# The Dirt on Solar Energy:
# A study of Dutch solar panel efficiency losses from soiling

by Talia R. S. Martz-Oberlander

Submitted in partial fulfillment of the requirements for the Degree of

Bachelor of Arts and Sciences

Quest University Canada
Unceded Squamish territory

and pertaining to the Question

*How can light inspire effective design?*

May 2017

# Contents



# Acknowledgements

For mentorship and support: Dr. Ian Hoffman and Dr. Melanie Hoffman (non-relatives)

For inspiration, guidance, and encouragement in math and the physical sciences: Court Ashbaugh and Dr. Sarah Mayes-Tang

For supervision and collaboration on my Keystone project at AMOLF: Dr. Bruno Ehrler and Moritz Futscher

# 1 Foreword

As all students at Quest University Canada do, I had the task of creating a research and focus plan for the second half of my Bachelors degree centered around a "Question". Thanks to Quest's interdisciplinary structure, I discovered a love of math and physics and the fascinating behaviour of light in the universe in my first semester. In the following three years I danced around a growing obsession with light: how does light work? What is it made of? How can we better use it to power our world? What ways can we design spaces, machinery, and other human items to work with and utilize light more effectively? How does light in human-occupied spaces affect how we interact with our built world? How is our mood affected by lights qualities? And so, in my second year I began pursuing the Question: How can light inspire effective design?.

I delved into math, physics, chemistry, and computer programming to better understand the physical process behind light. Loving the scientific method, and inspired by Dr. Tiffany Timbers on using computation as a tool for more effectively using data, I focused my research goals on bettering my programming skills in multiple areas, from theoretical material sciences to environmental effects on the speed of sound of a pipe organ in a chapel. Each deviation returned me to light, culminating with an internship with the Hybrid Solar Cells group at AMOLF Netherlands researching solar panelsthe most ubiquitous global research endeavour into how light inspires better design in efficient energy capture. Thanks to interdisciplinary thinking, I devised an opportunistic study based on a problem: six incredibly dirty solar panels and valuable, underutilized data. I devised a way myself and other researchers could manage and more easily ask questions of the solar test field combining solid state chemistry, soil science, physics, and mainly computer science.

This document contains a literature review of the effects of dirt on solar panels and an original study on how dirt differently affects six types of solar panel modules in the same location.

# 2 How Dirt Affects Solar Panel Efficiency: a Literature Review

## 2.1 Introduction: Solar Panels and Dirt

This literature review presents past research of solar panel efficiency in terms of electrical output explaining how soiling affects incoming radiation spectra, which interrelate with intrinsic and locational characteristics. Some relevant terms and concepts include: photovoltaic module (PVM), also known as solar panels, which are made up of small solar cells in series and/or parallel circuits; bandgaps; and their relationship to solar spectra. A bandgap is the energy difference, measured in electron volts (eV), between valence and conduction band in an insulating or semiconductive material. Solar cells most frequently utilize different types of semiconductors, a material where electrons do not completely fill its valence energy band and has the potential, with additional energy input, for its electrons to obtain enough energy for mobility into the conduction band and current generation. The bandgap in semiconductors refers to the amount of energy separating the conduction and valence bands. The energy obtained to move to conduction band from valence band comes from solar radiation.

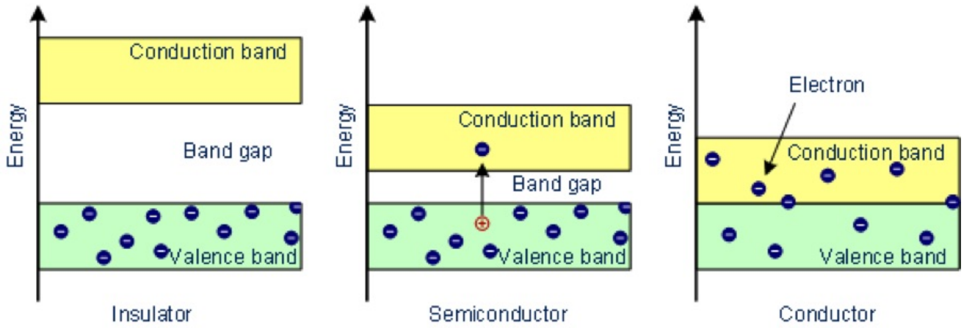


Figure 1: Electron structures and energy capture abilities of insulator, semiconductor, and conductor materials [1].

Photons, the suns energy carriers, possess different specific energies. An ideal bandgap is just below that of incoming photon energies to reduce waste from a higher-energy photon and to ensure excitation which requires a photon of at least as much energy as the bandgap. Location on earth, air composition, and other environmental qualities affect the energies of photons that reach PVMs. Because of this variation in concentration of photon energies, solar panels will convert more solar power if their bandgap is closely tuned to that energy. It is possible to develop solar cells with different bandgap strengths to increase solar energy conversion for a particular situation. This can be done by changing the elements and molecular arrangements of the solar cells and potentially by choosing multijunction cells (stacked layers of semiconductive materials each with different ideal band-gaps to increase the total range of absorbed solar spectra). It is because of local spectra and a range of photovoltaic cell bandgaps that understanding the distribution of photon energies at a given solar spectra, by location, time, season, etc. is crucial in choosing the right PVM.

Current research seeks to improve the overall efficiency of solar cells so that the electrical power output makes photovoltaic energy more cost-effective [2]. Due to the number of variables affecting of solar cells, investigators seek to improve both the engineering as well as the implementation of such technologies with intrinsic efficiency limits calculated around 35%, without deeper remodeling [3]. In addition to intrinsic and mechanical qualities, there are many climatic factors to solar panel performance, such as solar radiation, temperature, or humidity. Ultimately, costs need to be reduced and outputs increased, particularly for large-scale commercial applications.

