The Effect of Settling Dust in the Arava Valley on the Performance of Solar Photovoltaic Panels

By

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and approved by the senior thesis committee.

Terrence Bensel 5/3/11 Eric Pallant May 4, 2011

Dr. Terrence Bensel Date Dr. Eric Pallant Date

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Pledge

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Due to the increasing scarcity and growing demand of fossil fuels as a primary energy resource, energy security has become a global concern. The world's fear of global climate change has increased the severity of this energy crisis problem, while also creating an urgency to find alternative solutions. More scientists and researchers are looking towards renewable energy as a future way to resolve the issues, and they are searching for ways to use renewable sources more efficiently. One example is modeled in the potential for photovoltaic solar energy in Southern Israel. This region has one of the highest solar radiation densities in the world. Unfortunately, dust accumulation is one of the major hindrances to optimized radiation on the solar collectors. Dust decreases the performance of the photovoltaic panels. The intention of this study was to concentrate on the effects of settling dust on photovoltaic solar panels in the Arava Valley, in particular on Kibbutz Ketura. It was concluded that regular dust accumulation decreases the efficiency of solar photovoltaic panels by about five to six percent, which translates to large annual monetary losses. While cleaning the panels would increase panel performance, the cost of cleaning would need to be accounted for in the gross outcome of the solar panel's economic benefits. This study is considered a base to predict the level of degradation of any photovoltaic system that might be installed in the Arava Valley.

INTRODUCTION

Global climate change has instilled a worldwide fear of the future's geo-political stability. It has sharpened the competition over resources, most notably water, and it has increased environmental hazards in coastal regions. By provoking arguments over territories and resources, climate change and fossil fuel shortages are causing more international unrest. The combustion of fossil fuels has led to a dramatic environmental impact on the earth and in the atmosphere.

With increased shortages and a scramble for energy resources, energy prices will likely continue rising for the next decade. Political instability in the major oil and gas producing countries has made these countries less reliable for the nations that heavily depend on them. The trends, both environmentally and politically, will continue unless alternative technologies for obtaining energy are implemented. Energy resources that are safe for the environment, efficient enough to be used on large scales, and not dependent on fossil fuels are an important solution to evading the political and environmental problems involved with oil, coal, and gas.

As a result, individual countries are taking more measures to solve their own issues according to what they can do themselves. Renewable energy provides an option for those countries with sufficient access to renewable resources. Solar energy in particular has become a promising business, currently holding a $24 billion market value (Heiman 2004). Countries that can implement solar energy will be able to lessen their reliance on fossil fuels.

Solar Energy in Israel

Israel is one country that can implement solar energy resources extensively. Solar energy is an excellent option in Israel due to the abundant amount of sunlight. Solar energy on a massive scale is an exceptional option in Southern Israel, specifically in the Arava Valley where solar radiation is highest. Little of the Arava Valley land is arable, meaning it does not lend itself to farming purposes. This is another factor that promotes solar panel installation in the region.

The Arava Power Company, one of Israel's largest solar companies, announced its goal to generate at least 500 Megawatts and, eventually, 1 Gigawatt of solar energy in the southern part of the country. The main objective of the company is to generate renewable energy in the Arava region and sell it to the residents of the Arava and the Israel Electric Company. This major

shift in energy resources will have a great impact on Israel's energy market (Waldoks 2008). To date, the feed-in tariff acts as the most significant motivation tool for producing solar energy. The feed-in tariff incentive is a long-term purchasing price given to the owner, matching each kilowatt-hour of energy produced. This is a powerful tool for persuading homeowners, private firms, and utilities alike to invest in renewable energy. Many countries, including Israel, have adopted the purchasing agreement. According to the Deutsche Bank, feed-in tariffs have pushed approximately 75 percent of the world's photovoltaic installations since 2008 (Roney 2010).

The Arava Valley

The area in which the Arava Valley is situated has the highest solar radiation in all of Israel, making it an ideal place for solar power installation. However, the high rate of dust settling combined with minimal rainfall predisposes the Arava Valley to solar power challenges. Dust settling in the Arava Valley can make the solar photovoltaic panels less effective in converting sunlight energy into electrical energy. There are large expanses of erodible dust material which hinder the photovoltaic panels' ability to absorb the maximum amount of sunlight. Massive dust transportation covers an area of about 4,800 square kilometers in the Arava Valley (Bruins 1998).

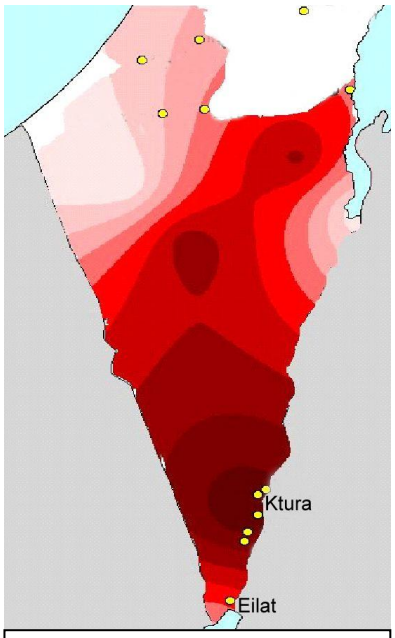


Figure [1]: Map of Solar Radiation in Israel

The map of Southern Israel displays the varying levels of solar radiation. Darker colors indicate higher levels of solar radiation. As the map shows, the greatest amount of solar radiation is located in the southern-most region of Israel, in the Arava Valley area. The annual incident solar irradiation in Israel is 2000 kWh per square meter. Furthermore, since Southern Israel is mainly desert land, there are wide expanses of land that could be used for solar power installation (Faiman 2010).

Photovoltaic Systems

Out of the wide variety of renewable energies studied, photovoltaic technologies are demonstrated to be a promising method for capturing and distributing solar energy. Photovoltaic systems have the ability to directly convert sunlight to electrical energy, and they also have an

environmentally compatible nature. Improvement of operational characteristics is the only way photovoltaic power can become a major competitor in the energy market. One concern brought up involves the questioned reliability of the system due to the foreseeable randomness in sunlight availability as well as the need for great electrical energy storage spaces (Kattakayam 1996).There are several different types of solar panels. The type of model that this study will focus on is the flat, photovoltaic solar panel. Photovoltaic panels are advantageous because they can provide a photovoltaic collector system which allows the solar panel to be integrated into a building or other structure. Photovoltaic panels are rapidly increasing in popularity. Figure [2] below displays a progressive increase in installed photovoltaic capacity between 1985 and 2009, with an 800 percent increase between years 2000 and 2007. As technology advances, photovoltaic solar panels are becoming more and more accessible and efficient (Boyle 1994).

