August 2019

Investigation of Efficiency Loss of Distributed Solar Power Due to Soiling and Efficiency Recovery by Rainfall

Amanda Mayumi Tanaka

Repository Citation

Tanaka, Amanda Mayumi, "Investigation of Efficiency Loss of Distributed Solar Power Due to Soiling and Efficiency Recovery by Rainfall" (2019). *UNLV Theses, Dissertations, Professional Papers, and Capstones*. 3750.
https://digitalscholarship.unlv.edu/thesesdissertations/3750

INVESTIGATION OF EFFICIENCY LOSS OF DISTRIBUTED SOLAR POWER DUE TO SOILING AND EFFICIENCY RECOVERY BY RAINFALL

By

Amanda Mayumi Tanaka

Bachelor of Science in Environmental Chemistry
Universidade de Sao Paulo, USP
2015

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Engineering - Civil and Environmental Engineering

Department of Civil and Environmental Engineering and Construction
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
August 2019

UNLV | GRADUATE COLLEGE

Thesis Approval

The Graduate College
The University of Nevada, Las Vegas

May 17, 2019

This thesis prepared by

Amanda Mayumi Tanaka

entitled

Investigation of Efficiency Loss of Distributed Solar Power Due To Soiling and Efficiency Recovery by Rainfall

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Engineering - Civil and Environmental Engineering
Department of Civil and Environmental Engineering and Construction

Jacimaria Batista, Ph.D.
Examination Committee Chair

David James, Ph.D.
Examination Committee Member

Sajjad Ahmad, Ph.D.
Examination Committee Member

Monika Neda, Ph.D.
Examination Committee Member

Shubhra Bansal, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Dean

Abstract

As the concern with global warming increases causing the need for CO_2 reduction, renewable energy is of great interest as it has lower carbon footprint when compared to conventional sources (natural gas, coal, oil and nuclear). Solar energy has been drawing worldwide attention since it can transform sunlight directly into electricity with the use of photovoltaic (PV) cells. However, this technology has some drawbacks that need to be addressed including dust deposition on solar panels, also known as soiling. Soiling can decrease PV panel's efficiency thereby resulting in less energy production. The soiling rates are very site specific and depend on the geographic location of the panels and the climate in that area. The solar panels can be cleaned naturally (by rainfall, snow or wind) or mechanically washed. This thesis addresses the impact of solar panel soiling and washing on the energy production of solar PV plants located at the UNLV campus.

The objectives of this project were (a) to evaluate whether rainfall alone, in the desert environment with low rainfall, is sufficient to clean up the solar panels, and, if possible, determine the minimum amount of rainfall necessary to clean up panels.; (b) to examine the efficiency loss caused by soiling using different methods of analyses and (c) to evaluate if panel washing is worthwhile given the cost and the efficiency gain that is obtained by washing. To calculate the efficiency of the panels, a model was developed to generate parameters that were not measured at the site. Panel efficiencies before and after rainfall events were compared to determine the minimum amount of rain necessary to clean the panels. It was found that at least 0.2 inches of rain was needed to partially restore clean-panel efficiency. In Las Vegas, the recurrence periods of different depths rainfall were calculated using data from the past 29 years.

It was observed that the 50th percentile recurrence period of a rainfall event with depth of 0.2 inches or higher was approximately 52 days.

Student Union: -0.0044%/day, CBC-C: -0.00099%/day, and Dayton Hall: -0.0034%/day

The amount of efficiency lost during the dry intervals (periods between rainfall events) was analyzed in three different ways. The average efficiency loss per day during the dry periods varied from -0.000171 % to -0.00533 %, depending on the method used and the building where the panels were located. However, there were some limitations to the calculations. It was not possible to completely isolate the effects of only soiling on the efficiency of the panels. The rate of decline seemed to be also impacted by seasonal effects.

To better evaluate the effect of washing, a professional company was hired to wash a set of solar panels located on UNLV’s Student Union building. The panels were washed with water with a low concentration of TDS. The power output and the efficiency of those panels were analyzed from before and after the washing. There was a very small efficiency and power increase due to the washing. Therefore, it was concluded that washing in this area is not worthwhile, and that rainfall events in excess of 0.2 inches can adequately restore the efficiency of the panels. If there is a change in cost of energy, washing, water or a great increase in the efficiency of the solar panels, it would be necessary to reevaluate the analysis.

Acknowledgements

First of all, I would like to thank God. He has given me strength, support, courage and faith so I could keep going during the hardest moments. He also provided me a supporting family and friends during this journey. He has been so good to me and has given me so many opportunities and I could not be more thankful for that.

Secondly, I would like to thank my parents, Marisa Baldi and Nelson Tanaka, for believing in me and supporting me financially and, most importantly, emotionally; not only throughout this process, but during my whole life. They are the best parents I could have asked for and without them I would not have achieved half as much as I have. I thank my brother, Thiago Tanaka, for all the love and fun he has always brought into my life and being there when I need him.

I would like to thank Dr. Batista for giving me this opportunity and helping me since when I started applying to UNLV throughout my whole time here. I thank her for providing me funding for the master’s degree and guiding me in my research. I want to thank my committee, Dr. Neda, Dr. Ahmad, Dr. James and Dr. Bansal, for their time and help reviewing my work and valuable insights. I would like to thank Dr. Neda for all the assistance she gave me with the results and statistics calculations.

I would like to specially thank Mark Elkouz for being a supporting boyfriend, spending late nights with me in the lab, proof-reading my e-mails and parts of my thesis, encouraging me to work when I was not motivated, listening to my complaints and for his companionship. It was a tough couple of years, but I could not imagine how much harder it would have been if he was not there for me.

I want to thank my family and friends in Brazil for all their support and my friends Ana, Alisson, Fernanda, May and Mayra for being there for me when I needed, always motivating me and sharing with me this experience. Also, thanks to Vivi for being a good friend and supporting me. I would also like to thank the Elkouz/Karacsonyi family: Jacquie, Elie, Sandra, Natalie, Joe, Noelle and baby Elias for welcoming me into their family and making me feel like home even when I am thousands of miles away from Brazil. Special thanks to my Kansas family, Rhonda, Dewayne, Kaylee and Kelsey for being the best host family I could have ever imagined and always being there for me.

I would also like to thank everyone that helped me in this research and made it possible for this thesis to come together. Special thanks to Aaron Sahm for the help with all my calculations and the inputs in my results. Thanks to Mr. Whinery, Mr. McMath, Chad, Mr. Henson for giving me access to the data and to the solar panels at UNLV. I would also like to thank everyone that helped me in the solar panel survey and shared their knowledge with me. I wanted to thank my colleagues from WSP for being very supportive and especially my supervisor, Joanna Opeña, for being very understanding, believing in me, and teaching me so much every day.

This research was only possible due to the financial funding provided by the National Science Foundation under Grant No. IIA-1301726. I would like to thank and acknowledge NSF for this opportunity.