One main area of research for solar panel performance is examining the effects of dirt buildup, or ”soiling” [4]. Solar cells are normally placed outdoors to maximize solar radiation and dirt builds up on the panels that are left for extended periods, particularly in commercial fields or in hard to reach locations in urban environments. It is known that soil can act as an attenuator for solar radiation [5]. Soil, or water, particles can absorb or deflect incoming photons reducing the electrical conversion potential of solar cells [6]. The effects of soiling broadlyboth in magnitude, patterning, and causesvary entirely by the location due to climate and panel set up. Therefore it is useful to understand soiling processes and quantify electrical losses from soil deposition both globally and specifically on location for a solar field.

## 2.2 Soiling Affects by Photovoltaic Surface Types

Before examining the effects of soiling, it is worthwhile to understand how solar panel surfaces affect environmental interaction. Some photovoltaic modules (PVMs) have a small frame, such as many polycrystalline silicon panels (Figure 2, a). Others, such as flexible CIGS modules have a flat, frame-less surface (b).

Figure 2: (a) Glass-covered polycrystaline silicon and (b) flexible-bodied epoxy CIGS at AMOLF, Netherlands.

There is some knowledge of how PVM surface interrelates with soiling. Epoxy and plastic surfaces accumulate more dust but offer reduced adhesion forces than glass [5]. These adhesion forces, including mechanical or electrostatic, affect the stickiness of different molecules, such as water or dust and the PVM surface. Some studies, looking to isolate the effects of local dirt varieties on solar transmittance able to reach the cells below the cover, use plain glass slides without frames or PV electronics underneath, as discussed later. There can be differences in surfaceenvironment interactions even within subtle glass differences. Humood et al. studied how sand differently wears down annealed versus tempered Solite, low iron glass [7]. While annealed and tempered glasses are composed of the same material, the subtle differences in the cooling and chemical processes during fabrication produce differences in how sand scratches the respective glasses.

While there are few studies on the edge effects of frames on soil deposition, Hao, Lu, and Wang show that wind patterns, subtly affected by small obstacles, do affect dirt buildup [8]. While glass is sometimes used to cover market-available PV products, different forms of glass or plastics are also often employed.

Anti-dust coatings, whether via electromagnetic or hydrophobic processes, do reduce the buildup of soil. It is beyond the scope of this literature review to address studies of anti-dust coatings; however, an important note on this topic is whether coatings interact differently with different types of dirt. The focus of this review and subsequent study of solar panels in The Netherlands is to examine local dirt types, not to compare the performance of the same panel types exposed to different soils. Therefore, the following studies present how different researchers in specific locales examine panel efficiency.

We see that the surface chosen in the design of solar panels is an important factor in how PVMs interrelate with soiling. The studies reviewed below highlight further how local environments affect dirt buildup and efficiency losses.

### 2.3 A Series of Soiling Studies Around the World

As the implementation of solar panels for grid electricity increases around the world, researches continue to investigate localized differences in cell performance [9]. Previous research shows significant efficiency reductions with soiling and the need to understand soiling patterns and cleaning solutions. Researchers have conducted both indoor and outdoor studies of changes in efficiency and power output of solar panels due to dust build up [4, 5, 10, 11]. Ultimately these studies aim to internalize externalities of cell performance. Influences of soil deposition are complex, and can include: wind currents and eddy diffusion, angle and gravitational force pinning soil particles to panel surfaces, and precipitation affecting runoff and soil caking [**?**]. Some researchers employ simulation studies to understand soiling patterns from wind tunnels or artificially laid dust types. This allows for more exact weighing of the dust, before or after deposition, with accuracy between 0.001 to 1 mg [**?**]. This however does not necessarily precisely model soil deposition patterns in the outdoors where many utility-scale solar fields are located. Therefore, much research seeks to study in situ solar cells.

A 2016 study in Norway and South Africa sought to improve knowledge of soiling effects by studying glass sheets used for solar panels in remote, outdoor environments to simulate large-scale solar fields [9]. Ultimately, researchers looked to directly measure the amount and nature of soil build up on loss of performance as opposed to other studies, which comparatively measure performance on cleaned and non-cleaned panels. Researchers cite high uncertainty of using wet cloths, then dried, to weigh dirt on the samples in the absence of a precise scale. This report combined tests in Norway and South Africa with unframed, anti-dust coated or non-coated glass sheets. Dirt density was measured by weighing the glass sheets. Researchers used SEM tests of soil samples to compare dirt transmittance with changes in glass transmittance. While optical tests were used to detect non-uniformity of soil deposition, no trends were found and researchers noted that the glass sheets were smaller and unframed in comparison to utility-style solar panels.

Soiling is a common concern for photovoltaics in dusty areas with little or seasonal rainfall, while this often coincides with highest hours of yearly sun exposure ideally suited to solar panels [12]. A 2016 study by Paudyal and Shakya in Kathmandu quantifies the effect of dust on panels. Researchers hope to improve the practical output of solar panels in Nepal, where hydropower often provides insufficient electricity to the grid in dry months. Since dust particulate is categorized as anything below 500 micrometres, particles can strongly adhere to solar panel surfaces electrostatically or through gravity. Soil composition can have varying soiling effects, where carbon is found to more greatly reduce photon energy available for electrical conversion. Therefore local geology and climate and human activities can influence the soiling effect on solar panels. Researchers reported on the geoclimate of the Kathmandu Valley, which has lower wind speeds, high air pollution from vehicular exhaust, and airborne dust from roads and collects pollutants in this densely populated region augmenting soiling. Paudyal and Shakyas study compares one cleaned and one non-cleaned panel in an urban area of Kathmandu. Multiple regression models were used to calculate the effects of irradiance, cell temperature, humidity, dust deposition density, rainfall, and ambient temperature on the power output of the solar modules. Soil density reached 9.3557 g/m2 after 150 days and a linear decrease in efficiency on the un-cleaned panel. Highest reduction in efficiency reached 29.76%. Researchers stress the need for a cleaning programme for solar fields in Kathmandu.