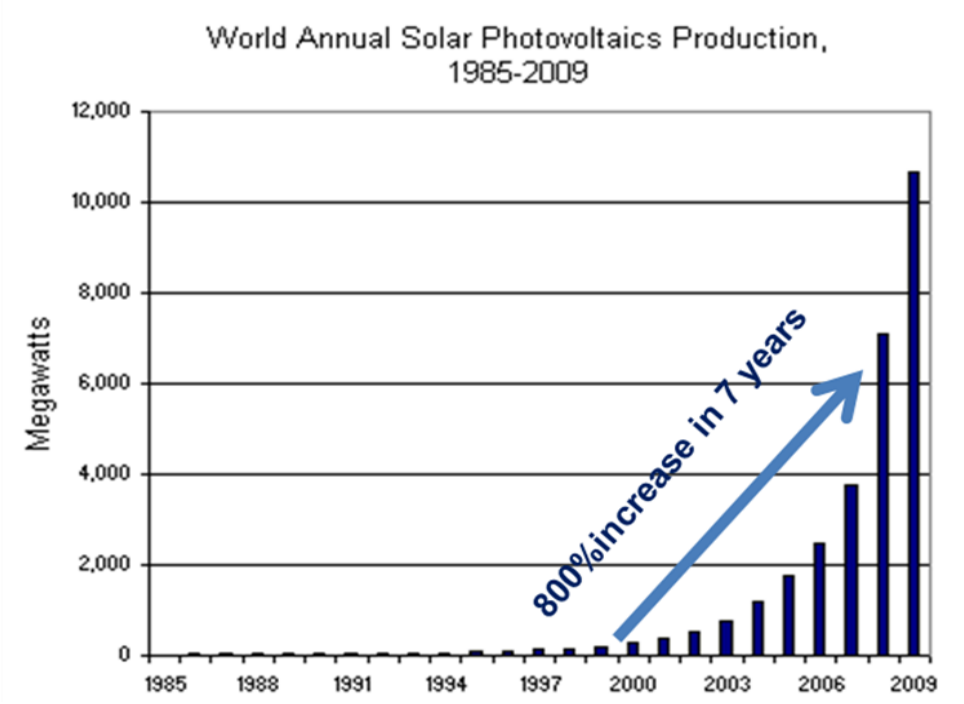


Figure [2]: Increasing Production: Annual Cumulative Installed PV Capacity Worldwide, in MW (Prometheus Institute; Greentech Media, 2010).

Flat plates are the most commonly used model of solar panel. They use solar cell materials over the entire exposed surface area. They are more efficient than other models

because the surface has even sunlight exposure with higher reliability. Flat-plate photovoltaic models make use of direct and diffuse sunlight. The most commonly used flat plate photovoltaic model has a single crystalline-silicon consistency. Single crystals of silicon have the highest efficiency, and the cost is directly proportional to the amount of silica inside the solar cell. Each solar cell is a thin, square slice (Boyle 1994).

The thin film shape of the photovoltaic panels is composed of layering. A photovoltaic cell consists of two thin sheets of a semiconductor, which is a material made from silicon. When two sheets of silicon are sandwiched together, an electric field is established between them (American Psychological Association 2010). This layering in the panel allows the semiconductors within the cell to optimize absorption and efficiently convert photon energy into electricity by knocking the electrons loose (Boyle 1994).

Photovoltaic devices use the photoelectric effect in semiconductor materials to change solar energy directly into electrical energy. The photoelectric effect controls how a photovoltaic cell converts sunlight into electrical energy. When a photon strikes certain materials, such as semiconductors, the material's electrons are able to capture the photon's energy. If the energy level is high enough, then electrons are released. The photovoltaic device works by creating a voltage difference within an environment that directs the migration of electrons to produce a current. This is achieved by arranging some of the semiconductor materials in a specific manner. There is a space for positive material and a space for negative material, and they are usually connected to each other (Boyle 2004).

The negative material allows electrons to move freely within it, making the electrons the current carriers. The positive material immobilizes the electrons. This immobilization creates a series of holes in the material, which is usually silicon crystal. The holes act as current carriers for the electrons (Al-Hasan 1998).

What is most important is that the photovoltaic system relies on the net efficiency of converting sunlight to electricity. There are many ways to measure efficiency. The highest values are often found in well-controlled conditions inside a laboratory with small cells, using artificial sunlight as an energy source. The last level is measured for complete photovoltaic systems installed in the field. Under intense sunlight at peak periods, the solar flux to the surface of a cell

produces a current of about 100 mA/cm squared at a solar-to-electric efficiency (Goossens 2010).

The performance of the solar energy system, whether it is a thermal or photovoltaic collector, is rooted in the ability of the glass cover. The glass cover allows radiation to penetrate through the collection surface. The factors that determine its effectiveness include the density of solar radiation at that area, the tilt angle of the panels, the properties of the materials, and the gradual degradation of collectors resulting from accumulation of dust particulates (Elminir, Ghitas et al. 2006).

Dust Accumulation on Panels

Since the early 1960's, scientists have noticed and studied the reduction of the collectors' performance due to the pollution on a solar cells' surface (Al-Hasan and Ghoneim 2005). Such studies, at that time, were focused mainly on the thermal cells and the effects of dust accumulation on the mirror reflectance (Dietz 1963). However, recent research has updated information that deals with solar photovoltaic panels. This research highlights the negative effects of dust on collectors. In this context, many experiments have been made to test the effect of dust on the solar panels in terms of the collected power, the effect of particles size, the effect of wind on the accumulated dust, and the effect of different types of dust, including limestone, cement and carbon (Goossens and Van Kerschaever 1999). Sand and soil are among the primary sources of natural degradation, among other airborne particulates, chemical weathering processes, as well as industrial carbon and other types of dirt (Bethea et al. 1983).

Recently, there have been a number of studies concerning the degradation of the performance of solar photovoltaic and thermal panels arising from environmental factors (Kattakayam; Elminar 2006; Mani and Pillai 2010). Many collectors show lower performance efficiency after a short period of time, both in electrical and thermal performance capabilities. Most panels are designed with the intention of correct operation for over two decades; however, their performance time is reduced by environmental conditions of the area, especially with settling dust. Because of the great impact dust has on panels, studying the degradation of the solar collectors proves vital. It could help bring about improvements in design and cleaning to better prevent or clean off dust accumulation. New progressions could help halt the efficiency

degradation from dust settlement and other environmental hindrances (Elminir, Ghitas et al. 2006).

Dust consists of tiny solid particles carried by air currents. These particles are formed by disintegration which is a process of fracturing the solids into small pieces through grinding, crushing, or impact among other ways. The Mine Safety and Health Administration (MSHA) defines dust as finely divided solids that may become airborne from the original state without any chemical or physical change other than fracture. Dust is generally measured in micrometers. (2009).

Dust in the Arava Valley is composed of earth, sand, and other fine dry particles. It is easily blown when the wind blows. There are two primary ways that dust affects the photovoltaic panels. First, dust settles directly on the solar photovoltaic panels, blocking the cells from the sun's rays. The tracing sensor may be covered by dust, inhibiting the panels from following the sun's direction (Khoshaim et al. 1983).

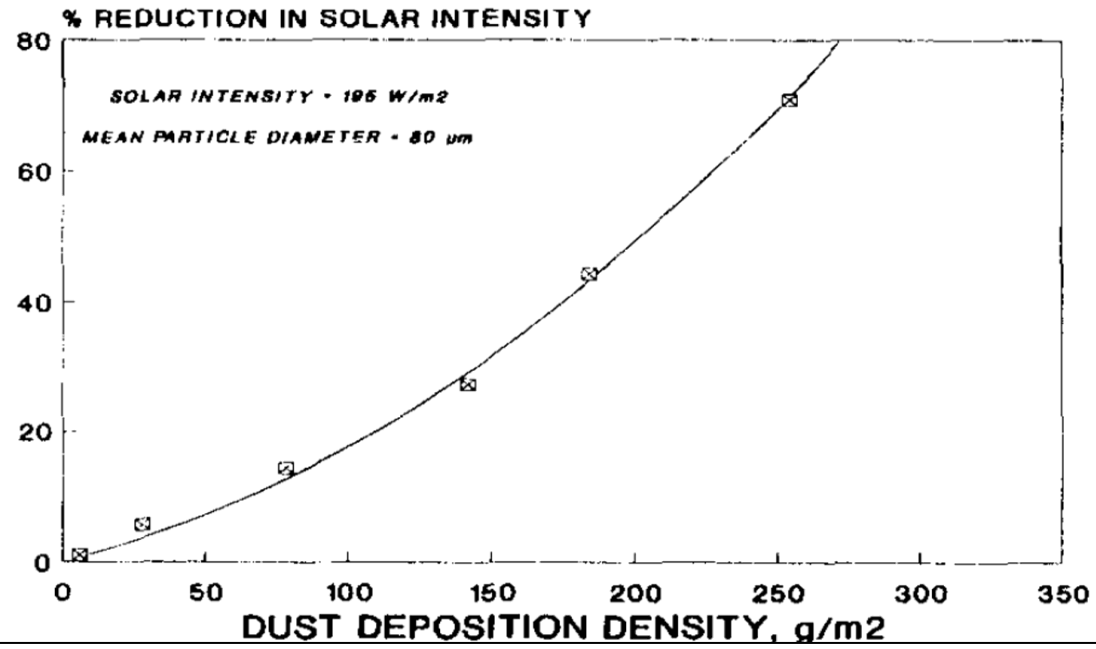


Figure [3]: Reduction in the solar intensity received by photovoltaic panels (El-Shobokshy,M. and Hussein, M,1993).