Table of Contents

List of Tables

List of Figures

List of Acronyms

α/β	Temperature Coefficient
BLM	Bureau of Land Management
CB	Conduction Band
CEMP	Community Environmental Monitoring Program
CG	Centralized Generation
CPCU	California Public Utility Commission
CPS	Concentrated Solar Power
DG	Distributed Generation
DNI	Direct Normal Irradiance
DP	Dry Period
DRI	Desert Research Institute
GHI	Global Horizontal Irradiance
FF	Fill Factor
I_{SC}	Short-Circuit Current
IOU	Investor Owned Utilities
ITC	Investment Tax Credit
MIDC	Measurement and Instrumentation Data Center
η	Efficiency
NREL	National Renewable Energy Laboratory
P	Power Output
PBI	Performance Based Incentives
POA	Plane of Array

PPA	Power Purchase Agreements
PTC	Production Tax Credit
PUCN	Nevada Public Utilities Commission
PV	Photovoltaic
RO	Reverse Osmosis
RPS	Renewable Portfolio Standards
SAM	System Advisory Model
STC	Standard Test Conditions
SU	Student Union
TDS	Total Dissolved Solids
UFI	Upfront Incentives
UNLV	University of Nevada, Las Vegas
V_{OC}	Open-Circuit Voltage
VB	Valence Band
WRI	Wright Hall

Chapter 1 – Introduction and Objectives

Solar energy has been drawing worldwide attention as it is able to transform sunlight directly into electricity with the use of photovoltaic (PV) cells, therefore providing a clean and sustainable type of energy (Maghami et al., 2016). However, most solar cells currently available, have limited efficiency, and are only able to convert around 15-20% of the sunlight into electricity (Mani & Pillai, 2010), hence it is important that the system is always operating in its full capacity. In addition to the lower efficiency of PV panels due to the limitations of materials used in manufacturing them, panels' loss of efficiency is also experienced during operation due to dust deposition. Dust deposition, also known as soiling, has the potential to decrease solar irradiance capture, thereby decreasing energy output.

Due to the Renewable Portfolio Standards, which require that a certain percentage of the energy produced in each state come from renewable sources (Durkay, 2017), there has been an increase in photovoltaic systems. To meet the RPS requirements of the state, energy companies are signing power purchase agreements (PPAs) with large-scale solar plants or are expanding distributed solar PV systems by supporting their installation on municipal and public urban landholdings (homes, schools, churches, municipal buildings, parking lots, etc.). The Bureau of Land Management (BLM), responsible for overseeing public lands with solar energy in Nevada, predicts a continued interest in public landholding for expansion of large solar energy as a result of the renewable standards established in this state ("U.S. Department Of The Interior Bureau Of Land Management" n.d.).

Dust accumulated on panels can be removed by natural events, such as wind and rainfall, or it can be removed by mechanical washing. Soiling, due to dust deposition on solar panels, is a major concern especially in desert like areas where rainfall is scarce (Adinoyi & Said, 2013). A study conducted by Asl-Soleimani et al. (2001) in Iran, found that air pollution can decrease the power output of PV panels by up to 60%. Another study conducted in Saudi Arabia also observed over 50% power output loss for PV systems that have not been cleaned, manually or naturally, for more than 6 months (Adinoyi & Said, 2013).

Studies have shown that soiling losses are not as high in the southwest of the United States, but it is still present. The higher soiling losses reported are typically associated with dust storms and higher average relative humidity, and those climatic conditions are normally not present in the southwest of the USA (Caron & Littmann, 2013). Kimber et al. (2006) analyzed several solar panels located in California and data from 46 sites showed that there was an annual energy loss of 1.5% – 6.5% depending on the location of the PV system. Solar panels located in Mesa, Arizona, showed energy losses related to soiling of up to 3.87% in a six weeks period for panels with a 0° tilt angle. The energy losses decreased as the tilt angles increased (Cano, 2011).

One way to recover the solar panel's efficiency is to clean them. Panels can be cleaned manually, with a mop or brushes, vacuum cleaning, or automatically, with the aid of a robot that possesses a rubber wiper and water pot (Hudedmani et al., 2017). Natural cleaning processes also have been studied such as rainfall and wind, and were shown to be efficient methods depending on the type of soiling and size (Jiang et al., 2018; Sayyah et al., 2014).

Some studies have shown that rainfall can be effective in cleaning solar panels. An experiment conducted by Caron & Littmann (2013) showed less than 1.0% soiling losses per month and up to 11.5% losses in heavy agricultural areas. In the study they determined that rainfall events, as small as a fraction of millimeter, was enough to recover partially the performance of solar panels, however, it was not possible to determine the minimum amount of rain necessary to completely clean the panels.

While there are reported studies on the impacts of soiling on large-scale solar plants, not much research has been performed on the impacts of soiling and PV panels' cleaning of distributed generation systems. In addition, due to increased attention to water resources, especially in arid areas, the investigation of any type of cleaning method that might minimize water use is important and welcome. If natural cleaning is sufficient, then less water would be used in solar energy generation, making it even more sustainable.

At the University of Nevada, Las Vegas, there exists sixteen small solar plants (with capacities ranging from 20-160 kW) installed on top of different buildings in the Maryland Campus and Shadow Lane Campus. Due to urban pollutants, bird droppings, and dust accumulation, the panels become soiled. Using UNLV's panels as a case study, the objectives of this research are:

1) To evaluate if rainfall alone is enough to restore the efficiency of the solar of UNLV's solar plants. And, if possible, to determine the minimum amount of rainfall necessary to clean the panels.

Research Question: Can rainfall recover some or all of the solar panel's efficiency and if so, how much rain is it necessary?

Hypothesis: Large rainfall events are sufficient to restore some of the solar panel's efficiency because they will remove large proportions of the surface soiling. However, small rainfall events can decrease their efficiency because if there is a light rainfall, water droplets will sit on top of the panels and evaporate, eventually, therefore, they will not remove the dirt and possibly deposit extra solids like salts or particles , in a process called wet deposition (Ogren et al., 1984), or draw deposited fine films of dust into denser patches through surface tension. In a previously published study it was shown that the highest concentrations of particulates (elemental carbon) in rainwater were found in smaller rainfall events (Ogren et al., 1984). Small water droplets can adhere to the glass due to the surface tension (Bonn et al., 2009), however, a larger mass of water is able to break the surface tension and generate runoff. Some studies have shown that rainfall can be effective in cleaning the solar panels. In an experiment conducted by Caron & Littmann (2013), they were able to determine that rainfall depths of as little as a fraction of millimeter were sufficient to partially recover the performance of solar panels. However, it was not possible to determine the minimum amount of rain necessary to completely clean the panels. In Egypt, Elminir et al. (2006) noticed that 0.1 in of rain was enough to wash the dust off the glass covers, increasing their power output. After a 0.4 in rainfall, it was difficult to differentiate the power output between formerly dusty cells and clean ones.

However, rain can also have negative impacts. As studies have shown, light rainfall made the performance of the solar panels worse, reducing their efficiency (Sayyah et al., 2014). Rainfall can promote the settlement of dust on the surfaces of the solar panels, as it is shown in research conducted by Rao et al., (2014).

2) To determine the soiling losses during a dry period (between rainfall events) using different methods of analyses.

Research question: How much efficiency is lost in a day due to soiling of the panels between rainfall events? Is that loss constant or does it vary with different dry period durations?