Researchers in California studied solar panels to quantify losses from soiling. Since soiling greater in drier, dustier areas (like California, similar to middle east), Mejia and Kleissl sought to better understand natural soil removal processes. The effect of rain in soiling was examined and found that only rain after a dry period ¿ 31 days made significant changes in dirt on the panels [13]. Efficiency was measured pre- and post-cleaning by rainfall by subtracting the difference in efficiency at time a and b. The study ultimately reports that rainfall does reduce soiling and that droughts therefore can exacerbate efficiency losses, which has significant implications in sunny, increasingly desert locations.

Other factors involved in the soiling process include tilt severity. Sayyah et al. looked at how the angle of the panels affect how dust rolls off or remains on panels and found that an increase in angling can reduce soiling [4]. Sayyah also reports that concentrated dust can cause hotspots on the panels, which is known to decrease performance [14]. This change in tilting should be calculated with regard to latitude placement to maintain optimal angle for incident solar radiation [10]. High relative humidity is also reported to cause more caked, residual soiling, which is more resistant to cleaning by rain [4]. Lu et al. report wind patterns to be of high importance in soil deposition. Wind speeds can affect the size of dust particles that fall on panels, which in turn have different scattering effects in their solar radiation interference [4, 10]. Additionally, larger particles show more strongly decrease power output [15].

## 2.4 Module Temperature Increase and Loss in Efficiency

Through the equation for open circuit voltage, it is known that Voc depends linearly on temperature [5, 16].

Zaihidee et al. explain how soiling does not only prevent the capture of photon energy but can also raise the temperature of the solar panel surface, as measured from a thermal camera. Research has shown that soiling can causes temperature increases by 10oC, enough to change the open circuit voltage by a factor of 10 [17]. This has significant impact on the output of cells in warmer climates. It is unclear how surface temperature relates to the temperature of the solar cells, which are millimeters to centimeters wide underneath the plastic or glass cover.

### 2.5 Impact of Local Climate on Solar Panel Efficiency

Beyond temperature, global climatic differences are a known factor in evaluating the type of solar cell appropriate for a given locale [18]. Temperature, wind speed, and humidity, among other factors are responsible for output losses [18, ?]. In fact, humidity not only speeds up degradation of the solar panel apparatus but can also affect the bandgap absorption of photon energy [?]. Humidity causes degradation of PV enclosures.

Ogbomo et al. sought to find feasible PV modules to withstand these extreme climate factors. High temperature, humidity, and low wind speed reportedly cause quicker than expected module degradation and reduce efficiency compromising financial feasibility. Ogbomo et al. studied factors including power output, solar energy conversion, and energy payback time from production costs. Since the ultimate output of PVMs depends on a range of intrinsic solar cell characteristics, engineering and circuitry design, and installation and maintenance, a range of collective solutions were tested such as: glass type encapsulating solar cells, and reviewed a range of market solar technologies. Searching for solar cell composition with a temperature coefficient that approaches zero helps reduce the negative impact of high ambient temperatures. With this characteristic, Cadmium Telluride CdTe show 0% in decrease in energy conversion efficiency from increased temperatures, which suggest that this type of PVM would fare better in the presence of dirt because of reduced losses from module heating.

One way to accommodate climatic characteristics such as temperature, humidity, and cloud cover is to create PVMs with different bandgaps [20]. This is because altering the bandgap of the semiconductor solar cells allows devices to absorb solar radiation of different energies. A table of optimum bandgaps for multiples numbers of multijunction PVMs are presented by inputting weighted spectra for different air conditions from clean to polluted. Researchers also report factors affecting the ideal bandgap for PVMs including latitude, cloud cover, and humidity. For tandem top cell modules, a change of 13.7% was noted from base condition at STC to subartic conditions (where base condition features clear skies at 40oN latitude at $40^o$ angle with AM1.5 global spectrum, the standard model for solar radiation). Much of these changes are due to spectral angles and from air composition and density at varying latitudes and altitudes. This report shows that by inputting climate characteristics, single or multijunction solar cells can be adjusted to ideal bandgaps to best capture solar spectra.

By reviewing multiple studies of soiling and solar energy efficiency, we see that higher density does not uniformly correlate with loss in PVM efficiency. Different factors could lead to this including dust particle size and the moisture of the soil, such as the caked nature from wet and dirt versus dust of a dry environment [5]. Each type of commercially available solar panel has its own enclosure and module characteristics and central bandgap and subsequent strengths in different climates with different solar spectra. Therefore it is important to study the performance of PVMs in locum to select or develop the best module due to changes in the absorbance spectra of dirt types, humidity and temperature, air quality, and more.

# 3 Empirical Study of Dirt and Efficiency

### The effects of soiling on efficiency of different types of solar panel modules in The Netherlands

**Authors:** Talia Martz-Oberlander[1,2,3], Bruno Ehrler[1], Moritz Futscher[1]

[1]AMOLF, The Netherlands

[2]Quest University Canada

[3]Amsterdam University College

**Abstract**

Solar power generation is a growing leader in global energy markets. Due to the dependence of the conversion efficiency on incoming solar irradiation and spectrum, regional environments affect performance and require localized research into the functionality of different types of photovoltaic modules (PVM). One such factor, soiling, the buildup of dirt on modules, is known to limit cell output due to reducing available light energy reaching the PVM. With reported efficiency losses of up to 40%, improving our understanding of soiling helps increase solar energy generation. While research has been conducted on controlled glass screens and with artificially deposited soil types, this study tests the dependence of soiling on six different commercially available solar modules outdoors in the Netherlands. The data show a relative change in efficiency of up to 53.5% is observed across different module types.

