrared [6]. Half of the electromagnetic waves are reflected back into space as it travels through the Earth's atmosphere and the rest is available for absorption.

2.2: Surface Roughness and Scattering

Light incident on the surface is scattered based on the roughness of its surfaces. Schultz and Myers investigated three methods that determine roughness funciton of a given material. They used a laser diode point range sensor to make their measurements where a variety of different grit sandpaper was explored [5]. Sandpaper, although not a material that would be used as a structural element of a building, provides a simple system for conceptualizing roughness [7]. Grit size indicates the size average diameter of the particles on the surface. The lower number implies a larger average diameter per particle, thus a more rough surface. For example, sandpaper of grit 36 is more bumpy than sandpaper of grit 220. The grit system is consumer based, meaning it may vary depending on manufacturer. The scientific unit of measure for the roughness of sandpaper is given as Average Particle Diameter (APD). Table 2.1 gives the coversions for the sanpdpapers used in the sample.

Table 2.1. Roughnesses of sandpaper given in Average Particle Diameter and Grit

Average Particle Diameter (micrometers)	Grit
530	36
348	50
256	60
190	80
140	100
115	120
92	150
68	220

The roughness of the surface determines the scattering of the incident light. Figure 2.1 shows a visual representation of how light scatters as it contacts a surface of arbitray roughness, whick follows the law of reflection [8]. Notice that in this illustration the surface is fairly jagged and bumpy; it will scatter light more than a smooth surface would.

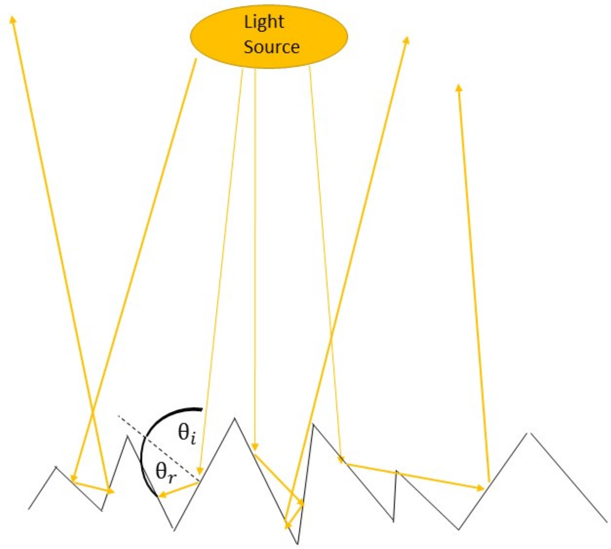

Fig. 2.1. Illustration of light incident on surface of some arbitrary roughness. The light reflects off of the surface determined by the law of reflection.

2.3: Reflective Efficiency

The efficiency of bifacial solar cells can be increased in two ways: by changing the properties of the cell itself, or changing the material reflecting the light into the cell. For this experiment, both the incident light and reflected light are measured for power. These two values are compared which yield the reflective efficiency of surfaces given as

$$\eta = \frac{Reflected\ Power}{Incident\ Power} \text{ x } 100\%. \quad (1)$$

The efficiencies are explored as a function of the light scattering. The material stays at a stationary position while the power meter detects the reflected power from angles 0-90 degrees.

2.4: Mathematical Relationships

To further understand the relationship between the reflective efficiencies and the scattering of light, the area under the curve of calculated efficiencies is measured for the sandpaper. The calculation is given below in equation 2,

$$Area = \int_0^{90} \eta(\theta)\, d\theta. \quad (2)$$

Where area is the integral of the efficiency as a function of the angles being measured (0 through 90) and $d\theta$ is the increments of the measurements. Also, it is expected that the scattering demonstrates behavior similar of normal distribution [9].that can be described as

$$f(\theta) = Ae^{-\beta\theta^2}. \quad (3)$$

The scattering is a function of θ, A is the power of the light at 0° , β (or beta) is the fitting constant which determines the slope of the distribution curve. The fitting constant is the relationship between $\frac{f(\theta)}{A}$ and θ^2, which is solved for by rearranging equation 3. Taking the natural log of both sides yields

$$\ln\left(\frac{f(\theta)}{A}\right) = -\beta\theta^2 \ . \quad (4)$$

Using this relationship, beta can be determined. Once beta is calculated for a given material, it can be plugged back into equation 3 to determine which material produces the largest bell curve. Therefore, it can be expected that beta is negative since a positive number is outputted by the bell curve formula is desired.

III: Experimental Method

In this experiment, the goal is to explore the reflectivity efficiencies of various materials. The first experiment will be the base case to which the rest of the experiment will be compared. For the base case, different grit sandpaper is used because of its linear roughness properties; as the grit number increases, the surface roughness decreases. In the second experiment, the same techniques are used to examine materials that would be considered standard construction material.