Hypothesis: Efficiency loss due to soiling is not expected to be very high in the Southwest of United States because the dust deposition rate in this region is much smaller when compared to other regions (i.e. Middle East) where efficiency losses are very high due to soiling. In southern Nevada, the dust deposition flux can vary from 4.07 – 18.96 g/m^2/yr (NASA, n.d.; Reheis, 2013); while in countries located in Central Asia (i.e. Kazakhstan, Uzbekistan, Turkmenistan) it can vary from 49.56 – 1,902.12 g/m^2/yr, reaching up to 4,980 g/m^2 in a month after a dust storm (Groll et al., 2013). When comparing to different regions around the world, the Southwest of the United States has one of the lowest dust deposition fluxes. Table 1.1 below, adapted, from Zhang et al 2007 (shows) dust deposition rates for different regions around the world:

Table 1.1 – Dust Deposition Flux for Different Regions Around the World (Table addapted from Zhang et al., 2017)

Continent	Location	Dust Deposition (g/m^2/yr)
North America	Kansas, USA	53.5 - 62.1
	New Mexico, USA	9.3 - 125.8
	Arizona, USA	54.0
Europe	Spain	17 - 79
Africa	Nigeria	137 - 181
	Niger	164 - 212
	Lybia	420.0
Asia	Israel	57-217
	Kuwait	2600
	Saudi Arabia	4704
	Lanzhou, China	108.0
	Iran	72-120

According to a research conducted in California by Mejia & Kleissl (2013), the efficiency losses caused by soiling averaged 0.051% per day. Kimber et al. (2006), also conducted a study of PV panels in California and found the losses to be 0.2% per day. The solar plants they studied are located in the arid climate areas, with weather similar to that of Las Vegas. Large portions of the Southwestern United States consist of arid ecosystem comprised of the Mojave and Sonora Desert. These deserts covers large parts of Southern Nevada, Southern California, Arizona and parts of Utah (Lovich & Ennen, 2011).

3) To determine whether washing the panels of distributed small-scale solar systems is worthwhile. To aid in examining the implication of soiling to energy loss in these plants, a survey was also conducted to analyze if non-residential establishments in the Las Vegas region with solar systems installed on their properties were washing their solar panels.

Research question: Is it worthwhile washing rooftop PV systems when cost of washing is taken into consideration?

Hypothesis: It is hypothesized that, at current prices for sale of PV-generated electricity, that the income gain resulting from cleaning panels to obtain higher efficiency, will not offset the cost rates for washing panels. The cost of washing, energy cost, the amount of water and its cost, and the efficiency of the solar panels are parameters that have to be taken into consideration when performing the analyses. In Nevada, the average price that a professional cleaning company charges to wash solar panels is $5/panel. Currently, commercial solar cells can convert between 10-20% of sunlight into electricity (Green, 2016). If, in the future, solar cells have higher efficiencies, more electricity would be produced and consequently more power would be lost due to soiling. Also, the commercial retail price of electricity in Southern Nevada is currently $0.07/kWh (NV Energy, 2019), if there is a great increase in energy price, this also might change the result of the cost analyses. Since the cost of washing is high, and electricity currently has a relatively low price, and since it is not expected that the solar panels lose much efficiency due to soiling, washing PV rooftop systems might not be worthwhile. In a study conducted in Southern California, near Los Angeles, on a rooftop PV system, the author concluded that the amount of extra energy produced by the washed panels was not worth the cleaning costs (Kimber, 2007).

Chapter 2 - Literature Review

2.1.Sustainable Energy

The increasing effect of global warming and climate change spurred the interest in new forms of clean energy with lower carbon footprint since conventional sources (natural gas, coal, oil and nuclear) besides having high CO_2 emissions (Turner, 1999), also have other environmental impacts such as ozone depletion, emission of radioactive substances, deforestation, acid precipitation and air pollution (Dincer, 2000).

Enough sunlight reaches the Earth's surface in a day to provide energy to the entire world for a year (Lewis, 2007). This is one of the reasons why solar energy has been an emerging technology in the past few years providing several benefits such as zero carbon dioxide emissions during operation, more job opportunities, energy independence in isolated locations and better life quality.

However, solar energy still accounts for only 0.65% of the electricity production in the United States, while conventional sources are used for 67% (Bukhary et al., 2017). Solar energy systems can be divided into photovoltaic (PV) and concentrated solar power (CSP). The first one transforms sunlight directly into electricity and its efficiency is dependent on the material that the panels are made of. They also suffer intermittency, producing electricity only during the day time, on sunny days. On the other hand, CSP converts sunlight into heat that is stored in a material, which is then transformed into electricity so it is a more reliable form of power generation (Bukhary et al., 2017).

However, there are environmental impacts associated with solar energy including on soils, land-cover change and land use, biodiversity, and especially on water resources. CSP systems with wet-cooling utilizes large amounts of water (0.811 gal/kWh), having a higher water consumption than conventional energy sources such as natural gas and coal combined. PV systems require water mostly for dust abatement and panel cleaning (Hernandez et al., 2014).

A study conducted by Macknick et al. (2011), showed that CSP systems with wet cooling are one of the energy generating technologies that consume the greatest amount of water when compared to renewable and non-renewable sources. Such CSP systems have water consumption varying from 0.725 gal/kWh to 1.057 gal/kWh depending on the type of technology employed. In comparison, the water demand for conventional sources of energy is: 0.30-0.48 gal/kWh for oil; 0.18 gal/kWh for natural gas; 0.40-0.72 gal/kWh for nuclear power plants; and 0.20 gal/kWh for coal (Frisvold & Marquez, 2013). For PV panels the water requirement for operation is on average 0.026 gallons/kWh (Macknick et al., 2011).

Frisvold & Marquez (2013) reported water use in different solar plants in the southwest of United States. Table 2.1 shows the water consumption in gal/year for different technologies solar sites in Arizona, California and Nevada.

Table 2.2 – Water Consumption for PV Plants in Arizona, California and Nevada (data obtained from Frisvold & Marquez, 2013)

Solar Site	State	Technology	Cooling	Water Use (gal/year)
Agua Caliente Solar	AZ	PV	none	1.30E+08
Quartzsite Solar Energy	AZ	tower	dry	1.30E+09
Mesquite Solar Energy	AZ	PV	none	3.26E+09
Solana Solar	AZ	trough	wet	1.96E+10
Sonoran Solar Energy	AZ	PV	none	2.15E+08
Antelope Valley Solar	CA	PV	none	9.78E+08
Beacon Photovoltaic	CA	PV	none	3.91E+07
California Valley Solar Ranch	CA	PV	none	5.87E+07
Desert Harvest Solar	CA	PV	none	2.54E+08
Desert Sunlight Solar Farm	CA	PV	none	2.61E+07
Genesis Solar	CA	trough	dry	1.42E+09
McCoy Solar	CA	PV	none	2.87E+08
SEGS I-IX	CA	trough	hybrid	1.81E+09
Copper Moutain Solar 3	NV	PV	none	1.96E+08
Moapa Solar	NV	PV	none	2.61E+08
Silver State North Solar	NV	PV	none	1.37E+08
Nevada Solar One	NV	trough	wet	2.61E+09

2.2. Classification of Energy Generating Systems

The energy production systems can be classified as Centralized Generation (CG) or Distributed Generation (DG) as it is explained in more details in the sections below.

2.2.1. Centralized Generation (CG)

This classification refers to the utility-scale (large-scale) energy generating plants. They are normally located far from the end-users and connected to high-voltage transmission lines. In the United States, that is the source of the electricity provided to most Americans. The electric power utility companies are responsible for production, generation and distribution of electricity to the end-users. They can own the power plants or purchase power from another company.

These power plants are susceptible to regulations enforced by state, tribal, local, and/or federal government (United States Environmental Protection Agency, 2018b).

CG power plants include conventional sources as nuclear power and fossil-fuel-fired power, and renewable sources as hydroelectric, wind farms, solar and others. The large-solar plants also known as solar farms occupy large land areas and generate large amounts of solar energy. Some of the large-scale solar plants in Nevada are listed in Table 2.2 below.