### 3.1 Introduction

With an increase in grid demand and desire for reduced cost of non-carbon based energy, solar power is a growing leader in energy research. Photovoltaics offer worldwide availability [21], however this global applicability introduces local environmental impacts on performance. The ultimate goal of solar cell research is to improve the efficiency of photolvoltaics to produce more energy in comparison with incoming solar radiation [2, 3]. However, solar cells output depends on the amount and type of incoming solar radiation, which is affected by local environments.

One well-known factor affecting incoming energy and photovoltaic performance is the buildup of dirt on solar module facesmost often located outdoors [4]. This process of soiling has been studied worldwide and has become a main area of research for solar panel performance due to its detrimental effects to PV module (PVM) longevity and efficiency. Solar energy conversation efficiency losses are reported as high as 35% from $20\text{gm}^{-2}$ dirt density [5].

Soiling is known to reduce the output of PVMs for a number of factors. Most importantly, dirt blocks sunlight, reducing the overall irradiance at the cell [**?**]. An increase in temperature causes linear decreases efficiency for most solar cells, and soil buildup has been shown to increase module temperature [7]. Furthermore, depending on the dirt composition, soiling can alter incoming spectra as certain dust types absorb certain frequencies of light [5]. Therefore, regions with locally unique environment characteristics, such as fine dust in the air, have varying effects on the spectrum hitting the cells [8]. The bandgaps of each solar cell type will affect its absorption of different wavelengths of solar radiation and it is beneficial to choose solar panels that fit the local frequency of incoming solar radiation.

Extensive research has been conducted to examine efficiency losses in different environments based on the absorptive properties of soil [8]. Efficiency is a widely used measure of module performance, where incoming solar intensity is related to power output in Watts. However, most preexisting research has been conducted in dry, dusty, or hot climates due to the decreased natural cleaning process [9, 10]. Many of these studies used one type of solar panel, sometimes in controlled laboratories [10, 11], or looked for reduced transmittance in glass slides [12]. A study with comparable climate to the Netherlands conducted in Norway only examines change in transmittance from glass slides as simulator [9].

Here, we compare the efficiency of six commercially available solar panels with different material compositions located together in Amsterdam, The Netherlands. This study is a direct investigation of how varied solar cells function with naturally occurring dirt buildup in wet, temperate regions as well as in urban areas, thought to offer warmer and less-ideal solar field locations [13]. We find that the different panel types collect different amounts of dirt, also depending on their direct environment. The dirt shows a relatively flat spectral response, and as a result the main determining factor for the solar cell efficiency change is the amount of dirt buildup.

### 3.2 Methods

#### 3.2.1 Solar Field Data Collection

This study uses data from six types of solar panels facing South at 33o tilt in an outdoor field at the Amsterdam Science Park, The Netherlands (see Figure 1). The solar field was constructed in December 2015 and the panels were not cleaned from installation

Figure 3: The solar field at AMOLF, Amsterdam, October 2016.

until October 14th 2016. The solar panel types in the study are as follows:

Table 1: Six types of solar cell modules at FOM Institute AMOLF, information from de Hart (2016).

| Name | Dimensions ($m^2$) | Band Gap (eV) | Efficiency listed by manufacturer (%) | Notes |
|---|---|---|---|---|
| Copper Indium Gallium Selenide (CIGS) | 2.017 x 0.494 = 0.996 | 1.2 (NREL record[1]) | 12.7 | Flexible unit |
| Cadmium Telluride (CdTe) | 1.200 x 0.600 = 0.720 | 1.45 (NREL record) | 12.0 | Smooth black and glass; broken face |
| Polycrystalline Silicon (Poly-Si) | 1.675 x 1.001 = 1.677 | 1.12 | 15.5 | Blue colour |
| Integrated Back Contact Monocrystalline Silicon (IBC-Si) | 1.559 x 1.046 = 1.631 | 1.12 | 21.5 | Clear black squares |
| Heterojunction Intrinsic Layer Monocrystalline Silicon (HIL-Si) | 1.580 x 0.798 = 1.261 | 1.12 | 19.4 | Black squares with lines, contacts in front |
| Copper Indium Gallium Selenide (back mirror) (CIGSe) | 1.656 x 0.656 = 1.086 | 1.12 | 14.7 | Plain black module |

Three types of data automatically logged every five minutes in addition to manually collected soil data were used for this project and are separated into pre- and post-cleaning datasets. Data collected individually from each type of module include the power at the maximum power point, current, fill factor, and incident solar radiation (see Appendix A for full list). A second measurement of the solar intensity is taken with a pyranometer. Thirdly, environmental data is collected from a local weather station including temperature, wind speed and direction, and precipitation. Dirt build up was measured visually and by mass and will be discussed in more detail later. To analyse the change in efficiency from dirty to clean panels, environmental variables of temperature and incoming solar irradiance, which effect solar cell power output, were accounted for by comparing similar environmental conditions only [24].

Given the fact that solar cell efficiency is dependent on the air temperature, and energy received from the sun, among other factors, this study compares power data sampled at times of similar spectra (quantified using the average photon energy, APE), solar irradiance, and air temperature. Other weather factors such as wind and air pressure were ignored. By controlling for major environmental variables, the data should reveal the effect of dirt on power output and efficiency. The data was grouped in bins with small ranges of APE (± 0.02eV range for each bin), intensity ($\pm 2Wm^{-2}$), or temperature ($\pm 0.5^{o}$C) [24].