The second type of dust blocks the sun in the air, deflecting the rays (Al-Hasan). Because of its high atmospheric concentration arising from industrial factors and sand storms, the dust can lower the solar collector quality. These factors cause the amount of radiation that reaches the panels to decrease (Goossens and Van Kerschaever 1999). Dust can also pass into the collectors under the glass cover, causing a decrease in overall mirror reflectance (Thomas et al. 1985).

Measuring Performance and Dust Interference

The effect of dust on a photovoltaic module is multifaceted. A fine layer can in fact increase the daily output of a module by reducing large angle reflections from the glass cover. Conversely, the transmittance level can also be reduced by dust on the glass. Soot and dust from industrial processes have effects different from agricultural pollen and windborne desert sand. A data analysis of dust particulates will be useful in determining the distribution of particulate type (Biryukov et. al. 1999).

There are numerous ways to measure the electric output of a solar photovoltaic panel. One method is an I-V curve. An I-V curve is a graphical presentation of the relationship between the current and voltage from a photovoltaic device. The curve's progression follows as the load is increased from the short circuit (no load) condition to the open circuit (maximum voltage) condition. The shape of the curve characterizes cell performance (Solar 2010).

The voltage at which actual power is maintained and the amount available from a photovoltaic field are necessary variables to measure with on-site panels. Data on these measurements could be useful for operation and maintenance. It is shown that the daily and environmental effects can severely reduce the net power availability. The curvature of the *I-V* curve at the maximum point of power can be used as an indicator of the overall performance of the panel (Kattakayam).

The goal of this project is to understand how dust affects photovoltaic solar panels' efficiency in the Arava Valley area. Understanding the extent to which dust affects the efficiency of the flat photovoltaic solar panels is of great importance because it may help researchers understand ways to prevent hindrance. This study could provide important

information for potential future studies that would look to maximize solar energy effectiveness and prevent the negative effects of dust on solar panel efficiency.

Research Statement

The purpose of this study is to find how performance of the solar photovoltaic panels are affected by the settling dust in the Arava Valley region, in order to better predict the extent of performance degradation on the panels. This study seeks to find how current and voltage are affected from various lengths of exposure to dust settlement on the panels. This will help predict how performance of a solar array or field will be affected from degradation as well as the economic implications of financial return. This study is crucial, as it may lead to further research focusing on improved technologies that will help prevent or better resolve the problem in a more time- and cost-effective way. I seek to answer the question: How does settling dust in the Arava Valley region affect the performance of solar photovoltaic panels?

Study Area: Kibbutz Ketura

This site was chosen because it houses the first commercial photovoltaic field made by the Arava Power Company. There are normally no industrial activities on Kibbutz Ketura that would increase dust settling in this area. This was the only location where electrical output of the panels was measured.

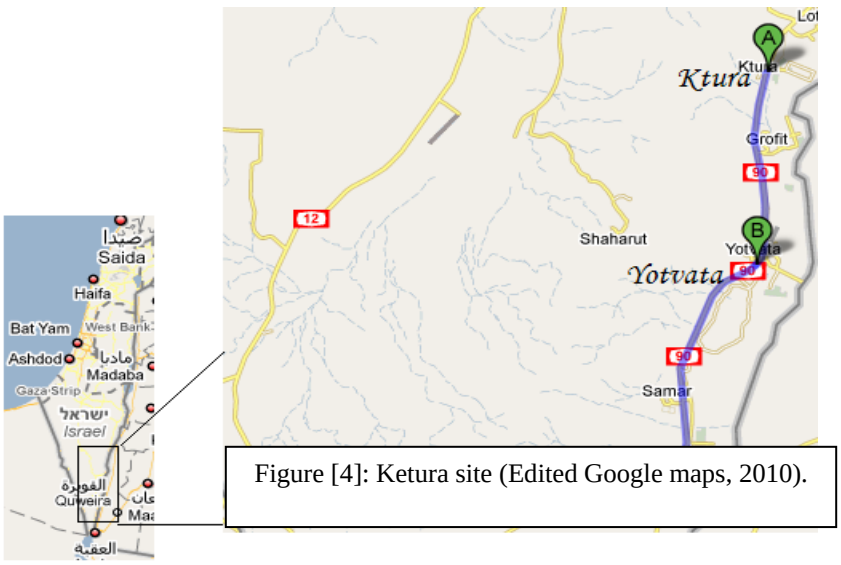


Figure [4]: Ketura site (Edited Google maps, 2010).

The local government has a vision to convert this area into a silicon valley for renewable energy. There is currently government and environmental support; therefore, this area will be a future location for further renewable power generation. This promotion of solar energy increases the importance of Kibbutz Ketura as a study area.

METHODOLOGY

The methodology of this study is based on data collected from Kibbutz Ketura. The experimental set-up for finding the mass of dust settling and its effect on electrical output of the solar panels was performed in the following way. Experimentation occurred between October 2010 and January 2011.

Effect on Electrical Output

In the beginning of the experiment, one set of mono-crystalline panels, rated at 240 watts of peak output, was used for the experiment. Halfway through the semester, studies began on a different set of panels: mono-crystalline panels from Bosch Company. Bosch Company rated the panels used in this study with an efficiency of approximately fourteen percent.

To measure the effect of dust on electrical output, the following methodology was performed:

1. Measure the amount of settling dust on panels (weekly and monthly recordings) with three panels:
a) Panel that will be kept clean all the time
b) Panel that will be cleaned weekly and
c) Panel that will be cleaned monthly

2. Measure the effect of dust on the amount of solar radiation: A pyranometer was placed underneath the glass to measure the amount of solar irradiance with varying amounts of dust.

3. Measure the effect of dust on photovoltaic performance (from task 1) by using the data from *SolarEdge* invertors and by using an IV Checker. An IV Checker is simply the machine that calculates the IV curve, power, and other irradiance data.



Figure [5]: IV Checker
Photo by L. Boykiw.

Solar radiation measurements were taken at the solar noon time, which was roughly around 11:30 am, each Monday. The best days to take readings were on days with bright sunlight, little to no cloud coverage, and low wind. If it was cloudy or raining, data collection was delayed until the next

clear day to take readings. Throughout the study, rain dates, humidity and other weather patterns were recorded to account for possible changes in degradation levels on the panels.

Measurements were taken in real time with standard testing condition values. Standard testing conditions account for the differences in parameters for different testing days including temperature, air mass, wind speed, and sunlight strength. The air mass impacts the spectrum of light arriving on earth and the radiation effect. In order to compare the data received on the different days of testing, the performance of the operating solar panels was made uniform under standard testing conditions. These conditions define performance at a cell temperature of 25 degrees Celsius (77 degrees Fahrenheit), sunlight strength of 1000 W/m^2, and an air mass of 1.5. The data of a given day for measurement had its raw data recorded as well as this data applied to standard testing conditions. Standard testing conditions allow for accurate comparisons between different testing days.

Field Measurements

To begin testing, the invertor was turned off as a safety parameter, allowing for safe cleaning. The invertor is an electrical convertor that converts direct current into alternating current. Next, invertor connectors were plugged in to the panels, which were used for testing the panels' performance.