Table 2.3 – Large-Scale Solar Plants in Nevada and Their Sizes (PUCN, 2019)

Plant Name	Technology	Nameplate Capacity (kW)	Starting Operating Year
Techren Solar	Solar Photovoltaic	3.00E+05	N/A
Boulder Solar Power	Solar Photovoltaic	3.00E+05	N/A
Crescent Dunes Solar Energy	Solar Thermal with Energy Storage	1.10E+05	N/A
Copper Mountain Solar 2	Solar Photovoltaic	6.90E+04	2007
Silver State Solar Power North	Solar Photovoltaic	5.20E+04	2012

2.2.2. Distributed Generation (DG)

Distributed Generation refers to systems, with limited capacity, which produces electricity near the end users and is directly connected to their power system (Tan et al., 2013). There are other terms referring to that type of energy generation: Europe and Asia use the term ‘decentralized generation’; ‘dispersed generation’ is often used in Anglo-American countries and ‘dispersed generation’ is another term used in North American countries (Ackermann et al., 2001).

In the literature, there are many variations in the definitions and rating of DG systems. Regarding size, the Electric Power Research Institute classifies systems from a few kilowatts up to 50 MW as distributed generation (Ackermann et al., 2001). According to Sharma & Bartels

(1997), Preston and Rastler consider from a few kilowatts to over 10^5 kW, however, Cardell & Tabors (1997) includes systems with lower capacity between 500 kW and 10^3 kW. Ackermann et al. (2001) have discussed the definition of DG according to location, technology, rating of distributed generation, purpose, mode of operation, power delivery area, environmental impact, ownership and penetration of distributed generation.

Those systems can serve a single structure such a business or a home, or it can be connected to a micro grid that is linked to the larger electricity delivery system such as in large university campuses, major industrial facilities or military bases (United States Environmental Protection Agency, 2018c).

The most common type of DG system are the PV solar rooftops that are usually installed on residential buildings (typically 10–50 kW) or industrial/commercial buildings, that can also be called non-residential or non-domestic buildings (up to 10^3 – $2x10^3$ kWs) (International Finance Corporation [IFC], 2015). Figure 2.1 gives an overall view of what has been discussed in this section.

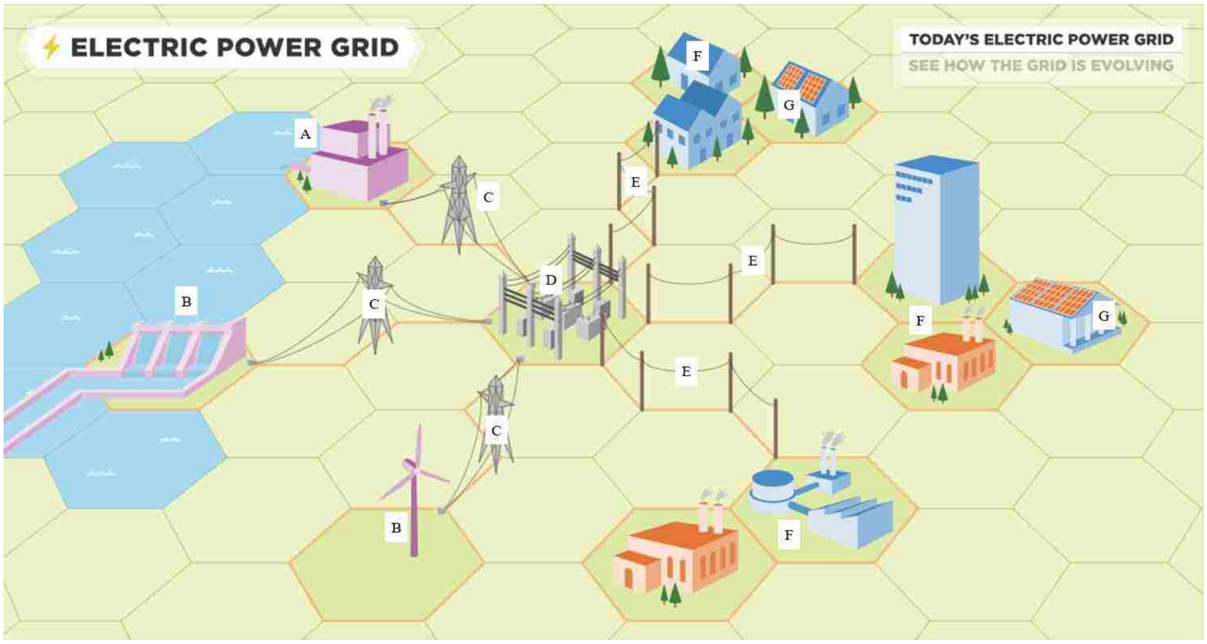


Figure 2.1 – Schematic Example of U.S. Electric Power Grid (retrieved and adapted from United States Environmental Protection Agency, 2018a)

In Figure 2.1, there are large-scale power plants which fall into two categories: conventional generation (A) and renewable generation (B). Those plants are connected to high voltage transmission lines (C) which conduct electricity to the substation (D). The power is then transformed from high-voltage to lower voltage and it travels to the end-users (homes, businesses, industries) (F) through the distribution lines (E). The Figure 2.1 also illustrates distributed generation (G), where there are solar panels installed on roofs of homes and businesses in which the electricity is generated near the end-users (United States Environmental Protection Agency, 2018a).

While there are reported studies on the impacts of soiling on large-scale solar plants, not much research has been performed on the impacts of soiling and cleaning feasibility of decentralized generation systems.

2.3. Components and Performance of Photovoltaic Solar Cells

A typical photovoltaic module is composed of the following: a transparent top surface (normally glass); encapsulant that holds together the top surface and the cell (typically sheets of ethyl vinyl acetate); PV cells (two types are polycrystalline and amorphous); rear layer of thin polymer sheet to seal the module (generally Tedlar); the frame (usually aluminum) and the electrical connections (Nelson & Starcher, 2016a).

The performance of a solar cell is evaluated by the efficiency of its energy conversion. The average efficiencies for commercial solar cells can vary from 10% to 20% depending on the material of the cell (Green, 2016).

Basic PV systems consists of fixed-tilt panels. For optimal performance, the array should be placed with the long axis aligned at 90 degrees to the south azimuth, and the tilt angle set to the latitude of the location. These types are less efficient than the tracking systems, as the sun's position changes during the day and with different season of the year (Nelson & Starcher, 2016a).

To better compare solar modules, standard test conditions have been established as 1 kW/m^2 of solar irradiance, air mass ratio of 1.5 (AM1.5) and cell temperature of 25℃. Manufactures provide the data sheet with cell's performance such as the values of V_{MPP}, P_{MPP}, I_{MPP}, efficiency, I_{SC} and V_{OC}, under STC (Masters, 2013).

The efficiencies of most commercial solar cells vary from 10% to 20%. Efficiencies are affected by different factors like properties of sunlight, temperature, degree of panel soiling, etc. Those factors are further discussed in the next section. The efficiency (η) is given by Equation 2.3 (Mekhilef et al., 2012).

$$\eta = \frac{I_{SC-max} V_{OC-max}}{A_C} \qquad \textit{Equation 2.1}$$

Where: $I_{SC\text{-}max}$ = short circuit current (A)

$V_{OC\text{-}max}$ = open circuit voltage (V)

A_C = module's area (m^2)

Another way to calculate efficiency is by the following Equation 2.4 (Kimber et al., 2006):

$$\eta = \frac{PO}{\text{AxPOA}} x \left[1 + \alpha(T_0 - T_m)\right] \qquad \textit{Equation 2.2}$$

Where: PO = total AC energy production (kWh)

A = area of the module (m^2)

POA= measured global irradiation on the plane of array (kWh/m^2)

α = module temperature coefficient (%)

T_0 = reference temperature (℃)

T_m = average cell temperature (℃)

One important factor that contributes to the performance of the system is the plane of array (POA) which affects the incident irradiance on the array. It is dependent on several factors such as: array orientation, ground surface reflectivity, irradiance components, sun position and shading. The POA can be calculated or measured with a reference cell, a pyrometer, or reference module mounted with the same array's orientation (National Technology and Engineering Solutions of Sandia, 2018).