We analysed the differences in efficiency caused by environmental factors during two days before cleaning and two days afterwards (October 12-15th 2016). Efficiency was calculated using the equation:

$$\text{Efficiency} = \frac{\text{power (W)}}{\text{incoming radiation (Wm}^{-}\text{2)}} * \text{solar panel area (m}^2\text{)} \quad (1)$$

Relative change in efficiency used to compare dirty and clean data is [22]:

$$E_{relative} = \frac{(E_{clean} - E_{dirty})}{E_{clean}} \quad (2)$$

And APE is calculated by calculating average incoming photon energy in the wavelength range between 350-1050nm, due to insignificant data from the spectrometer beyond this range.

$$\text{APE} = \frac{1}{q} \int \frac{E_\lambda d_\lambda}{E_\lambda \phi_\lambda} \quad (3)$$

#### 3.2.2 Dirt Methods

Dirt was collected at night to avoid impacting data collection during sunlight hours. Before cleaning the solar modules, dirt was characterized visually using camera photos of dirty and clean sections of the panels (see Figure 6). To measure the amount of dirt buildup on the panels, method similar to Sulaiman et al. examining dirt density in $gm^{-2}$ was used [15]. A 20cm x 20cm quadrant was marked out in a random non-edge location of each panel. A glass scraper was used to collect the dirt from the quadrant for later analysis and the process was repeated for each panel type (see Appendix A, Figure 11).

Figure 4: Thin but heavily caked on dirt from ten months can be seen on the CIGS with back mirror, Module 6, while Module 1 the flexible CIGS panel shows small, sparse, sappy dots (pictures taken 13th October 2016).

While sampling the soil from each quadrant, qualitative differences were noted. Modules 1 and 2 seemed to have more pasty dirt built up and dots of residue, which felt sticky-oily to the touch, whereas modules 3, 4, 5, and 6 had more loose, dry soil. All soil was fairly dark, but module 3 had lighter brown/grey soil.

The modules were cleaned with water and small amount of dish soap, a scrubby brush, wash cloth, and some Glasex glass cleaner for two of the panels, before rinsing with water.

The measure the mass density for each panel, an empty petri dish was weighed, and its weight compared to a petri dish with the soil from the 20 cm x 20 cm sample area. The dirt density varies dramatically between the panels, as can be seen in Table 3. After weighing the petri dishes to find the soil density for each panel, the soil was dispersed in water for absorption measurements. The soil masses were put in small glass vials filled with 1 ml deionized water (see image below).

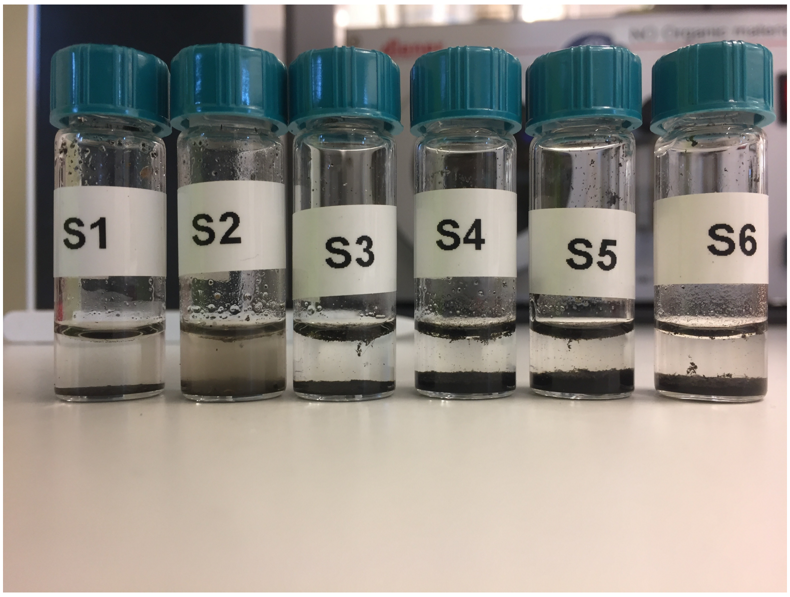


Figure 5: Soil and water dispersion used to find absorption spectra.

After drop casting 10 drops of the soil dispersion onto 1 cm  1 cm glass slides, the absorption spectra of the soil was measured for each panel with a UV-Vis spectrometer (see Figure 10).

### 3.3 Results

The measurements show a statistically significant change in efficiency for most of the solar modules before and after cleaning. Each type of panel studied exhibits different efficiency improvements after cleaning. The Heterojunction silicon (HITSi) module had the highest overall change in absolute efficiency from data collected immediately before and after cleaning at $9.11\% \pm 1.53\%$. The Cadmium Telluride (CdTe) module changed the least at $0.29\% \pm 0.26\%$.

The efficiency of the different panels could be affected in different ways due to their different bandgap. However, our results for the absorption measurement of the dirt collected from the panels show a reasonably flat response for all panels (see Figure 8).

In Figure 7 the efficiency change is plotted for a range of different conditions (different bins, as described above). The efficiency changes in a very similar fashion for the different bins, indicating that the environmental conditions play a less important role compared with the difference between clean and dirty panels.

By comparing soil density on the solar modules, we find that soil density is closely related to change in efficiency, where panels that originally had less heavy soiling showed less increase in efficiency after cleaning. After isolating environmental variables, the correlation between area dirt density and relative changes in efficiency for each panel was calculated. We find that they are well-described with a linear fit, with a correlation coefficient of 0.96.

Figure 6: Before and after cleaning the back contact monocrystalline silicon module.

To investigate and isolate for the effects of APE, solar intensity, and temperature, the bins of data mentioned in methods were superimposed to see that using a wider range of these three variables in a master bin would still yield the same efficiency results. This bin has ranges of: $\pm 2^{o}$C temperature, $\pm 2$ eV APE, and $\pm 10$ $Wm^{-2}$ intensity, was used for results of relative change of efficiency seen in results below.