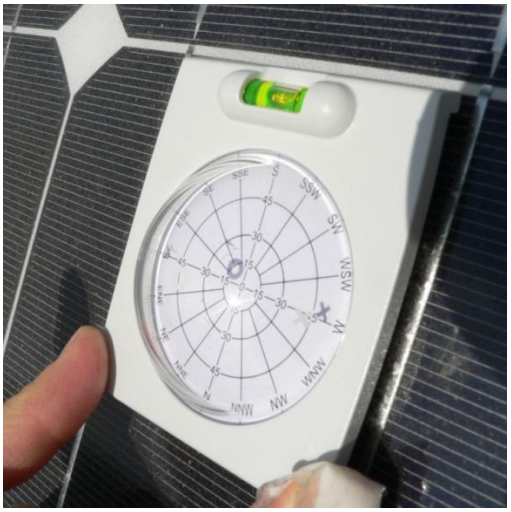


Figure [6]: Sun Gauge lined up on panel
Photo by L. Boykiw.

Then the panels were cleaned with water, according to the frequency of cleaning originally proposed. Water was used to give a more thorough reading since it removes the smallest particles from the panel.

A sun gauge was then placed on the corner of one of the solar cells to find and orient the angle of the panel. The shadow "O" in the sun gauge was centered at the center "0" for the most accurate readings at the solar noon time. Before each testing, the gauge was placed on the top right corner of one of the solar cells, as shown in the Figure 6. This leveling throughout the study allowed for consistent readings in the solar angle of incidence. The sun gauge provided a frame

of reference for how the panel should then be moved for the most abundant sun exposure possible to obtain better readings. Based on the sun gauge reading, the panel angle was shifted accordingly to move the shadow to "0".

Two thermocouples were then attached to the back of each solar panel. The thermocouples provided the temperature throughout the experiment. A thermocouple is a type of thermometer, consisting of two wires of different metals which are joined at both ends. One measures the air temperature and the other remains at a fixed lower temperature. The current generated in the circuit is proportional to the temperature difference.

Thermal grease was applied to the tips of the thermocouples, touching the back of the panel. Thermal grease is a good heat conductor and allows for accurate temperature readings.

An isosecondary standard pyranometer, with a certificate of standardization, was used for this study. A pyranometer measures the broadband solar irradiance on a surface; it is designed to measure solar radiation from a view of 180 degrees. The pyranometer used for the experiment traced back to a master calibrating system, with an uncertainty level of 2% in figures. This is a small amount of uncertainty with an acceptable range of error. The pyranometer was placed above the panel to gather statistical data that was generated into the IV Checker. Electrical contacts with clips were plugged in to connect the IV Checker to the power box of each solar panel. The pyranometer was held in place with a cable tie and made as flat as possible for preferable readings.



Figure [7]: Isosecondary Standard Pyranometer, model view.

After preparation, testing was delayed until the solar noon began. The time, weather, and panel cleanings were recorded before each testing. Three to four measurements of each panel were taken at standard testing conditions.

Panel 1 from December 13 was used as the control, and data from December 13 was used for standardizing the rest of the data since the panels were cleaned in a way that allowed a method of standardization to be implemented. Baseline data was taken for measuring efficiency differences among the panels. The control numbers were

extrapolated for monthly cleaning. The data of December 13 was used to calibrate all the panels together.

Performing a measurement consisted of operating the IV Checker, which provided an IV curve, and data of efficiency, voltage, current, and a maximum power point. The IV curve is a visual representation graphing the relationship between current and voltage generated from the solar panel. As each reading took place, the IV curve was briefly examined on the IV Checker screen for its smoothness to ensure that a proper reading had taken place. When the curve did not follow the normal, smooth pattern, it was understood that some variable, such as shading or a poor connection, skewed the data. Measurements were taken every few minutes until each panel had multiple solid measurements.

After completion of the field work, the panels were reset to their original angles to continue data collection in the most accurate way possible.

SolarEdge

Following the field work, the data from the IV Checker were analyzed on the computer using the *SolarEdge* Software program. The *SolarEdge* program provides the photovoltaic power output of each panel as well as temperature, IV curves, and maximum power points. *SolarEdge* systems are based in Israel and serve the purpose of improving solar-system efficiencies.

IV curves were examined more carefully on the software program for discrepancies in the current and voltage relationships among the different panels. The conversion efficiency at standard testing conditions was also compared among the different panels and different dates.

Conversion efficiencies taken at standard testing conditions were the main piece of data examined among the different pieces of numerical data. When there was a drop in power, the amount lost was shown in the conversion efficiency. Efficiency tests were performed with a function for temperature and relative temperature differences. The temperature function was added to account for any changes in solar efficiency that would have been due to temperature; therefore, the variations in data are focused on one changing variable, which is the dust deposition.

Data Calculation

The difference between the control and baseline data was used to describe the amount of panel degradation. Theoretically, the measurement of Panel 1 (Clean) on December 26 should be the same as Panel 1 on December 13. This would show that there is no degradation in the actual panel; therefore, any discrepancies between these two are accounted for by dust accumulation. The change in efficiency, Δn, is an empirically measured piece of data.

For example, an efficiency loss with a two-week difference is calculated as:

$$\Delta n = n(\text{Dec. } 13) - n(\text{Dec. } 26)$$

For Table [1], the data was found by the following process: based on the control data from Panel 1, a projected value for each panel was calculated. These projected values represent the efficiency level of each panel over a designated period of time—one week, or one month—without factoring in dust accumulation. The actual (dirty) numerical data from each panel, without cleaning for one week or one month, was subtracted from the projected value. The absolute value of this difference represents a change in efficiency, or Δn. For the difference in performance, the ratio to project the increase, and the differences in efficiency provide an absolute percentage value.

December 13 was a day where all the panels were cleaned and measured at the same efficiency, so the data of December 13 is used to standardize all of the other data.

On December 26, all the panels were soiled; however, an increase in efficiency is displayed by the raw data. When the projections from Panel 1 (Control) data are applied to the December 26 data, a different conclusion is found. If the panels were clean, then the efficiency would have improved by 1.4% for all of the December 26 data.

For example, the difference between Panel 1 of December 26 and Panel 1 of December 13 was 0.7%. The difference between that of December 13 and the control is 1.4%. This difference is due to dust.

This 1.4% increase is applied to all of the December 26 data and the differences between the actual measured efficiency and the projected efficiency. The next step was to project this

equivalent amount of change on Panels 2 and 3 for December 13. This is why the difference, 1.4%, is used.

Sample Calculations

1. Here is an example of the calculation to project the efficiency of a panel when the projections of Panel 1 (Control) are applied. These values are taken from data of Panel 2, as seen in Table [2], where:

- 11.3 is the efficiency value from December 13
- 11.5 is the efficiency value from December 26
- 1.014 represents the 1.4% increase in the control and the December 13 data, with the difference accounted for by dust deposition.

$$(11.3 * 1.014) – 11.5$$

2. In this calculation, the ratio increase is sought out. The difference between Panel 1 (December 13) and Panel 1 (Control) is 1.4:

$$12.6\text{-}11.2 = 1.4$$

1.4/11.2 = .125, which signifies a 12.5% increase in efficiency. If the 12.5% increase is applied to Panel 1 (Clean), which has a raw efficiency value of 11.2, then a final value of 12.6 is found. 12.6 is the projected efficiency value of Panel 1 if dust had not interrupted its use.

$$11.2* (1.125) = 12.6$$

11.9 is the efficiency after dust accumulation. A simple subtraction gives the decrease in efficiency.

$$12.6 - 11.9= 0.7\% \text{ decrease in efficiency}$$

Then this percentage decrease value is divided by the control panel (clean) value to get an answer that represents the difference in efficiency in an absolute decline value. To clarify:

$$0.7/12.6 = 0.5555, \text{ a } \mathbf{5.5\% \text{ reduction in efficiency}}$$

When the 12.5% increase is applied to Panel 2 (Clean), at 11.3, an efficiency value of 12.65 is found. 12.65 - 11.5 = 1.15% decrease in efficiency.