2.4.Factors Affecting the Performance of the System

2.4.1. Soiling

Washing of the panels is performed in some PV solar plants due to soiling, which is the naturally occurring deposition of dust, dirt, bird droppings, snow or any other particles on top of the panels that cover the PV module and potentially decreases the power output and efficiency of the system (Maghami et al., 2016). Kimber et al. (2006) analyzed the effect of dust deposition on efficiency loss in solar panels located in California in regions that experience long periods without rain. They found that the PV system's efficiency decreased between 1.5 – 6.2% annually depending on the location of the panels. Rao et al. (2014) conducted indoor and outdoor experimentation in order to study the outcome of soiling on PV panels in Bangalore, India. The research showed a 5 – 6% loss in power output for the outdoor panels due to dust settling and a 45 – 55% loss for the indoor panels when compared to the power output of the clean panels. Maghami et al. (2016) reviewed the decrease in the power output caused by soiling and concluded that the characterization of soiling buildup has two interdependent variables: the local environment where the panels are located and the property of the dust.

Al-Ammri et al (2013) conducted a study for three months analyzing the effects of dust on street solar panels in Baghdad, Iraq. The study showed that the total average losses for the solar panels that were weekly cleaned were 14.1% and for the ones never cleaned, 58.96%.

Khonkar et al. (2014) compared solar panels, located in Riyadh, Saudi Arabia, before and after cleaning. To clean, it was used: reverse osmosis filtered water as the TDS was wanted as low as possible because high TDS can have a negative effect on the cleaning; surfactants, due to the formation of a thin oily film on the panels; and a commercial grade pressure washer, that was chosen to save water and to avoid scratching the surfaces. The photovoltaic system showed only a 3% loss.

In another study conducted by Martinez-Plaza et al. (2015), the impacts of cleaning outdoor PV panels located in Qatar were analyzed during one year. The different washing schedules were weekly, bimonthly and biannual. The panels showed a decrease in their performance of 1%/day when there was no rain, or they weren’t cleaned for more than 30 days. The results concluded that weekly cleaning is sufficient to obtain continuous yield levels.

Ali et al. (2015) evaluated the effect of dust deposition on monocrystalline and polycrystalline silicon PV modules located in Taxila, Pakistan. The panels were set outside and exposed to real conditions for 11 weeks. They noticed that the performance of the panels decreased as the dust deposition on their surface increased. There was a reduction in the power output with an average of 20% for the monocrystalline and 16 % for the polycrystalline modules. The efficiency also decreased with the dust deposition, on average of 3.55% and 3.01% for monocrystalline and polycrystalline, respectively.

Zorrilla-Casanova et al. (2011) analyzed dust losses in PV panels in the University of Malaga, south of Spain. The panels had a mean value of daily energy loss of 4.4% during the one year the experiment was conducted, when the soiling losses during the dry periods taken into consideration. Light rain, under 1 mm, was able to recover efficiency and clean the glass. However, when there were long dry periods, the daily losses due to soiling exceeded 20%. In a study conducted in Puglia, Italy, two 1 MW PV solar systems were analyzed before and after cleaning. One of them was built on a sandy site and showed 6.9% power loss, while the other one that was on a more compact ground showed only 1.1% power loss (Massi et al., 2011).

Considering the negative impacts mentioned above, there are different ways to clean solar panels and recover their efficiency including manual cleaning with a mop or brushes, vacuum cleaning, and automatic cleaning with the aid of a robot that possesses a rubber wiper and water pot (Hudedmani et al., 2017). Natural cleaning processes also have been studied such as rainfall and wind, and were shown to be efficient methods depending on the type of soiling and size (Jiang et al., 2018; Sayyah et al., 2014).

Some studies have shown that rainfall can be effective in cleaning solar panels. An experiment conducted by Caron & Littmann (2013), showed less than 1.0% soiling losses per month and up to 11.5% losses in heavy-cultivated agricultural areas. In their study they were also able to determine that rainfall as little as a fraction of millimeter was enough to recover partially the performance of solar panels, however, it was not possible to determine the minimum amount of rain necessary to completely clean the panels.

Mejia et al. (2013) performed experiments on PV panels in California and observed that during the dry period (around 108 days) there was a decrease in efficiency from 7.2% to 5.6%. After a 0.1 in rainfall event, the efficiency of the solar panels increased from 5.6% to over 6.5%. Other larger rainfalls depths (0.4-0.6 in) were able to recover the efficiency to 7.1%.

In Egypt, Elminir et al. (2006), analyzed the energy yield of PV solar cells installed outdoors. The authors noticed that 0.1 inches of rain was enough to wash the dust off the glasses increasing their power output. After a 0.4 inches rainfall, it was difficult to differentiate the power output of the formerly dusty cells to the clean ones. It was concluded that even scarce rainfall was enough to reestablish the PV cells to their original condition.

The tilt angle also impacts the amount of dust accumulated on top of the panels. There is larger dust deposition with lower tilt angles as it has been demonstrated in previous study (Cano, 2011). Lower tilt angles favor the accumulation of dust on the panels. One of the reasons is that one of the parameters that influence the dust accumulation is the gravitational effect (Qasem et al., 2014). Cano (2011) stated that modules with tilt angles less than 15° had higher water retention on the panels, which combined with the dust produced a “sticky matter” that besides not being able to be blown off by wind, also resulted in the accumulation of more dust particles.

However, in many areas, especially desert like areas, rainfall is rare and many times not enough to clean the panels completely, therefore requiring additional cleaning.

Although PV systems require less water when compared to conventional sources and even some renewable ones, it is important to optimize the water usage and analyze if there is a need for panel cleaning or if natural cleaning is sufficient, in order to reduce water usage for this type of technology.

2.4.2.Humidity

Humidity can affect the cell's performance in two major ways. One of them is the effect that water vapor particles have on sunlight's irradiance level. The incident light can scatter or be absorbed when it hits a water particle. Scattering reduces direct normal irradiance and increases global horizontal irradiance, and absorption reduces total irradiance, both of which interfere with the irradiance reaching the cell and consequently affecting the efficiency (Mekhilef et al., 2012).

Kazem & Chaichan (2015) performed an experimental study to observe the effect of relative humidity on the output of PV panels. They observed that performance of solar panels was greatly impacted by relative humidity, and that measured voltage and current, and calculated power and efficiency of the solar panels decreased with an increase in humidity. One of the reasons for this result is that the high atmospheric water vapor concentrations impacts received solar irradiance by scattering the radiation arriving at the top of the atmosphere and thereby reducing the solar intensity (Kazem & Chaichan, 2015).

Humidity is the amount of moisture of the atmosphere. One of the measurements of humidity is the dewpoint (T_{dew}), which is the temperature at which the atmosphere becomes saturated with water vapor (Kimball et al., 1997).