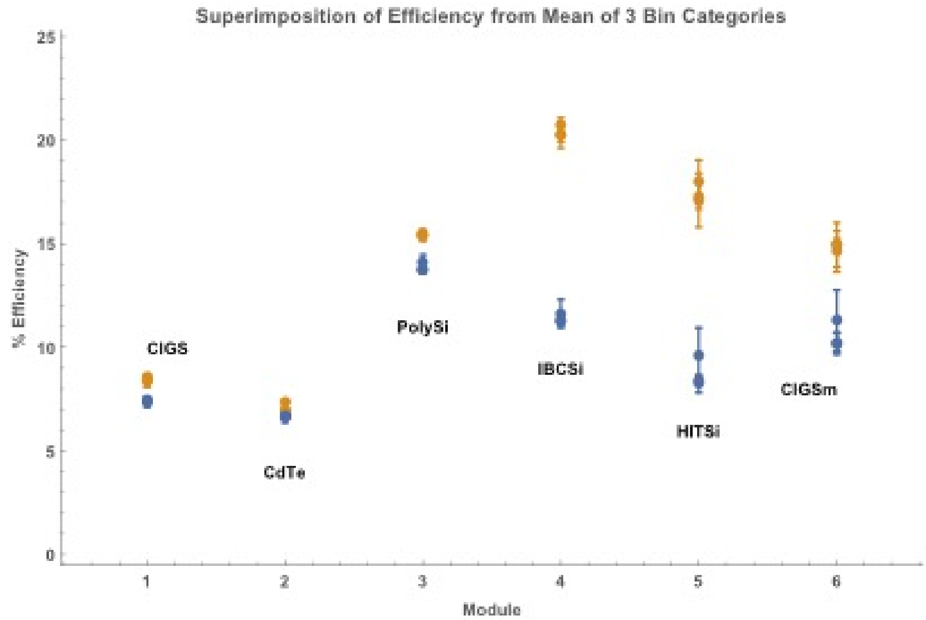


Figure 7: Superimposition of efficiency from different bins before (blue) and after cleaning. This shows the overlap of efficiency regardless of environmental factors within the selected dates in October.

UV-Vis spectroscopy showed consistent visible light absorption from the soil as sampled from all six panels (see Figure 8). Differences in absorption intensity can be related to the thickness of soil deposited onto the slides. By normalizing the modules absorption curves we see steadiness across the significant bulk of the solar spectrum as utilized by the modules.

Ultimately we see that we can find the mean values for each panel before and after cleaning with combined error.

By comparing soil density on the solar modules, we see that soil density is closely related to change in efficiency, where panels that originally had less heavy soiling showed less increase in efficiency after cleaning.

After isolating environmental variables, the correlation between area dirt density and relative changes in efficiency for each panel was calculated and fit line generated [24].

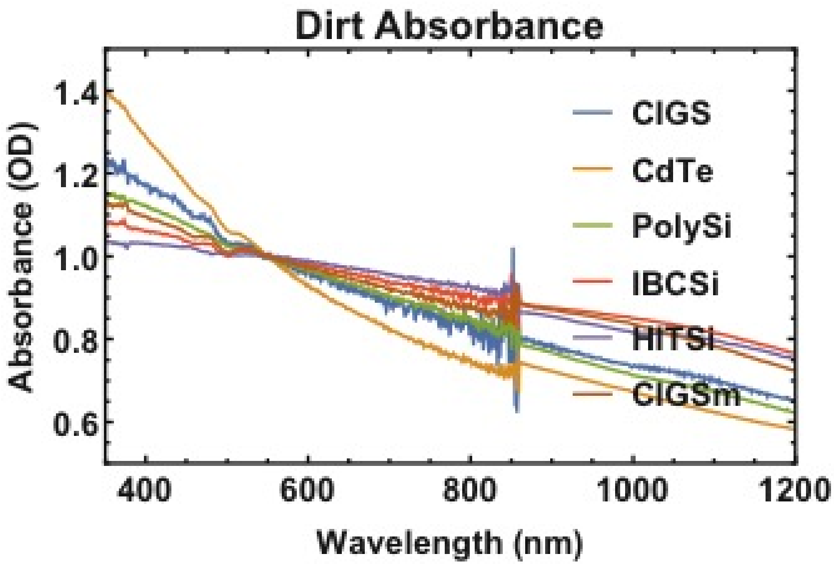


Figure 8: Normalized absorption for samples of the six modules shows stable light absorption from 350-1200 nm.

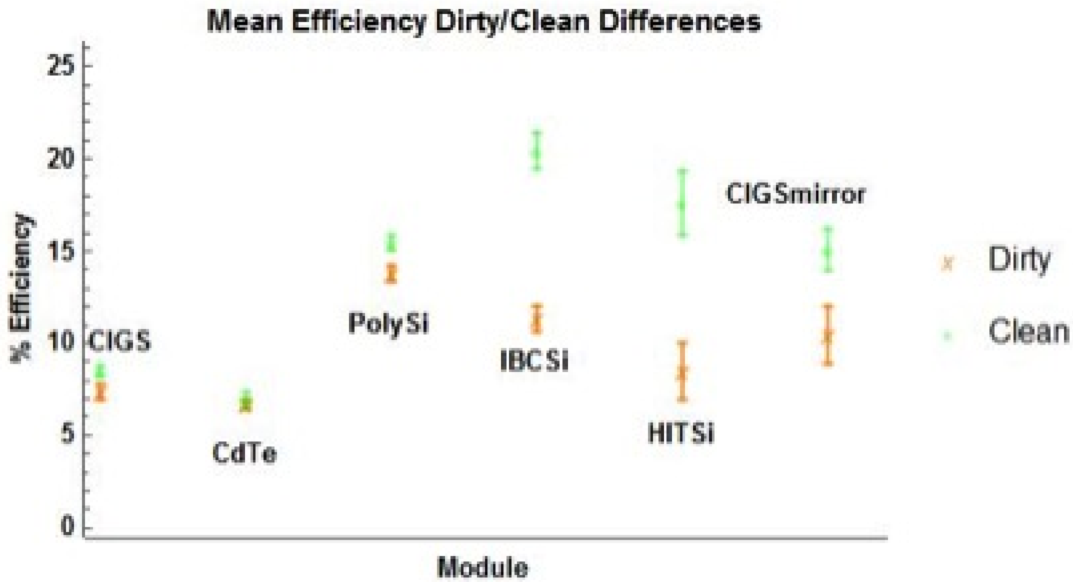


Figure 9: Changes in efficiency in clean and dirty data from each module from the larger bin of comparable data.