3.1: Supplying Power for the Source

A power source that imitates the solar energy is required. The light source use was a Sylvania Halogen Flood Faisceau Large Bulb; a 50 watt, 12 volts, 4000-hour bulb. A variable autotransformer was used to supply power to the halogen bulb. To measure the output of the variable autotransformer, a (Keithley 175 AutoRanging Multimeter) multimeter was connected to the output. For this experiment, the ideal output was around 8.3V because any higher and the halogen bulb was found to burn out. Lower voltages supplied didn't produce enough light to observe any disparities in the data being collected.

3.2: Collimating the Light

A halogen light was used as the light source in exchange of the sun. It is important that the light is collimated prior to contacting the surface. This way the reflected light can be easily analyzed. Collimating light can be described as light rays that are parallel to one another, so that as they propagate, the image it produces does not change in size [10]. An example of perfectly collimated light would be a laser beam; however, in order to replicate the light spectrum emitted by the sun, a halogen bulb is used. The convex lens is thicker in the middle, which bends the light.

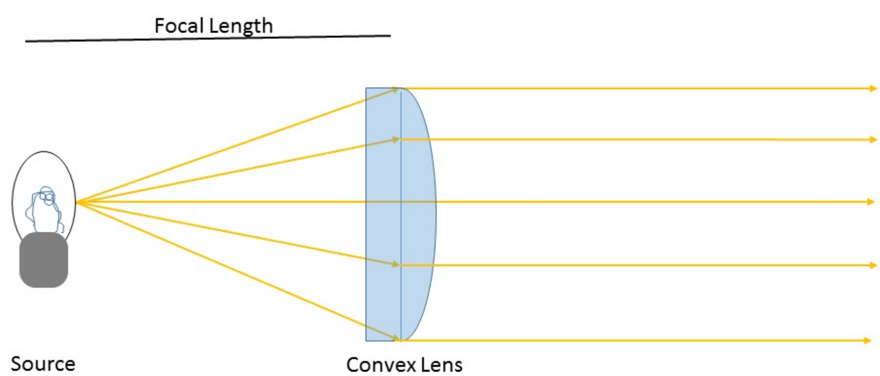

Fig. 3.1. Light emitted from a source are collimated as it refracts through a convex lens, where the source is 1 focal length away.

Light emitted from the source is collimated by the concave lens as seen in fig 3.1. The collimated light is incident on the surface of the material being observed. To collimate the light, the focal length is needed to determine the placement of the convex lens relative to the source. Some lenses may have their focal length written on them or on instruction that came with them. The lens was placed at a distance equal to the focal length away from the source. Be sure that the center of the source is lined up (same x-z plane, x is a line, z is elevation). If the focal length is unknown, it can be determined by holding the lens directly under and parallel to the light source illuminating the room. Adjust the elevation of the lens while observing the image it creates on the floor. The height at which the image is most focused is the lens' focal length.

3.3: Measuring The Incident and Reflecting Light

In order to measure the incident and reflected light, proper set up is required. The material being observed was initially aligned perpendicular to the collimated light; however, it proved difficult to measure the full arc length of 0-90 degrees because the lamp and lens were obstructing the detectors between the angles of 0 and 10 degrees. To correct this issue, the material was rotated 15 degrees, thus allowing the power meter to gather measurements of reflected light for the full 90 degrees.

Prior to measuring the reflected light for each material, the measurement for the incident light was taken. This is important because the efficiency calculation given in section 2.4 is a percentage of the reflected light energy on the total energy supplied. First, the detector must be in the correct range for it to output a correct reading. For incident light at 8.3V, this was about 30-40mW range. The power meter was zeroed by placing a dark cloth over the detector and adjusting the range to the appropriate scaling. To make the measurement, the Melles Griot Broadband Power/Energy Meter 13PEM001 was placed perpendicular to the collimated light at the same position the material will be tested. For this experiment, that distance was 54.7 cm.

As stated above, the platform holding the material being observed needs to be rotated 15 degrees. The power meter was 35 cm away attached to a cord centralized directly under the material so it could rotate freely, as seen in figure 3.3. This way the power meter is at a fixed distance from the material for each measurement taken. Theory section 2.3 describes how light reflects of a surface. Using this information, it can be determined where to initially start the measurement for the reflected light. Since the material is rotated 15 degrees, that means the power meter starts taking its measurement 30 degrees from the incident light. This is following the law of reflection shown in figure 2.1. An illustration of the setup is given below in figure 3.2.