Thornton et al. (2000) studied the relationship between radiation (irradiance over a period of time) and humidity. The effect of humidity can be converted into radiation by the following equations (Kimball et al., 1997):

$T_{dew} = T_{min} [-0.127+1.121 (1.003-1.444EF$ *Equation 2.3*

$+12.312EF^2-32.766EF^3) + 0.0006(T_x - T_{min})$

Where T_{dew} = dewpoint (K)

T_{min} = minimum daily air temperature (K)

T_x = maximum daily air temperature (K)

$EF = [(E_p/\rho_w)t_{day})]/l_{P,ann}$ *Equation 2.6*

Where $EF = l_{Ep,day}/ l_{P,ann}$

$l_{Ep,day}$ = daily potential evapotranspiration (m)

ρ_w = water density (kg/m^3)

t_{day} = daylength (s)

$l_{P,ann}$ = annual precipitation (m)

$E_p = \{\alpha[\Delta/(\Delta+\gamma)](R_n - G)\}/\lambda$ *Equation 2.7*

Where, E_p = Potential evapotranspiration (kg m^2/s)

Δ = Rate of change of saturation vapor pressure with temperature (Pa/K)

γ = Psychrometer constant (approximately 0.66 Pa/K)

R_n = Average daily net all-wave radiant energy flux (W/m^2)

G = Average daily surface conductive energy flux (W/m^2)

λ = Latent heat of vaporization (J/kg)

α = Priestley-Taylor parameter (dimensionless)

Figure 2.2 shows the relationship between irradiance and relative humidity. The figure was plotted based on the parameters described above and with the help of a Microsoft Excel™ program from NREL based upon Bird & Riordan (1985) and equations based on Reitan (1963) . The graph shows that the higher the humidity, the lower the irradiance, as was expected. It is possible to observe that up to 20% RH, the decline in irradiance is steep. After 20%, irradiance continues to decrease, however, at a smaller rate.

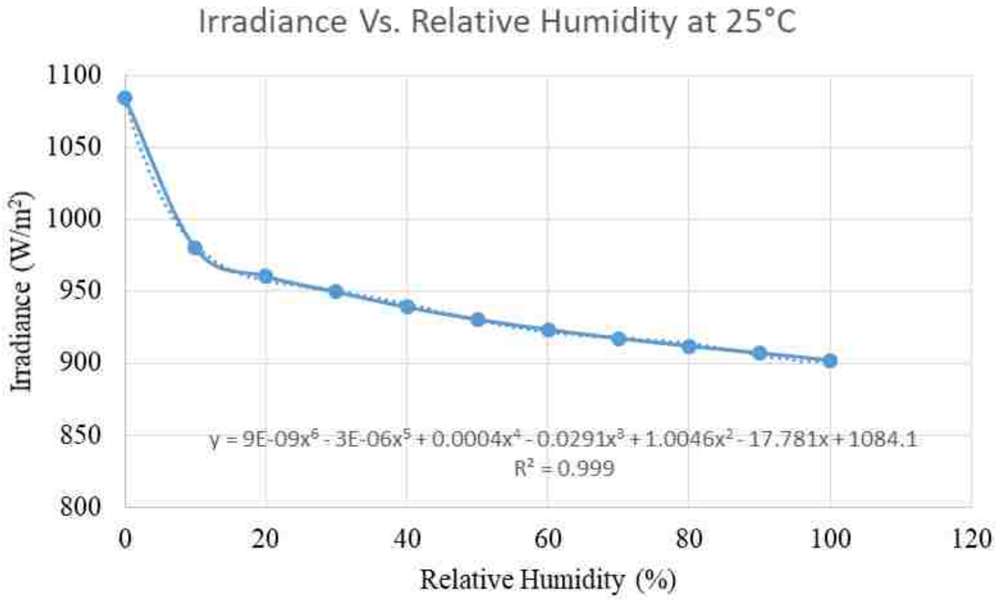


Figure 2.2 – Graph Showing the Correlation Between Irradiation and Relative Humidity at 25°C

The second way that humidity impacts solar panels is by the degradation of the cell's performance due to module failure as a result of long-term exposure to humidity. The delamination of the encapsulant material from the cell can result from high humidity. This can cause failure at scribe lines or at cell interconnections and can lead to corrosive moisture and embrittlement of the encapsulant material depending on the cell type (Mekhilef et al., 2012).

2.4.3.Tilt Angles

Panel tilt angle also impacts the amount of dust accumulated on the panels. There is larger dust deposition with lower tilt angles as it has been demonstrated in a previous study (Cano, 2011). One of the reasons is that dust accumulation is influenced by the gravitational effect (Qasem et al., 2014). Cano (2011) stated that modules with tilt angles less than 15 degrees had higher water retention on the panels, which combined with the dust present produced a "sticky matter" that besides not being able to be blown off by wind, also resulted in the accumulation of more dust particles.

The primary mechanisms for dust deposition are diffusion and gravitational settling. When panels have fixed angle β above horizontal, the projected surface area of the collector would be $A\cos\beta$, where A is surface area of the module. Therefore, the concentration of deposited particles and their distribution are both dependend on the angle β. With larger values of β, larger dust particles can more easily roll off from the surface of the panels or slide to the lower parts of the panels due to a stronger influence of gravitational forces, which increase with the sine of angle β (Sayyah et al., 2014).

Afridi et al. (2017) also analyzed the relantionship between soiling and the tilt angle of a PV system. They used an experimental set up, located in Pakistan, with modules with tilt angles of 0°, 20° (most typical installation angle), and 33.5°, which the latitude angle of the area where the experiment was being conducted. The modules installed at a 33.5° showed over 50% less soiling losses than the panels installed at 0°. The authors observed that the water from the rain would mix with dirt and form mud, and this mud would remain on top of the panels that had a horizontal (0 degree) tilt angle.

Lu & Zhao (2018) studied the mechanics of dust particle deposition on the panels and how they are related to different tilt angles. A major finding was that the higher the tilt angle, the lesser dust deposition occured. In addition, they found that wind has a more significant impact on the deposition of smaller dust particles (50 µm) and they deposit on the panels due to the capture effects of the turbulent eddies, which decrease as the panel's tilt angle increases. For larger particle sizes (150 µm), gravitational forces were the main mechanism for dust deposition and the effects of wind were weaker due to higher inertia of the larger particles. However, for all particle sizes, when tracking their trajectory, they observed that the higher the tilt angles, the smaller the number of dust particles reaching the solar panels.

2.4.4.Temperature

The efficiency of the solar panels is directly related to the temperature of the modules. Those parameters are related through the following equation (Evans, 1981):

$$\eta = \eta_r[1 - \beta(T_c - T_r)] \qquad \textit{Equation 2.8}$$

Where η is the cell's monthly average efficiency, η_r is the module's efficiency at solar radiation flux of 1 kW/m^2 and at reference temperature, T_{ref}. β is the temperature coefficient which is dependent on the panel's material (e.g.: 0.004K^{-1} for crystalline silicon modules), and T_c is the monthly average temperature of the cell. Normally, β and T_{ref} are provided by the cell's manufacturer.

The power output is also related to the module's temperature. Equation 2 shows that relationship:

$$P = G_T\tau_{pv}\eta_r A[1 = 0.0045(T_c - 25)] \qquad \textit{Equation 2.9}$$

Where G_T is the irradiance on the cell (W/m^2), τ_{pv} is the transmissivity of the glass and A is the module's surface area (m^2) (Skoplaki & Palyvos, 2008). The remaining parameters are the same as the ones listed in Equation 1.

The module temperature is directly influenced by local temperature, wind characteristics and cloud patterns whereas the rate at which the temperature changes depends on the position of the frame and the material of the PV cells (Kaldellis et al., 2014).

Skoplaki & Palyvos, 2008, published a review on the different equations found to relate the PV array's efficiency and power output as a function of temperature. Most equations are linear and similar to Equations 2.4 and 2.5, for efficiency and power output respectively. However, there are other non-linear equations that take other factors into consideration, for example, the fact that the cells within a module are different from each other.

2.4.5. Wind

Wind can have a positive or negative impact on the efficiency of the cells. Mekhilef et al. (2012) states that high wind velocity can remove heat from the surface of the cell and decrease the atmospheric air's relative humidity, therefore increasing the efficiency of the module. On the other hand, wind also lifts and scatters dust, which potentially leads to higher soiling deposition on the panels and consequently decrease of efficiency (Mekhilef et al., 2012).