1.15/ 12.6 = 0.0912, which is a 9.12% absolute reduction in efficiency.

The same process is repeated for the other panels.

Interpreting tables and graphs

In the following section of results, a series of tables and graphs are presented to provide visual grounds for the trends observed through data calculation.

Table [1] displays the average efficiencies for each panel after dust deposition. The experiment efficiency values were obtained from the actual data collection, while the percentage change in efficiency was used to represent the absolute decline in efficiency.

Table [2] provides the averaged efficiencies over the time span between December 13 and December 26 in addition to the increase projected from Panel 1 (Control).

Graph [1] shows the levels of performance efficiency after two weeks without cleaning among the three panels. The control panel data is presented as well for comparison purposes. The graph shows that after dust collection, the performance of the solar panel is inhibited, lowering its efficiency by a relatively significant amount.

It should be noted that the data comprised in graph [1] were measured prior to panel cleaning. The control panel was already cleaned before the efficiency measurement was taken. The control panel accounts for and describes panel degradation, since this parameter is not measurable under standard testing conditions.

Graph [2] displays the estimated annual power produced for each panel. Assuming conditions for each test remain constant, the data for the graph were extrapolated to one year's time to estimate how much power would be produced in total.

Graph [3] displays the percentage drop in efficiency for each of the three panels in comparison to the control panel.

RESULTS

Tables

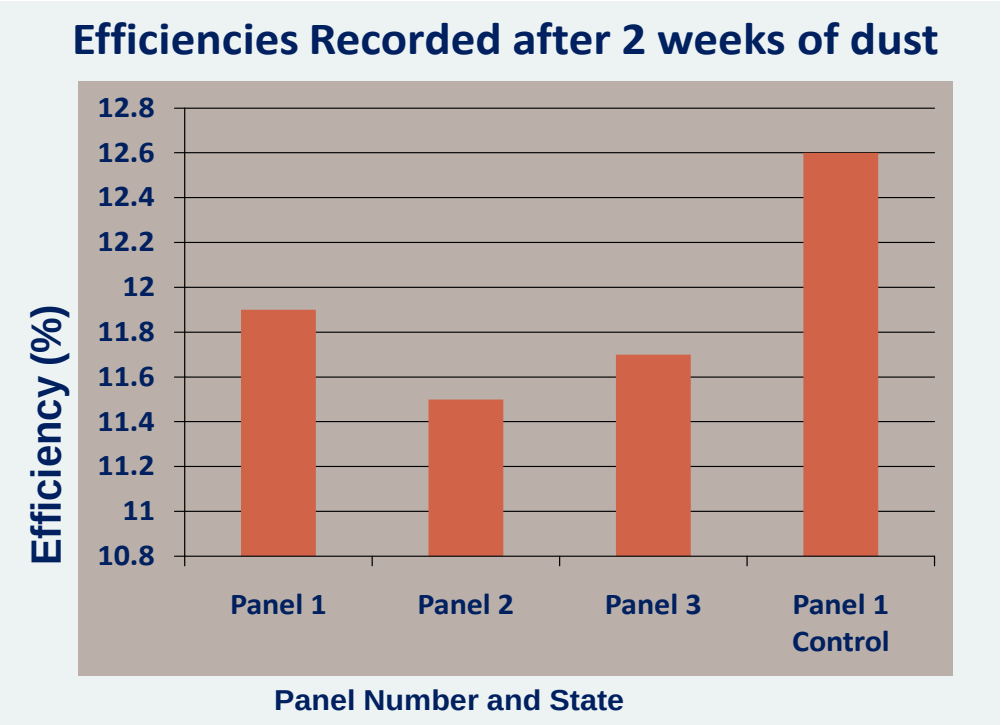
Table [1]: Average Efficiencies (%) of each panel

Panel date/modification	Panel 1	Panel 2	Panel 3	Panel 1 Control
Experiment Efficiency Value	11.9	11.5	11.7	12.6 (clean)
Percentage Change in Efficiency	0.055	0.087	0.071	0

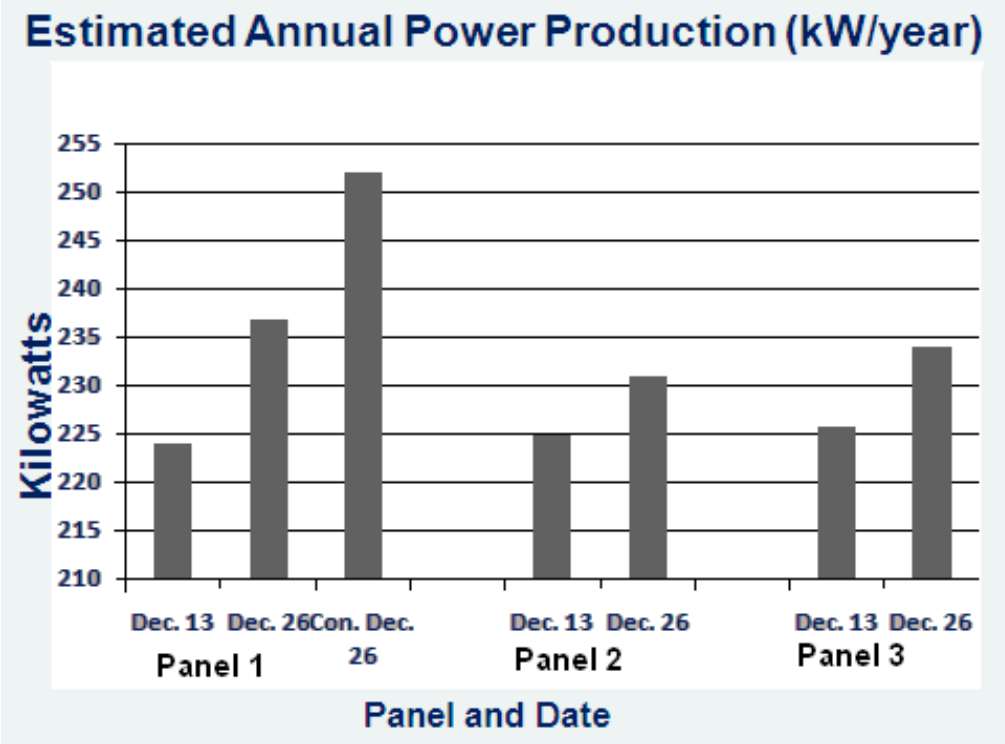
Table [2]: Average Efficiency Results (%) by date and state

Panel Date/Modification	Panel 1	Panel 2	Panel 3	Panel 1 Control
December 13	11.2	11.3	11.3	---
December 13 with 12.5% Increase	12.6	12.65	12.65	---
December 26	11.9	11.5	11.7	12.6