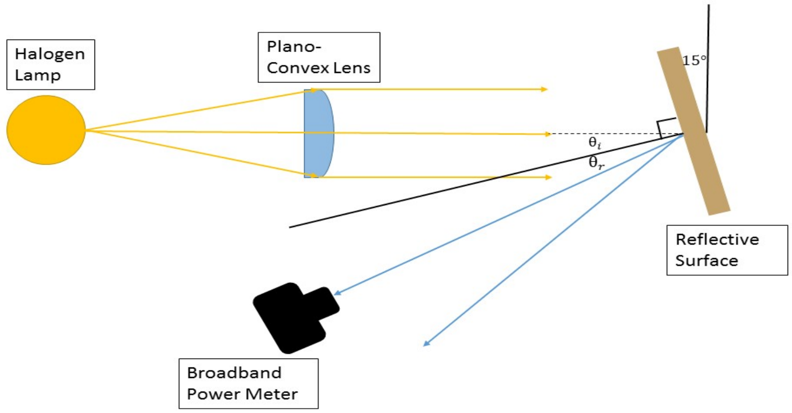

Fig. 3.2. Experimental model for measuring the reflective power for various surfaces. The halogen lamp is the source that generates the light. The light is then collimated as it passes through the convex lens. As the light comes in contact with the reflective surface it scatters at various angles. The yellow lines and the blue lines represent the incident and reflected light respectively.

Before the material was placed on the platform, the power meter was zeroed once again. The device range was checked to the appropriate scale for the material. For all materials, except the mirror, were in the 0-0.4 mW range. This will eliminate any error caused by reflected light off other objects in the room that are undesirable. The desired material was placed on the platform. Based on the material's characteristic roughness the light will scatter at various intensities. Theta is the angle of reflection between the light source and the power meter. The detecting device is then swept from 0 degrees to 90 degrees. The power meter is set 90 degrees from the initial 30 degree offset. For each degree, measurements are taken for power and recorded in a spread sheet. Both experiments, the base case and application materials, are conducted using this experimental method.

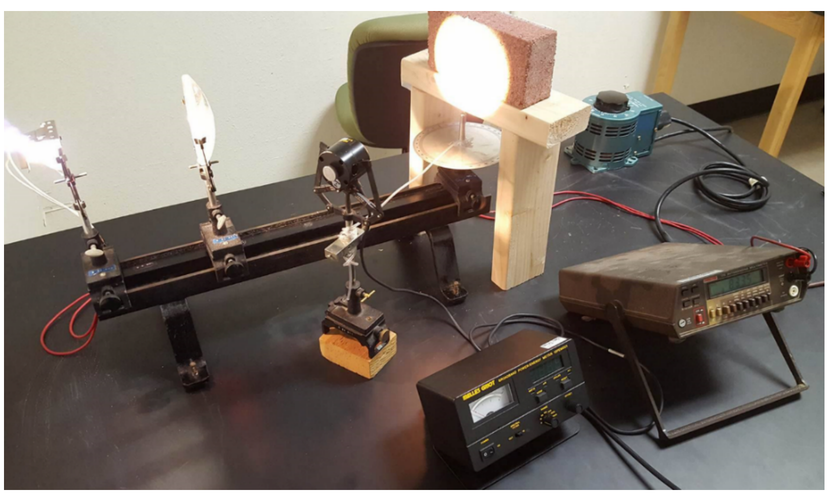

Fig. 3.3. The actual experimental set up for measuring reflective materials using a broadband power meter.

The setup for the experimental apparatus is difficult because it requires precision in the alignment of each element. Without precise alignment, would be significant error in the measurements. All the elements must be set on the same plane. The light source, convex lens, and the detector must be on the same linear axis. Lastly, the detector (power meter) is perpendicular to the reflected light.

IV: Data and Analysis

4.1: Characterizing Efficiency as a Function of Roughness

The first experiment used sandpaper for the reflective material. While sandpaper is not a material that is used as a rear reflective surface for bifacial solar cells, it is classified by the average particle diameter, which is its roughness. The reflective nature of the sandpaper is explored using the same experimental techniques as a traditional rear reflective surface. The reflectivity is expected to be a function of the characteristic roughness of the surface; that in turn is the amount of scattering the incident light experiences. The incident power and reflected power of the light is measured. Figure 4.1 used equation 1 to calculate the efficiency of each sandpaper sample in the set and compare it to the angle of reflection.