Overall, we see a wide range of changes in efficiency across the six module types. This fits with high correlation of dirt density to efficiency losses, but does not all relate equally across panels, as seen most clearly in the case of the IBCSi and HITSi. Both have insignificant differences in dirt density but do show significant differences in relative efficiency losses.

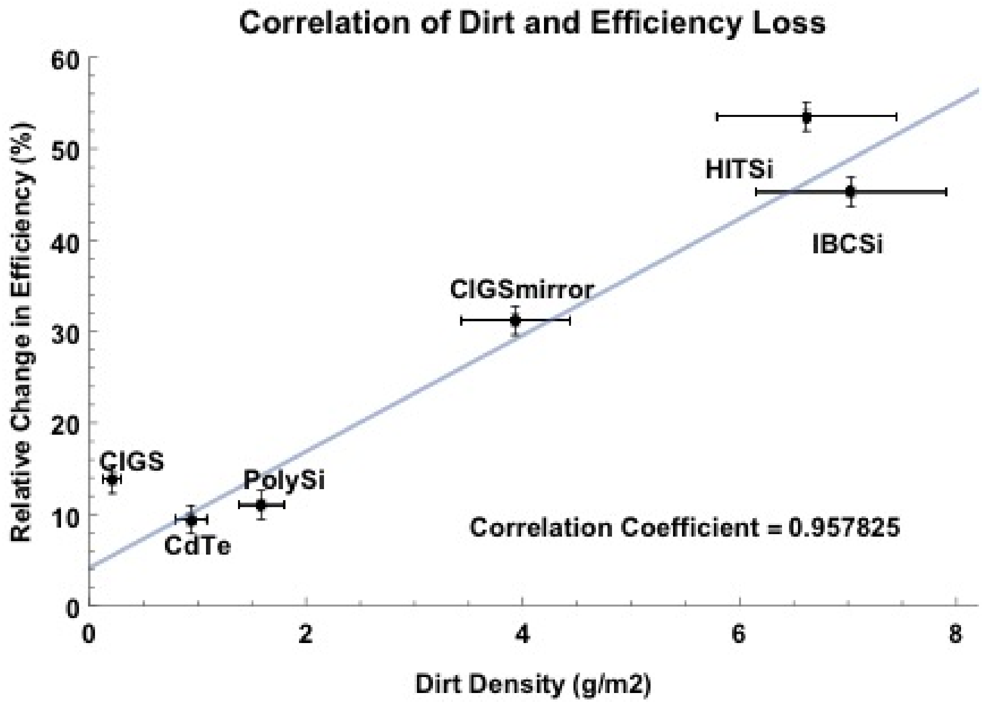


Figure 10: The correlation of dirty density to relative change in efficiency from selected data from Oct 12-13th and 14-15th.

Table 2: List of relative change of efficiency for each module from dirty to clean.

| Name | Relative Change in Efficiency % |
|---|---|
| CIGS | 13.86 |
| CdTe | 9.48 |
| PolySi | 11.05 |
| IBC MonoSi | 45.30 |
| HIT MonoSi | 53.51 |
| CIGSmirror | 31.21 |

### 3.4 Discussion

There are clear differences in the change in efficiency for each panel type, mostly determined by the differences in soil buildup. These difference could originate in the proximity to a nearby tree, and in differences in the surface of the solar modules. Module 4 and 5 are located closest to the tree (see Figure 3), and we observe the larges soil buildup on these modules. At the same time, module 1 has a rubber surface, and module 2 a flat glass surface, while the other modules have a rough glass surface. Module 1 and 2 show comparably little soil buildup, presumably because the soil washes off more easily on the flat surfaces.

When comparing our figures to preexisting literature, Zaihidee et al. in 2014 presented that a 20 $gm^{-2}$ buildup of soil could cause a 15-35% relative reduction in efficiency [5]. Jiang et al. showed a 26% decrease in efficiency from 22 $gm^{-2}$ area dirt density, which is much less when compared to the results of this study at 53.5% decrease in efficiency with 7 $gm^{-2}$ soiling [22]. The differences could stem from the different kind of soil in the damp climate studied here, or the different soil distribution. Of the Mono-, Poly-crystalline, and amorphous silicon cells Jiang et al. tested, the Epoxy-surfaced polycrystalline module showed the greatest loss in efficiency. The polycrystalline module in this study also features the highest reduction in efficiency, even higher than that of Jiangs lab-controlled study.

Changes in efficiency could be different across the panel types due to localized sap deposits on certain panels more than others. Dorobantu et al. 2011 noted that localized depositions can cause localized output losses [17]. It should be noted that data from the CdTe module offers limited analysis because the glass covering is cracked due to its holding clamps.