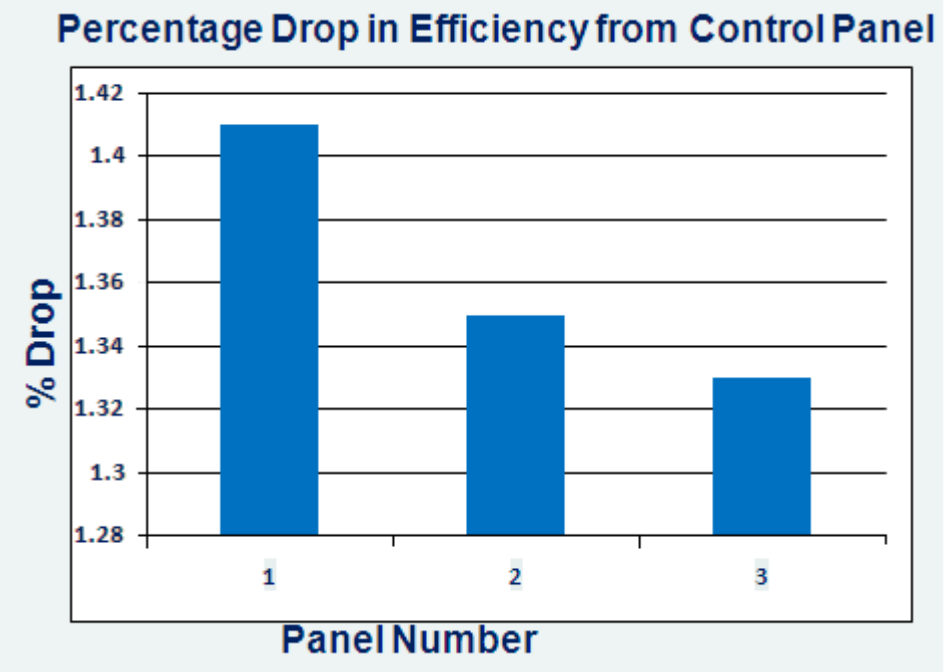
Graphs



Graph [1]: Panel efficiencies after dust settling



Graph [2]: Estimated total power production per year (kW/year)



Graph [3]: Percentage drop in efficiency, *n*, from control panel

Financial Significance

The Israeli Electric Company provides feed-in tariffs, or subsidies, for electrical fields. These subsidies help with calculating money lost from dust deposition on the solar panels, as well as extrapolating the amount of money saved to arrays and fields of photovoltaic solar panels. The total amount of money lost in the solar field can be found by using empirical data that accounts for the overall difference in irradiance between the days that measurements were taken. After all of the data was collected, the amount of money lost from the hindrance on solar performance from dust accumulation was determined.

Calculated Loss for One Panel

To find the theoretical maximum financial return, the numerical amount of power produced by each panel is multiplied by the power purchasing agreement number. The power purchasing agreement number is a value designated by the policy of the Israeli feed-in tariff. This value varies based on the size of the solar field. To summarize, with $\underline{Y}$ and $\underline{X}$ as stand-in numerical values:

$\underline{Y}$ kWh/m^2/year * ($\underline{X}$ NIS/kWh) = Theoretical Maximum Financial Return

For example, the net arrival of energy for the first measurement was 2200 kWh/m^2/year. If the efficiency without dust was 12% while the efficiency after dust settling was 10%, the following calculation would take place:

(.12)* 2200 = 264 kWh/m^2/year (The baseline financial return found)
264 * 2.83 = **747.12 NIS/m^2/year**

(.10)*2200 = 220 kWh/m^2/year
220 * 2.83 = **622.6 NIS/year**

747.12 – 622.6 = **124.52 NIS/year lost**

1 New Israeli Shekel = 0.2879 U.S. Dollars, or 1 U.S. Dollar = 3.474 NIS. Based on this conversion, the amount of money lost annually is equivalent to: U.S. **$35.85 lost**.

The following example from collected data will use this concept regarding finding financial significance.

One reading of panel 2 showed that 170,000 kWh/m^2/year were produced. A later reading, taken after some dust settling, displayed a power level of 161,500 kWh/m^2/year produced. There was a 0.5% efficiency drop related to watt hours produced. To see this difference, it is first established that *n* lost is 0.5% and that the actual amount of money paid for a solar field of this size was 1.5 NIS. To calculate the loss in earnings due to the 0.5% drop in efficiency:

170,000 * 1.5 = 256,000
161,500 * 1.5 = 242,250

256,000 - 242,250 = 12,750 NIS lost

The USD to NIS conversion shows the above calculation is equivalent to a loss of $3670.

The example used for calculating the financial return originated from policies implemented by the Arava Power Company. The feed-in tariff value is 1.58 NIS/kWh for a power plant size of 4.9 Megawatts. Once the change in efficiency, Δn, is established, the change in revenue of the photovoltaic system can be calculated. Based on the efficiency drop between

the control and baseline data of December 13, the overall decrease in efficiency was 1.3 to 1.4%. If the panels are cleaned, there is a potential gain of 150,000 NIS per year.

Calculated Loss for a Solar Field

The Israeli subsidy value for a solar field that is at or about 50 kilowatts in size was used for performing financial projections. As mentioned in the previous section, the Israeli feed-in tariff for a field of this size is designated at 1.58 NIS/kWh. The photovoltaic group used on Kibbutz Ketura is 4.9 Megawatts, or 4900 Kilowatts. There are approximately five hours of sun in the region. These different variables are necessary for calculating the financial significance of a solar field's losses from dust deposition.

The purpose of the following calculation is to relate the incoming energy (performance percentage) *n* as a factor per square meter. The length of time is chosen as one year since annual ratings are frequently used in research. Remember, this calculation assumes that the panels are perfectly clean.

To summarize, the input data includes:

- 1.58 NIS/kWh
- Sun hours = 5 hours
- 1 year = 365 days
- 4.9 MW = 4900 kilowatts

4900 kW * (1.58 NIS/kWh) * (5 hours/day) * (365 days/year) = 2.83 million NIS/year.

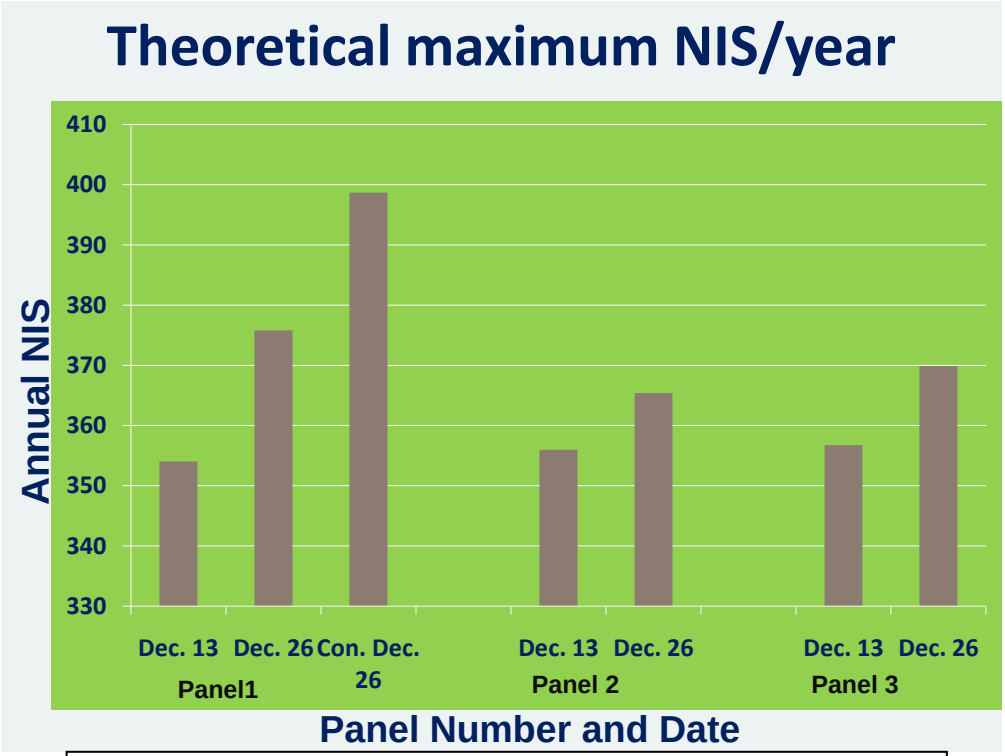
This value, 2.83 million NIS/year, is multiplied with (output of dirty/output of clean). The ratio values are given as efficiency values at standard testing conditions, and the ratio represents a percentage difference in efficiencies. This calculation stands for the theoretical financial return multiplied by the ratio of losses. Essentially:

$$2.83\ \text{MNIS/year} * (n\text{dirty} / n\text{clean})$$

The USD to NIS conversion means that the above calculation is equivalent to $814,757 of annual incoming energy.