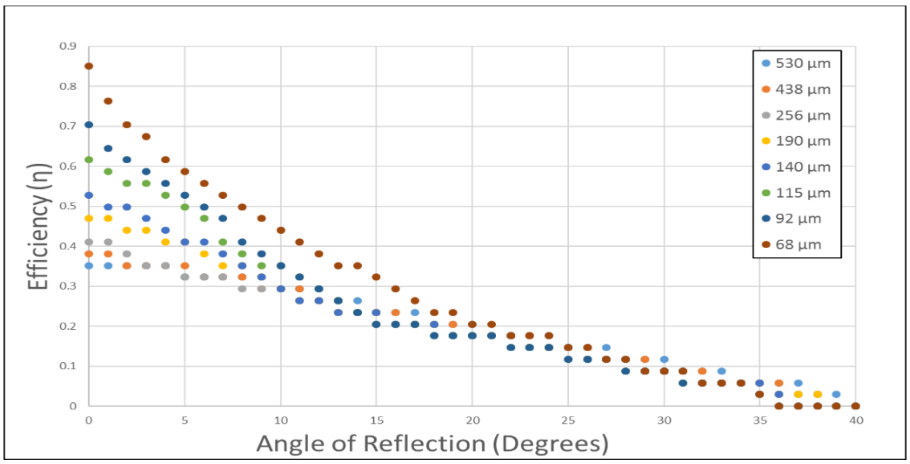

Fig. 4.1. Measurements for the efficiency of reflection by different grit of sandpaper (in terms of average particle diameter) are compared to the angle of reflection. The general shape resembles the normal distribution described in equation 3.

As stated in the section 2.3, the APD is inversely proportional to the roughness. The scale for this sample ranges from rough to smooth, which is 36 grit to 220 grit respectively. It was observed that the efficiency increased as the roughness of the sandpaper decreased. The efficiency at 0^{o} for 68 µm and 530 µm sample sandpaper was 0.850 and 0.351 respectively, with a difference of about half a percent. Comparing results from Hazel's experiment, in which he explores semi-mirrors as the rear reflectors, he found that the mirrors efficiency ranged from 1.35η to about 1.75η [3]. This confirms that the data observed in figure 4.1 is within a reasonable expected range. Also, the smoother the material the less it scatters the light. The 68 µm sample stopped reflecting light at about 35^{o}, where some of the rougher surfaces stop reflecting around 40^{o}. Figure 2.2 illustrates the nature of scattering light as a function of surface texture, so the results support the theoretical model.

The data gathered in the first part of the experiment can be further analyzed. As it was predicted, the scattering of light should distribute in a bell curve manner. Figure 4.2 takes the data from figure 4.1 and confirms the bell curve relationship. Only several sandpaper samples that encompass the whole range of grits are shown to reduce clutter in the figure.

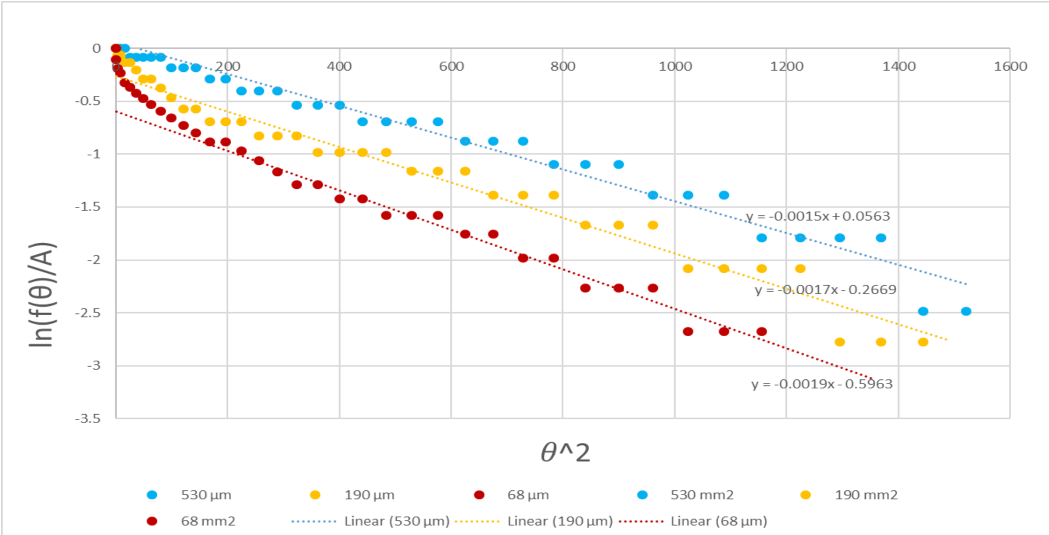

Fig. 4.2. Semi-log plot of $\ln\left(\frac{f(\theta)}{A}\right)$ vs θ^2. Best Fit Function excludes data for θ^2< 200.