### 3.5 Conclusion

This study shows that soiling in damp climates on photovoltaic panels causes significant power output losses. By examining local soiling phenomena including deposition thickness and absorbance alongside solar module efficiency we can better understand the practical output of photovoltaics. There is a large range in efficiency losses suffered from the different six modules studied, mostly correlated to the dirt density on the panels. We find a relative efficiency loss of roughly 9% greater than with roughly 12 $gm^{-2}$ less soiling than previously reported efficiency losses in other literature. The soil buildup in damp climates might differ from the conventionally studied dry climates, and the laboratory studies, and the local buildup of soil on the panel might further reduce the efficiency in a disproportional fashion.

Considering the cost of energy generation, ultimately the decision must be made whether to spend money on cleaning panels or to lose money in their output and lifetime from soiling losses. Another tradeoff is the use of surfaces that are excellent for light-trapping, such as the rough glass, or surfaces where dirt is more easily washed off. Knowledge of the magnitude of power losses helps guide those decisions.

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# 4 Appendices

## 4.1 Appendix A: Data

### Complete list of data types available

1. ***Weather***
   - Average temperature ($^o$C)
   - Dewpoint ($^o$C)
   - Humidity (%)
   - Air pressure (hPA)
   - Air density (kgm$^{-3}$)
   - Wind speed (kmh$^-$1)
   - Wind direction ($^o$)
   - Wind measurement quality (%)
2. ***Solar Radiation***
   - Sensor temperature
   - Wavelength (nm)
   - Irradiance (W/m$^2$/um)
3. ***Module Parameters (collected separately for each of the six panel types)***
   - Voltage at maximum power point (mpp) (V)
   - Current at mpp (A)
   - Power at mpp (W)
   - Open circuit voltave (Voc) (V)
   - Closed circuit current (Isc) (A)
   - Fill factor (%)
   - G (a second pyranometer reading) (Wm$^2$)
   - Module temperature (oC)
   - G_pyranometer irradiance (Wm$^2$)
   - Voltage range (s/sec)
   - Current range (s/sec)
   - Scan rate

Table 3: Mass of soil sampled off the 20x20cm quadrants on the solar panels on 13.10.16

| Name | Soil removed from panel (mg) ± 0.05mg plus human sampling error | Soil/water dispersion (mg) | Soil Density on panel gm$^{-2}$ |
|---|---|---|---|
| CIGS | 8.5 | 2.8 | 0.02125 |
| CdTe | 37.5 | 21.4 | 0.9375 |
| PolySi | 63.5 | 13.4 | 1.5857 |
| IBC MonoSi | 281.1 | 25.7 | 7.0275 |
| HIT MonoSi | 264.7 | 43.6 | 6.6175 |
| CIGSmirror | 157.2 | 22.8 | 3.9300 |

Figure 11: Glass cleaner scraping tool and method used to take dirt from quadrants marked out on the solar panel.

## 4.2 Appendix B: Code

Samples of Mathematica code, downloadable at: https://github.com/taliamo/Soiling
The code outline.

**Constants**

**Functions**

**A. Imports**

Three types of data inputs from three data logging apparatuses: Weather, Solar Spectra, and Module data

A.1 Weather
Each Weather station file consists of one hour of data collected every 5mins
Code imports data by day, as an aggregate of hourly files. The dimensions of this Mathematica list is then: 24 lists each with 14 sublists

A.2 Solar Spectra
Data is imported by day, as a list of hourly datafiles

Within each spectra there are 24 lists with 2056 items in each list

A.2.2 APE
Where efficiency increases with increase in photon energy

From Ruby

A.3 Module Parameters
Data is imported by **module per month** where each file contains a row of data for every 5mins
Length of each dateframe is defined, although you don't really need this. List/datafile length depends on the strength of solar irradiance at early and late times of the day.

**B. Creating cleaned absolute time files for 3 data types**

**C. Creating Master List**

**D. Master Grabber Function; compares time points only**

**E. Master Grabber 2.0, needs fixed Tair, I, APE min/max value inputs**

BIN 1: Chosen list based on a set range and set T, I, APE values. Both days need same values

BIN II - change in APE

BIN III - change in APE

**F. PLOTS, clean-dirty efficiency comparison**

A sample section:

## C. Creating Master List

This section creates a master list by grouping the three data types--solar, weather, and 6 module files-- by their absolute time stamps into one main list of lists. The selValue function selects data at a certain level in the original list; then a function loops through all inputted data in the selValue to match time (element [[1]]) into the empty newList__.

Entire list is 288 lists long, for the 288 5 minute time stamps per each 24hrs.
Since Module data does not log for 24 hrs, there will be "none" values before ~9.30 and after ~17.30

SelValue imputs: the data file/list name and the level in the list in which the timestamp is found (eg. the first element [[1]])

NewList** is a list of 9 lists as follows:
-newList**[[i,1]]: time stamp
-newList**[[i,2]]: weather file
-newList**[[i,3;;8]]: module files
-newList**[[i,9]]: APE values

```
selValue[data_, level_] := If[data == {}, {"None"}, data[[level]]]
```

Run this to make a list for the 14th

```
timeList14 = abstweather14[[All, 1]];
```

```
newList14 = {};
For[i = 1, i < Length[timeList14] + 1, i ++,
 AppendTo[newList14, DeleteCases[
   Join[{timeList14[[i]]},
    selValue[Select[abstweather14, #[[1]] == timeList14[[i]] &], All],
    selValue[Select[abstmodule114, #[[1]] == timeList14[[i]] &], All],
    selValue[Select[abstmodule214, #[[1]] == timeList14[[i]] &], All],
    selValue[Select[abstmodule314, #[[1]] == timeList14[[i]] &], All],
    selValue[Select[abstmodule414, #[[1]] == timeList14[[i]] &], All],
    selValue[Select[abstmodule514, #[[1]] == timeList14[[i]] &], All],
    selValue[Select[abstmodule614, #[[1]] == timeList14[[i]] &], All],
    selValue[Select[abstAPE14, #[[1]] == timeList14[[i]] &], All]]
   , "None", 1]]]
```