Vasel & Iakovidis (2017) analyzed the effect of wind direction on the performance of PV solar systems. They conducted the study on a utility-scale solar farm, with fixed-tilt type of panels, in the United Kingdom. It was observed that for south facing systems, southerly wind significantly increased the power production of the solar site. This can be attributed to the cooling of the modules by the wind. Southerly wind causes improved cooling due to the fact that the wind hits directly the surface of the panels since they are facing south. On the other hand, northerly wind was not found to be as efficient on cooling once it hits the back of those panels. For solar sites located on southern hemisphere, panels should be facing north for higher energy production, therefore, wind from the north will enhance the system's performance (Vasel & Iakovidis, 2017).

2.4.6. Field Failure

Solar panels can lose efficiency due to degradation of the panels caused by field exposure. There are many factors that can contribute to the degradation modes such as weather, type of technology used, load, mounting configuration, etc (Jordan et al., 2017). One failure mode was described in the section above, when discussing the impacts of humidity on the efficiency of the panels. Jordan et al. (2017) analyzed the most common degradation modes that occurred in different climates: moderate, hot & humid and desert. Figure 2.3, retrieved from Jordan et al. (2017) shows the degradation modes that can occur in the modules and the probability of a certain degradation mode occurring.

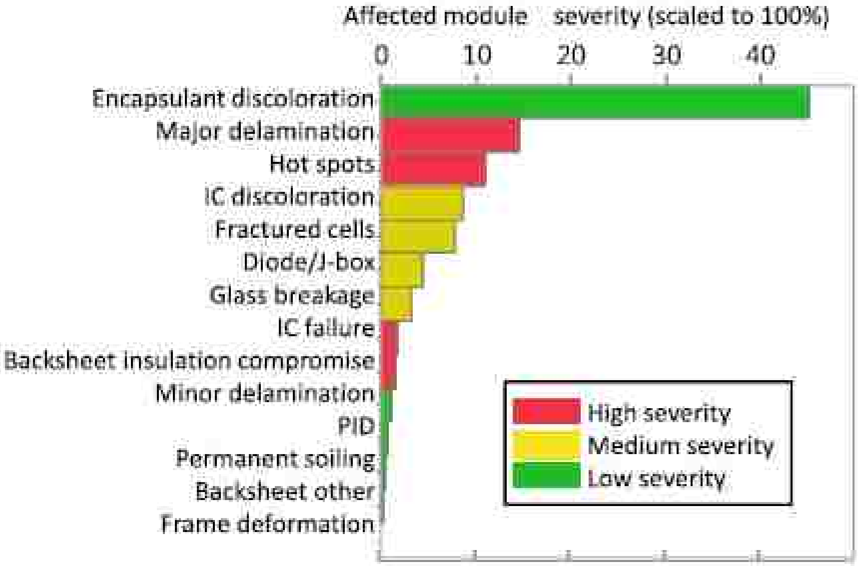


Figure 2.3 – Most significant degradation modes that can occur in PV modules and the probability of each one happening (figure retrieved from Jordan et al., 2017, and used with permission)

The authors evaluated the severity of different degradation modes and observed that the modes which have major effect on power and safety were the backsheet insulation compromise and hot spots. Backsheet insulation compromise includes adhesion problems such as flaking, cracking and peeling that have substantial impact on power production and also indicate a safety hazard. This failure can also be related to major delamination (Jordan et al., 2017).

Hot spots are caused when there is shading of a sub-string part, causing the other cells to produce higher voltages. It can also be caused by cracked cells. Those can be visually identified, as there might be burn marks in the modules (Köntges et al., 2014).

Other more common failure modes include front glass breakage, encapsulant discoloration, major delamination, fractured cells and diode problems. In desert climates, the major degradation modes that occur are encapsulant discoloration due to the high temperatures, glass breakage and internal circuit failure and discoloration. The systems can present different degradation modes concurrently (Jordan et al., 2017).

2.5. Renewable Portfolio Standards

The U.S. has been seeking ways to reduce greenhouse gas emissions, and one of them is the establishment of the Renewable Portfolio Standards (RPS). RPS have been implemented in several states in the United States and they mandate the electricity provided by the suppliers possesses a certain percentage of the total energy from renewable sources by a determined year. The amount of energy coming from renewables and the targeted year varies from state to state. Renewable sources include solar, wind, biomass and geothermal. RPS are implemented to stimulate the states to progressively increase the use of renewable energy since the goals they need to meet increase over time (Leon, 2012). Currently there are thirty-two states that have mandatory RPS and nine states that have non-binding goals. Table 2.3 shows all the U.S. states and their RPS specific characteristics.

Table 2.4 – Renewable Portfolio Standards for U.S. States (based on data from Durkay (2017))

No	State	Abbreviation	Title	Year Established	Amount from Renewables	Year To Meet Goals	Applicable Sectors	State Standards/Laws
1	Alabama	AL	-	-	-	-	-	None
2	Alaska	AK	-	2009-2010	50%	2025	-	None
3	Arizona	AZ	Renewable Energy Standard	2006	15%	2025	a, b	Enforced
4	Arkansas	AR	-	-	-	-	-	None
5	California	CA	Renewables Portfolio Standard	2002	33%	2020	a, c	Enforced
					40%	2024		
					45%	2027		
					50%	2030		
6	Colorado	CO	Renewable Energy Standard	2004	30%	2020 (IOUS)	a, c, d	Enforced
					10% or 20% municipalities and electric cooperatives			
7	Connecticut	CT	Renewables Portfolio Standard	1998	27%	2020	a, b, e	Enforced
8	Delaware	DE	Renewables Energy Portfolio Standard	2005	25%	2025-2026	a, b, e	Enforced
9	Florida	FL	-	-	-	-	-	None
10	Georgia	GA	-	-	-	-	-	None
11	Hawaii	HI	Renewable Portfolio Standard	2001	30%	2020	a	Enforced
					40%	2030		
					70%	2040		
					100%	2045		
12	Idaho	ID	-	-	-	-	-	None
13	Illinois	IL	Renewables Portfolio Standard	2001 (voluntary) 2007 (standard)	25%	2025-2026	a, b	Voluntary
14	Indiana	IN	Clean Energy Portfolio Goal	2011	10%	2025	a, b, c, d	Enforced

15	Iowa	IA	Alternative Energy Law	1983	105 MW of generating capacity for IOUs		a	Enforced
16	Kansas	KS	Renewable Energy Goal	2009 (standard)	5%	2015	a	Voluntary
				2015 (goal)	20%	2019		
17	Kentucky	KY	-	-	-	-	-	None
18	Louisiana	LA	-	-	-	-	-	None
19	Maine	ME	Renewables Portfolio Standard	1999	40%	2017	a, b	Enforced
20	Maryland	MD	Renewable Energy Portfolio Standard	2004	25%	2020	a, b, e	Enforced
21	Massachusetts	MA	Renewable Portfolio Standard	1997	Class I: 15% and an additional 1 percent each year after	2020	a, b	Enforced
					Class II: 5.5%	2015		
22	Michigan	MI	Renewable Energy Standard	2008; 2016	15%	2021 (standard)	a, b, c, d	Enforced
					35%	2025 (goal)		
23	Minnesota	MN	Renewables Energy Standard	2007	27%	2025 (IOUs)	a, c, d	Enforced
					25%	205 (other utilities)		
24	Mississippi	MS	-	-	-	-	-	None
25	Missouri	MO	Renewable Electricity Standard	2007	15%	2021 (IOUs)	a	Enforced
26	Montana	MT	Renewable Resource Standard	2005	15%	2015	a, b	Enforced
27	Nebraska	NE	-	-	-	-	-	None
28	Nevada	NV	Energy Portfolio Standard	1997	25%	2025	a, b	Enforced
29	New Hampshire	NH	Electric Renewable Portfolio Standard	2007	24.8%	2025	a, b, d	Enforced
30	New Jersey	NJ	Renewables Portfolio Standard	1991	24.5%	2020	a, b	Enforced