Initially, the function was graphed $\frac{f(\theta)}{A}$ and θ and the trend lines displayed a parabolic function ($ax^2 + bx + c$). It is observed that when θ^2 is used as the scale for the x-axis that the relationships become linear ($mx + b$), thus proving the logarithmic relationship shown in equation 4. The slope of each trend line is the best fit factor, beta. However, section 2.5 described that the significance of beta was its impact of determining the slope of the bell curve function. It can also be noticed that the best fit lines are relatively perpendicular to each other, illustrating that they do indeed follow normal distribution. The data collected prior to 200 θ^2 does not follow this trend because the cross section of the collimated light measured was over an area rather than a single point. This cross sectional area contributed to those angles observed. The material that is the most efficient is a bell curve with the largest area. The slope compared to the APD is given in figure 4.3.

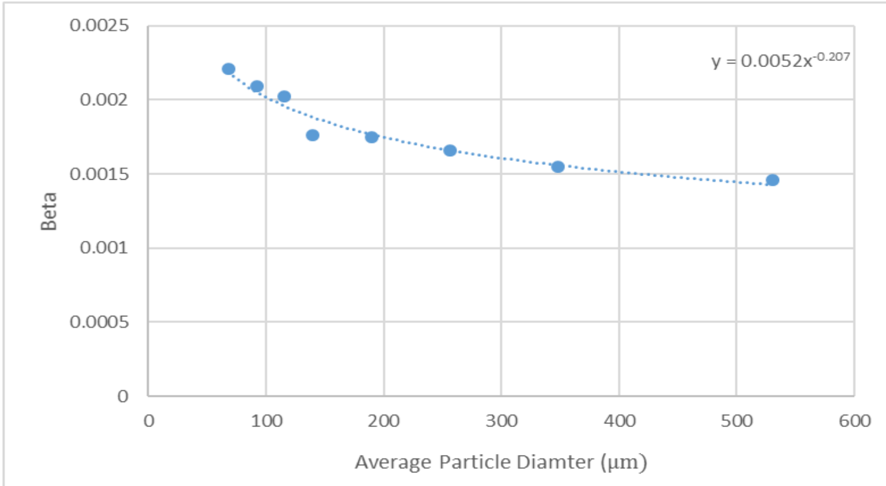

Fig. 4.3. Calculated beta for each sandpaper tested. The dotted line is the power function $y = 0.0052x^{-0.207}$.

The relationship between beta as a function of APD is a power function. As previously stated, the beta value determines the slope of the normal distribution curve. What also can be concluded is the correlation of the amount of scattering observed. With larger beta value there was less scattering and low smaller betas there was more scattering of light. Using this relationship, a theoretical average particle diameter can be inferred, later given in table 4.1. The beta value gives the slope of the normal distribution, that in turn is related to the amount of scattering that is experienced. A greater beta value correlates to a lower amount of scattered light. To prove that beta compared to APD is a power function, the natural log is taken of both axes'.

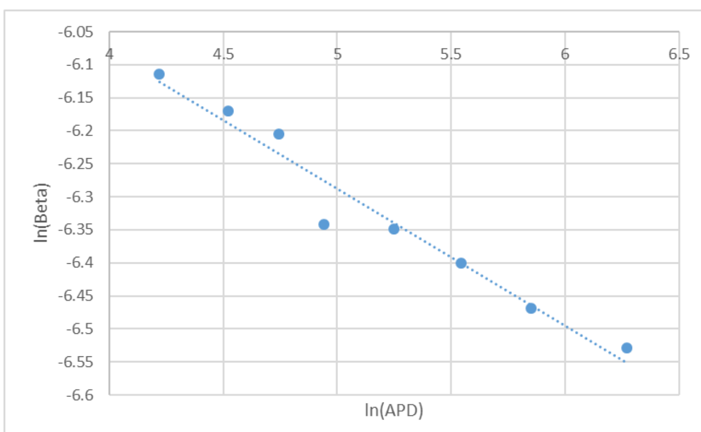

Fig. 4.4. The natural log of figure 4.3 yields a linear function, verifying the power law.

To tie all the data together, the normal distribution relationship given in equation 3 is analyzed. The known beta values for each sample as well as their scaling constant A, which was the initial intensity at 0^{o} to create the normal distribution curves that are given below.