After the baseline efficiency data are collected, the percentage value is multiplied by the amount of incoming radiation, represented in kWh/m^2. The resulting answer is the annual value of the amount of energy produced by the panels. Remember to make the distinction that the loss for one panel was calculated in one example to be at $3,670. For the solar field on Kibbutz Ketura, at 4900 kilowatts, this would translate into a financial loss of $74,929,167.

Graph [4] displays the theoretical maximum shekels gained annually, based on the original readings taken for each panel.



Graph [4]: Theoretical Maximum New Israeli Shekels gained per year

DISCUSSION

For Table [2], it was expected that the differences would be much greater between the panel that was cleaned monthly and the one that was kept clean all of the time. Because of rain and construction, the data was skewed, since construction created unnatural dust clouds and the rain eliminated the accumulating dust.

The data of December 13 has the lowest efficiencies in the beginning, and the December 26 data has efficiencies that are just slightly higher. For example, the efficiency for panel 2 was 11.3 on December 13 as opposed to 11.5 on December 26. While this is a seemingly insignificant difference in efficiency, the difference in power produced adds up quickly over the course of one year. The estimated power yielded for a year from Panel 2/December 13 is 225 kW; for Panel 2/December 26, the estimated annual power produced is 236 kW for a year. The most important distinction in this graph is the large difference in annual power produced by the control panel in comparison to those panels with dust.

The data from December 26 data shows a discrepancy of 0.7% even after adjustment from the Panel 1(Control) percentage. This technique of finding conversion efficiencies shows an inversion in the data, and that there is actually a decrease in efficiency overall from the dust.

At a glance at the numerical data, it appears that dust actually increased the efficiency on the solar panels. This opposes the expected outcome; however, after reassessing where the data were coming from, a different conclusion was discovered.

Because the panels are all of the same company and model, it is assumed that each begins in the same condition. On December 26, all of the panels were measured, and they were all producing more power even though a longer

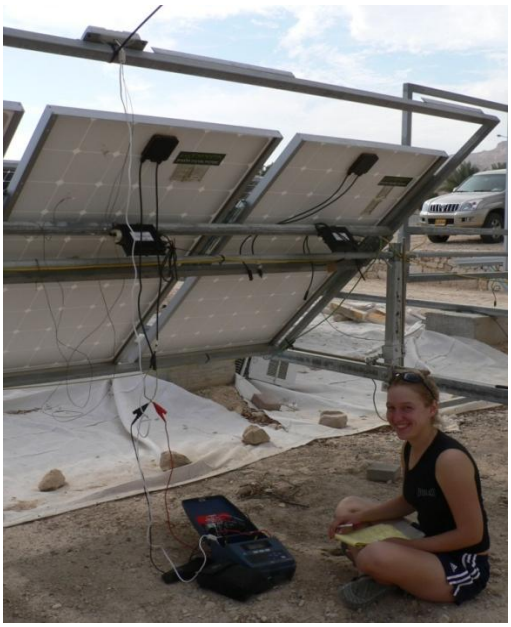


Figure [8]: Solar noon Measurements

period of time had taken place for dust to settle on the panels. A statistical analysis using a chi-square test was used to account for this discrepancy.

Through the statistical examination of Panel 1 (Control) against the baseline data, it was concluded that the chi-square value came out to 0.443 which is far too high of a chi-square value to rely on; therefore the data that show an increase in efficiency from dust do not represent statistically significant values. This analysis means that the efficiencies did not increase as much as they should have. There is actually a loss in efficiency.

On December 26, the dirty panels produced more power than December 13, but they did not increase as much as expected. This demonstrates that there was actually a loss in efficiency. The rise in the conversion efficiencies can be explained from two different points. First, a thin layer of dust can actually increase efficiency. Also the temperature must be accounted for in standard testing conditions since it skews the solar panel's performance (Hegazy 2000). Overall, a consistent reduction in efficiency of five to six percent was found when dust accumulated on the panels for one week or longer.

Interpreting Financial Significance

Notice that in graph [4], the control panel reading jumps up above the other readings, just below 400 NIS annually, which is about $115. The amount of shekels for the cleaned control panel is thirty to forty shekels higher in earnings than the various December 13 readings. While thirty to forty shekels could be seen as an insignificant difference, remember that this is only showing the results for one panel. Consider how much the difference would be with an array of panels or with an entire field. The larger the amount of panels, the more shekels gained per year.

Based on the data gathered, the dust can cause a 5 to 6% decrease in the solar panel efficiency in one week. If the panels are cleaned on a regular weekly basis, there is a potential gross gain of 150,000 NIS per year.

Factoring in Cleaning

While it is shown that photovoltaic solar energy yields great financial rewards, it is also important to take the costs of cleaning and maintenance into account. According to the

Department of Energy, maintenance and operation costs of a solar-powered system are roughly $30 per megawatt hour. A second figure estimates that the lifetime maintenance and cleaning costs for a system size would cost about $2000. When the costs of maintenance and cleaning are taken into consideration, it is estimated that recouping the costs of solar energy savings would take between five and ten years depending on the size of the system. A solar energy system has an expected lifetime of forty years on average; therefore, over the life of the system, the owner would earn around three times more than the cost of installing, cleaning, and maintaining a solar system (USA 2011).

It takes more time than money to actually clean all the solar panels since maintenance includes inexpensive activities such as cleaning the array and removing debris. A non-abrasive cleanser, water for rinsing, and a towel are the only tools required to clean a solar panel. The U.S. Department of Energy recommends dedicating only eight to sixteen hours per year to solar panel cleaning for the solar panels to be working in their best condition (Demeo 1984).

Issues with the Study

One problem encountered in this study was the weather. The field work took place during the rainy season in southern Israel, which made weather patterns more unpredictable and prone to windy, wet weather. This affected the amount of dust settling on the panels. For the experiment, the rain was not conducive to obtaining reliable data; however, it should be noted that rainfall is very helpful for keeping the panels clean. Rain offers a cost-free, labor-free way of clearing dust off the panels.

It was intended to have three sets of experimental data, but for the "monthly cleaned" panel, rainfall patterns made it impossible to obtain four weeks of dust settling data. Instead, data from the other panels was extrapolated to one month's length.

Another problem was the presence of unnatural dust settlement. The area surrounding the solar panels was exposed to construction work for a large chunk of the study time; therefore, the solar panels were subjected to levels of dust that did not resemble natural settling dust but industrial dust created from dust clouds coming from machines, activity and movement in the vicinity.

Because of weather concerns and other considerations regarding construction and academic schedules, the studies were not consistently taken on the same day each week which made the levels different within the study on occasion.

Intermittently, water was not used for cleaning the panels and a brush was used instead, especially if there was little time to clean the panels before the solar noon time.

The IV Checker became erratic towards the later stages of the study. Though the battery was replaced, the IV Checker did not respond to power for an extended period of time. The IV Checker was later deemed defective. The company that the IV Checker was purchased from was made aware of this defect.

It should be noted that wind can affect the thermal grease, dabbed on the back of the solar panel, by up to two degrees.

Future Research Recommendations

The effect of dust on the performance of solar photovoltaic panels in the Arava Valley will continue to be studied even though this particular project is finished. An extensive project will have to be undertaken over the course of several years to more fully understand the ways in which dust affects the panels.

Since the average solar photovoltaic system has a lifetime of forty years, a study that is longer should be considered since it could help model the other long-term processes involved, which may include panel degradation, and other maintenance needs that did not need to be considered in this short-term study. Furthermore, a study spanning several years will allow for comparisons between seasons and between different years to gain an understanding of how seasonal changes are related to dust levels and how this in turn relates to the solar efficiency levels. After a number of years, trends in dust accumulation and solar performance may be identified and analyzed for further understanding of when the panels are most vulnerable.