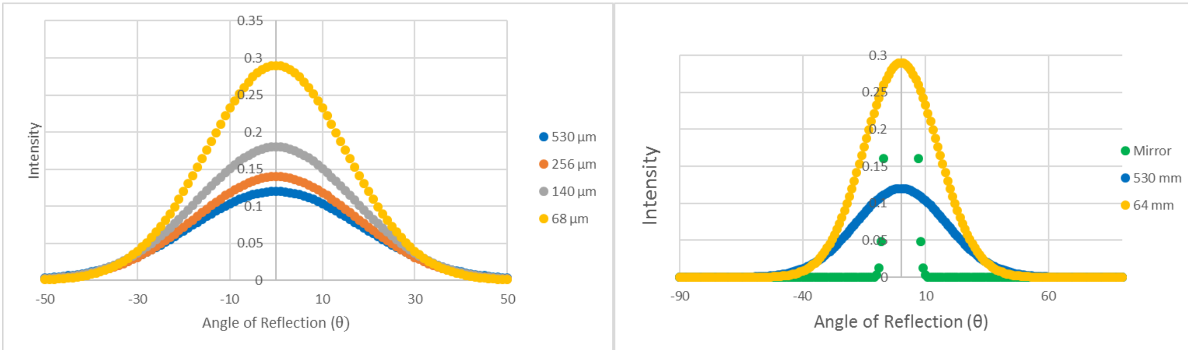

Fig. 4.5. A) The calculated normal distribution curves for the sandpaper samples B) The minimum and maximum average particle diameter samples compared to the distribution for the mirror.

There is a relationship between the distribution and the sample roughness. As the average particle diameter decreases the overall distribution curve increases. In 4.5A there is a slight increase in the slopes of the curve as they become more smooth, however this is more apparent in 4.5B. With the addition of the smoothest surface, the mirror, there is a significant increase in the slope of the distribution curve relative to that of the sandpaper samples. The curve is integrated as a function of the angle in order to calculate the total area given in figure 4.6.

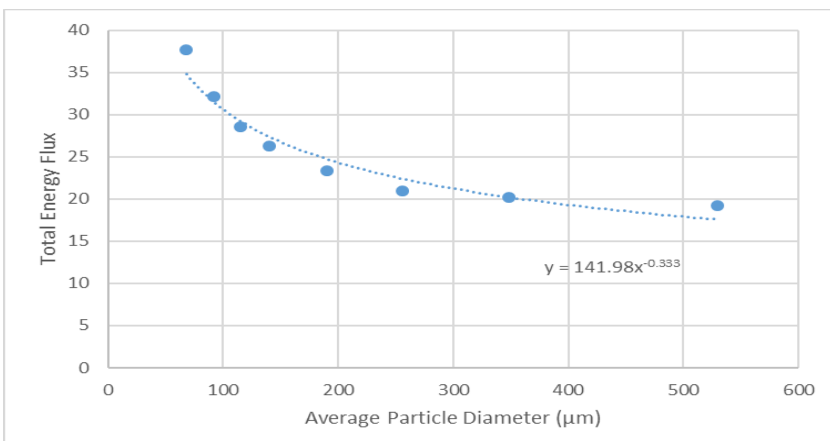

Fig. 4.6. The total area under each normal distribution curve given in figure 4.5.

The total area of the distribution curves displays a similar curve to that of figure 4.3, which displays the relationship of beta to the average particle diameter. This shows consistency in the results and analysis, furthering the confidence in the relationship. This is telling us that smoother surfaces would prove to be better, even though they do not scatter the light as much. What this means is that it is better to have a higher efficiency material that reflects light for a shorter amount of time.

4.2 Application of Standard Surfaces for Buildings

Typically solar cells are placed on a variety of structures ranging from home, industrial buildings to solar cell farms out in the rural country. Currently, monofacial solar cells dominate the market due to cost and availability. As more research and development is contributed to bifacial solar cells, there will be an increased need to understand best method to implementing them. The overall purpose of this experiment was to test surfaces that might be used in development of buildings or architecture that would maximize the output of bifacial solar cells. Knowing the optimizing angle and surface is important in the placement if the solar cell with respect to the sun.

Standard construction materials such as bricks, wood, and paint were compared using the same methods as the sandpaper, which is shown in figure 4.7B. Several variable went into selection of the materials. In the case of the bricks, there are two different colors, red and gray, to determine if color has a significant impact on the reflectivity. Also, materials with different roughnesses are compared, such as wood and brick. Lastly, both kinds of materials are painted white, which impacts both surface roughness and color. A mirror was added to the set because it outputs “almost perfect” reflection that is close to the theoretical data.

There are 3 materials that were investigated not shown in figure 4.7B, which are the aluminum mirror, brick painted black and wood painted black. Both materials painted with acrylic black paint has relatively little reflectance to be considered noticeable. The mirror on the other hand had almost perfect reflectance which skewed the scale of the figure.

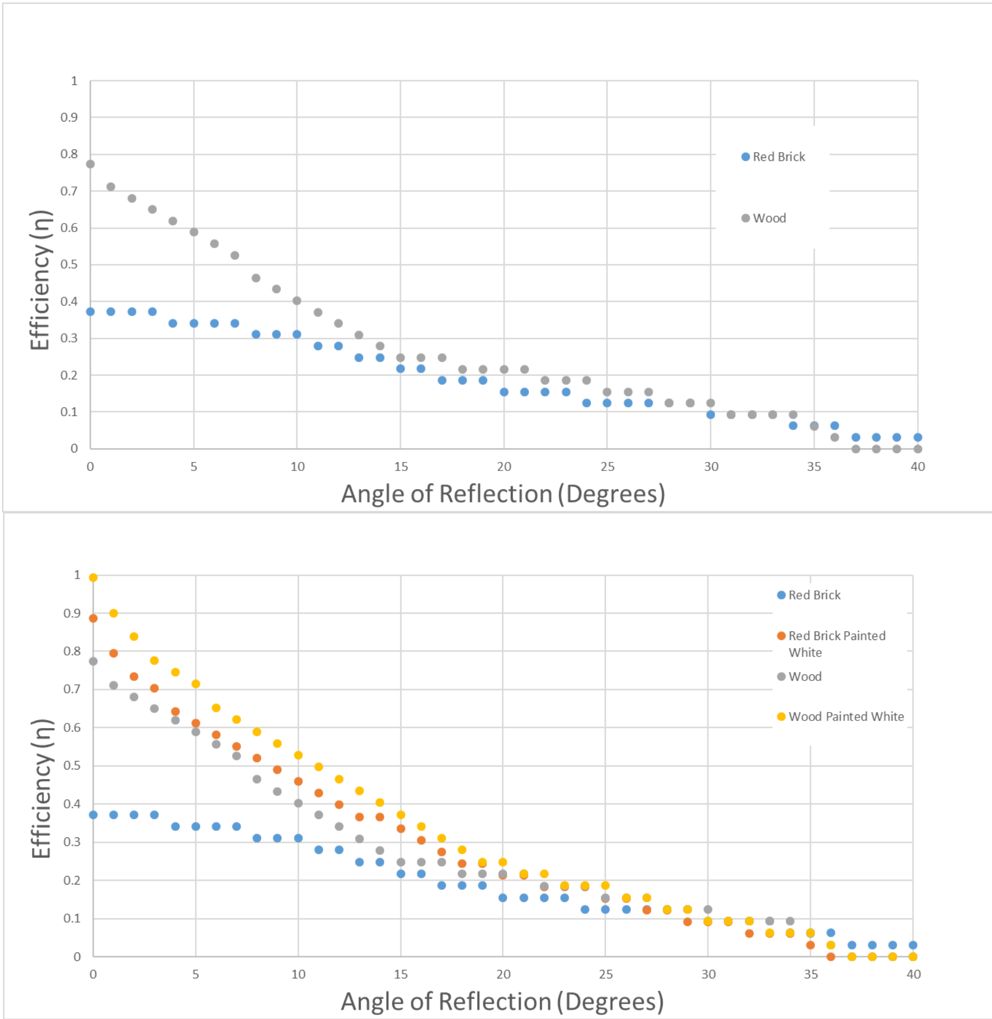

Fig. 4.7. Measurements for the efficiency of reflection by several materials are compared to the angle of reflection. A) Shows the difference of efficiency between the red brick and the wood. B) Shows the additional measurements of when the materials in part A were painted with white acrylic paint.

Similar to the data found in section 4.1, there is a strong correlation between the efficiency of the reflected surface and the roughness of the material. The most efficient material was the mirror (not displayed in this data set), which is to be expected. It displayed a peak efficiency of 22.46 at 0^{o} , but scattered only 7^{o} compared to the other material's 35^{o}-40^{o} scattering. However, when the brick and wood are painted white, there are noticeable increases in their efficiency of about 0.51% and 0.22% respectively. The reason the brick saw a more significant increase than the wood is because the paint was able to fill the crevices in the brick making it more smooth. Whereas the wood was "relatively smooth" (compared to the brick), it did not see the same gains in efficiency as the brick. It can be said that the paint smooths the surface, along with being white it is the optimal color for reflection. On the other side of the argument, if the surface was painted black it would absorb most of the light rather than reflecting it.

Applying the same methods of analysis used on the sandpaper some general conclusions can be reached. The efficiency data displayed in figure 4.5 yields the beta value for each material investigated. There is a problem because there are no existing measurements for the roughness of the surfaces to be compared to. Working backwards from the relationship given in figure 4.3 yields

$$x = (\frac{0.0052}{y})^5. \quad (5)$$

Where x is the APD for the given material and y is the beta value calculated. Table 4.1 givens the calculated measurements for the different materials.