A study continuing several years could also potentially incorporate the new self-cleaning solar technology. This technology is not yet commercialized but scientists claim that close to ninety percent of the dust can be removed within a few minutes after dust piles up. This technology also does not use water. Self-cleaning would be especially helpful with larger solar

fields since it is very time-consuming to clean each panel thoroughly. The efficiency levels would benefit and the maintenance costs would decrease if these trends continue (Zhu 2009).

Another point to consider in future studies is identifying if there is the dust particles carry a charge, and if there is a charge present, how it relates to the charge of different solar panels. Such an analysis could lead to new information on the way solar cells are constructed to detract dust.

The same model and type of panels should be used throughout the study in order to maintain consistent results. Using a larger sample size of solar panels should also be considered for future studies. This experiment used only three panels. If more panels were used in each of the three groups (cleaned monthly, weekly, and all the time), a more accurate set of data describing the relationship between dust and performance could be obtained. A larger sample size allows for minimization of error arising from any one individual solar panel.

Additionally, back-up measuring tools including a second IV Checker should be accessible so that measurements need not stop for several weeks at a time. For a longer study, a larger group of people should be incorporated for consistent times of each measurement.

CONCLUSION

The main conclusions drawn from this research project include the following:

- Dust can cause a 5 to 6% decrease in the solar panel efficiency in one week
- Conversion efficiencies were found by consistently comparing data back with Panel 1 (Control) and performing a chi-square test to demonstrate that the panel efficiency decreased as a result of dust under standard testing conditions
- Several thousand New Israeli Shekels can be lost each year as a result of the dust decreasing the solar panels' efficiency
- If panels are cleaned at least weekly, there is a potential gain of 150,000 NIS/year
- Further research is necessary for more affirmative results. It will take several years of conducting the study to work in presenting more reliable results. More panels and a longer amount of time are essential for more accurate results.

In the Arava Valley and other desert regions, solar panel installation is ideal with the abundant sunlight and large expanses of vacant land. The benefits of solar energy in southern Israel are well-known; however, the way in which dust can affect the solar panels' efficiency values is often not considered. Dust storms combined with little rainfall jeopardize the efficiency and performance of solar photovoltaic panels in the region since dust accumulates on the solar panels.

Finding solutions to the problem of dust will allow the Arava Valley to flourish more in the $24 billion solar power industry in the midst of an energy crisis. Using renewable energies such as solar power, will help protect the environment from further harm and reduce dependence on fossil fuels, allowing for a diminishment of the associated environmental and political tension.

Works Cited:

Al-Hasan, Ahmad Y. "A New Correlation for Direct Beam Solar Radiation." *Solar Energy* 63.5 (1998): 323-33. *ScienceDirect*.

Al-Hasan, A. Y. and A. A. Ghoneim (2005). "A new correlation between photovoltaic panel's efficiency and amount of sand dust accumulated on their surface." International Journal of Sustainable Energy 24(4): 187 - 197.

American Psychological Association (APA). semiconductor. (n.d.). *Investopedia.com*. Retrieved April 12, 2010, from http://dictionary.reference.com/browse/semiconductor.

Bethea R. M., Collier E. G. and Reichert J. D. (1983) Dust storm simulation for accelerated life testing of solar collector mirrors. J. of Solar Energy Engineering 105, 329–335.

Biryukov, S., D. Faiman, and A. Goldfeld. "An Optical System for the Quantitative Study of Particulate Contamination on Solar Collector Surfaces." *Solar Energy* 66.5 (1999): 371-87. *ScienceDirect*. Web. 28 June 2010.

Boyle, G. *Solar Photovoltaic Systems. Annual Reviews of Energy and the Environment.* Chapter 13. Renewable Energy: Power for Sustainable Future, Oxford University Press Inc. New York, 2004.

Bruins, Hendrick J., and Harvey Lithwick. "Solar Energy in Arid Frontiers: Designing a Photovoltaic Power Plant for Kibbutz Samar, Israel." *The Arid Frontier: Interactive Management of Environment and Development*. Netherlands, 1998. *Google Books*. Kluwer Academic Publishers.

DeMeo, E. A., and R. W. Taylor. "Solar Photovoltaic Power Systems: An Electric Utility R & D Perspective." *Science* 224.4646 (1984): 245-51. *JSTOR*. Web. 1 Apr. 2011.

Dietz A. G. H. (1963) Introduction to the utilization of solar energy. In Diathermassous Material and Properties of Materials, Zarem A. M. and Erway D. D. (Eds), McGraw Hill, New York.

Elminir, H. K., A. E. Ghitas, et al. (2006). "Effect of dust on the transparent cover of solar collectors." Energy Conversion and Management 47(18-19): 3192-3203.

Faiman, David. "Solar Energy in Israel." (2010). *Jewish Virtual Library*. Web. 13 Sept. 2010. <http://www.jewishvirtuallibrary.org/jsource/Environment/Solar.html>.

Goossens, Dirk, and Emmanuel Van Kerschaever. "Aeolian Dust Deposition on Photovoltaic Solar Cells: the Effects of Wind Velocity and Airborne Dust Concentration on Cell Performance." *Solar Energy* 66.4: 277-89. *ScienceDirect*.

Heiman, Michael, and Barry Solomon. "Power to the People: Electric Utility Restructuring and the Commitment to Renewable Energy." *Annals of the Association of American Geographers* 94.1 (2004): 94-116. *JSTOR*. Web. 1 Apr. 2011.

Kattakayam, Thomachan A., Sumanta Khan, and Kandadai Srinivasan. "Diurnal and Environmental Characterization of Solar Photovoltaic Panels Using a PC-AT Add on Plug in Card." *Solar Energy Materials and Solar Cells* 44 (1996): 25-36. *JSTOR*. Web. 29 June 2010.

Khoshaim B., Huraib F. and Al-Sani A. (1983) Performance of 350 kW concentrating photovoltaic power system after two years. In *Proc*. 5*th E.C. Photovoltaic Solar Energy Conf*., *Kavouri, Greece*, Palz W. and Fittipaldi F. (Eds), pp. 207–214.

Lodge, James P. Particle Fallout Container Measurement of Dustfall from the Atmosphere. 1998.

Mine Safety and Health Administration Webpage updated 2009. Retrieved April 5, 2010, from http://unionsafe.labor.net.au/hazards/107413937128257.html.

Mani, Monto, and Rohit Pillai. "Impact of Dust on Solar Photovoltaic Panels." *Renewable and Sustainable Energy Reviews* 14.9 (2010): 3124-131. *ScienceDirect*. Web. 13 Sept. 2010.

RISE Information Portal - Technologies - Photovoltaics (PV). *RISE - Research Institute for Sustainable Energy*. 2008. Web. 20 June 2010. <http://www.rise.org.au/info/Tech/pv/index.html>.

Roney, M. J. "Solar Cell Production Climbs to Another Record in 2009." *Eco-Economy Indicators: Solar Power*. Earth Policy Institute, 21 Sept. 2010. Web. 1 Mar. 2011. <http://www.earth-policy.org/index.php?/indicators/C47/>.

"Solar Energy Technologies Program: Glossary." *Energy Efficiency and Renewable Energy*. 7 June 2010. Web. 29 June 2010. <http://www1.eere.energy.gov/solar/solar_glossary.html>.

Thomas M. G., Fuentes M. K., Lashway C. and Black B. D.(1985) Reliability of photovoltaic systems: A field report. In Proc. 18th IEEE Photovoltaic Specialists Conf., Las Vegas,USA, pp. 1336–1341.

United States of America. Department of Energy. Energy Efficiency and Renewable Energy. 10 Mar. 2011.

Waldoks, Ehud Z. “A Solar Revolution Dawns in the Desert.” *Jerusalem Post*. 4 Nov. 2008:1.

Zhu, Jia. "Nanodome Solar Cells with Efficient Light Management and Self-Cleaning." *American Chemical Society Publications* (2009). *Nano Letters*. Web. 1 Apr. 2011.