Table 4.1: Beta and average particle diameter values calculated based on measurement for the construction materials.

Material	Beta	Average particle diameter (μm)
Red Brick	0.00149	581
Red Brick painted White	0.00215	80
Wood	0.00181	85
Wood Painted White	0.00221	74

From table 4.1, the same analysis can be made with the area given in figure 4.6. A better understanding can be made about the construction materials due to the theoretical roughness's calculated. Comparing the materials to the sandpaper experiment, it can be observed that the red brick has a similar average particle diameter to the roughest sandpaper observed. The wood was similar to some of the more smooth sandpapers, yielding a higher reflective efficiency.

These values are plotted to observe the relationship in figure 4.9.

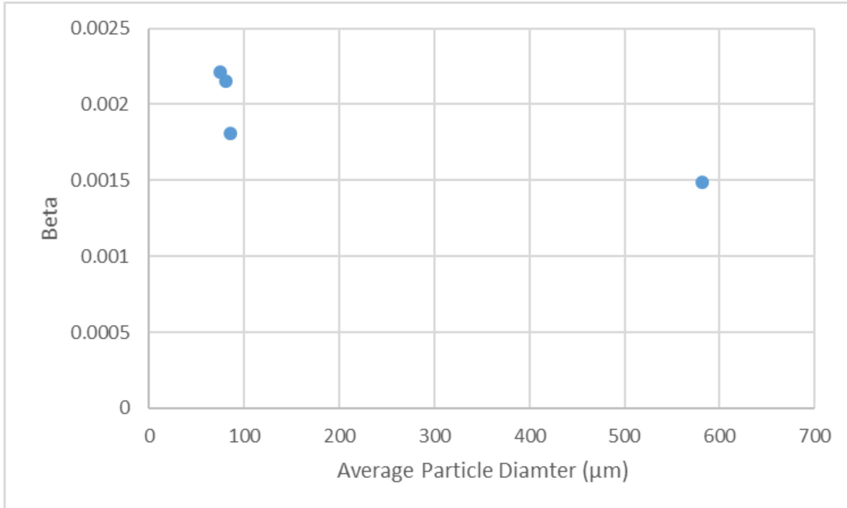

Fig. 4.8. The theoretical equation 5 calculated the particle diameters for each material measured and is plotted against their beta value.

Figure 4.8 represent a similar tend to that of the sandpaper analysis. Given a larger sample size of materials would either prove or disprove this correlation.

V: Conclusion

Sandpaper proved to be a solid theoretical case to build understanding of the relationship between reflectivity of materials and its roughness. It was found that of all the materials investigated, the aluminum mirror was the most efficient, with a beta value of -0.7915. This was well beyond that of the next closest material, which was the oak wood painted with acrylic white paint with a beta value of 0.00221. Finding the connection between the bell curve and the scattering help developing the foundation for this experiment. Using the bell curve equation (3), the best fit constant could be determined for each material and a linear relationship was observed. As the surface because more smooth, there was less scattering but a high efficiency. Hence, the statement can be made that smooth materials are more efficient at reflecting light than rough materials. However, rough materials are better at scattering light. Lastly, there was a slight side experiment that was observed in the process. Two materials, wood and brick, were painted with white and black acrylic paint. It was found that the color white significantly increased the efficiency while the color black decreased the efficiency but both normally distributed the same. This shows that the surface roughness and color are indeed two separate variables that impact reflectivity.

There were several components that contributed to the error observed in the experiment. The lack of precision of the experimental set up this could have been a result. An issue was the variable autotransformer that supplied power to the halogen bulb would oscillate about 0.2V, meaning that the source was constantly changing its intensity. The standard supply voltage was about 8.3V but it ranged anywhere from 8.1V to 8.5V, thus impacting the consistency of the data. Along with the variating light intensity, it was a 50 watt bulb, which did not supply a sufficient intensity of light. With a greater intensity source there would be more sufficient disparities in the measurements, which is important for finding relationships.

The current model is simple and more complexities need to be added. Taking the experiment to the field and testing it with actual bifacial solar cells would be a first step. Also, looking at the orientation of the materials relative to the solar cell would be interesting. Another factor to consider would be the zenith angle and how dispersion occurs to the light through the atmosphere. Lastly, it would be interesting to inquire from a business standpoint and compare the cost of each material to reflective efficiencies. This is an important area of research because although the mirror has the highest efficiency of the materials explored, it was also the most expensive. Perhaps one of the other materials have a higher cost efficiency score.

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