31	New Mexico	NM	Renewables Portfolio Standard	2002	20%	2020 (IOUs)	a, d	Enforced
					10%	2020 (co-ops)		
32	New York	NY	Renewable Portfolio Standard; Reforming the Energy Vision (REV)	2004	29%	2015	a, b, c, d	Enforced
					50%	2030 (REV- currently in process)		
33	North Carolina	NC	Renewable Energy and Energy Efficiency Portfolio Standard	2007	12.5%	2021 (IOUs)	a, c, d	Enforced
					10%	2018 (munis and coops)		
34	North Dakota	ND	Renewable and Recycled Energy Objective	2007	10%	2015	a, c, d	Voluntary
35	Ohio	OH	Alternative Energy Resource Standard	2008	25%	2026	a, b	Enforced
36	Oklahoma	OK	Renewable Energy Goal	2010	15%	2015	a, c, d	Voluntary
37	Oregon	OR	Renewable Portfolio Standard	2007	25%	2025 (utilities with 3 percent or more of the state’s load)	a, b, c, d	Enforced
					50%	2040 (utilities with 3 percent or more of the state’s load)		
					10%	2025 (utilities with 1.5–3 percent of the state's load)		
					5%	2025 (utilities with less than 1.5 percent of the state’s load)		

38	Pennsylvania	PA	Alternative Energy Portfolio Standard	2004	18%	2020-2021	a, b	Enforced
39	Rhode Island	RI	Renewable Energy Standard	2004	14.5%	2019 (with increases of 1.5 percent each year until 2035)	a, b	Enforced
					38.5%	2035		
40	South Carolina	SC	Renewables Portfolio Standard	2014	2%	2021	a	Voluntary
41	South Dakota	SD	Renewable, Recycled and Conserved Energy Objective	2008	10%	2015	a, c, d	Voluntary
42	Tennessee	TN	-	-	-	-	-	None
43	Texas	TX	Renewable Generation Requirement	1999	5,880 MW	2015	a, b	Enforced
					10,000 MW	2025 (goal achieved)		
44	Utah	UT	Renewables Portfolio Goal	2008	20%	2025	a, c, d	Voluntary
45	Vermont	VT	Renewable Energy Standard	2005 (voluntary target) 2015 (standard)	55%	2017	a, b, c, d	Enforced
					75%	2032		
46	Virginia	VA	Voluntary Renewable Energy Portfolio Goal	2007	15%	2025	a	Voluntary
47	Washington	WA	Renewable Energy Standard	2006	9%	2016	a, c, d	Enforced
					15%	2020		
48	West Virginia	WV	Alternative and Renewable Energy Portfolio Standard - REPEALED	2009 - Repealed 2015	10%	2015-2019	-	None
					15%	2020-2024		
					25%	2025		
49	Wisconsin	WI	Renewable Portfolio Standard	1998	10%	2015	a, c, d	Enforced
50	Wyoming	WY	-	-	-	-	-	None

51	Washington, D.C.	DC	Renewable Portfolio Standard	2005	20%	2020	a, b	Enforced
					50%	2032		
52	Guam	GU	Renewable Energy Portfolio Goal	2008	25%	2035	a, c, d	Voluntary
53	Northern Mariana Islands	MP	Renewables Portfolio Standard	2007; goal reduced in 2014	20%	2016	a, c, d	Enforced
54	Puerto Rico	PR	Renewable Energy Portfolio Standard	2010	20%	2035	a, c, d	Enforced
55	U.S. Virgin Islands	VI	Renewables Portfolio Targets	2009	20%	2015	a, c, d	Enforced
					25%	2020		
					30%	2025		
					up to 51%	after 2025		

a. Investor-Owned Utility; b. Retail Supplier; c. Municipal Utilities; d. Cooperative Utilities; e. Local Government

One potential way for energy utilities to meet the RPS requirements of the state is to support the installation of small solar plants on municipal and public urban landholdings. Another potential way is for utility companies to build large solar plants or buy electricity generated by an independent solar plant. The Bureau of Land Management (BLM) oversees millions of acres of public lands with great solar energy potential in six states: Nevada, Arizona, California, Utah, Colorado and New Mexico. The BLM predicts a continued interest in public landholding for expansion of large solar energy as a result of the renewable standards established in those states ("U.S. Department Of The Interior Bureau Of Land Management" n.d.).

2.6. Solar Energy and RPS Compliance in Nevada

The renewable standard portfolio was established in Nevada in 1997 by the Nevada Legislature, NRS 704.7801. It has been changed several times since the date it was adopted, and the current requirement is to have 25% of the total energy produced in the state coming from renewable sources. It is also included that at least 5% of the total renewable must come from solar source by 2015 and 6% by the beginning of 2016. Another requirement is that 50% out of the 25% must be from measures installed at residential locations of customer services (PUCN, 2017d).

The State of Nevada Public Utilities Commission (PUCN) is the regulatory agency that certifies that the utilities in the state fulfill the laws established by the Nevada Legislature. They ensure the compliance of the RPS through regulations included in NAC 704.8831 through 704.8899 (PUCN, 2017c).

The State of Nevada's Legislature has developed several programs to stimulate the installation and usage of renewable energy. In those programs, customers are incentivized to install wind and solar systems at small businesses, on residential property, on waterpower systems for use in agricultural settings, at schools or on public buildings, and on tribal lands. As the incentive, rebates are offered to those customers (PUCN, 2017b).

In 2007 the Solar Energy Systems Incentive Program (“Solar Program”) was created by Nevada Legislature, NRS 701B.010 - 701B.280. In this program, public utilities electricity suppliers in Nevada were required to offer rebates to customers that install qualifying solar systems on their property. The PUCN regulates the program through evaluation of the utilities' annual plan filings and also through regulations contained in NAC 701B.050 - 701B.185. There are three categories that can participate in this program and they are 1) small business and private residential property; 2) school property and 3) public and other property. The total amount that a utility may grant in incentive funding is $255,270,000 through July 1, 2010 until June 30, 2021. The value awarded to each customer varies depending on the categories listed above and the value amount of the available incentives decreases over time (PUCN, 2017e).

2.6.1. Net Metering in Nevada

Net metering is defined by the existing law as the energy amount between the difference of electricity provided by the utility company and the electricity produced by the customer’s system and that is fed back to the grid (Legislative Counsel, 2017)

If a customer’s system produces more energy than it used in a month, the excess will be put back in the grid and used by other customers. The customers will receive credits for the extra electricity they generated. The amount will be recorded in his account and applied to the next billing period in which the electricity consumption is greater than the electricity production (PUCN, 2017a).

In June 2017, the rate structure for net metering customers constituent under the Assembly Bill 405 (AB 405), passed by Nevada Legislature, came into effectiveness. This rate structure concern systems up to 25 kilowatts, which is the usual size of a rooftop solar system installed in small commercial businesses and residential properties. It is structured into tiers that decrease over time and as the amount of solar systems installed increases. Each tier has an 80-megawatt benchmark, and the retail rate decreases according to the Table 2.4 below after that benchmark is achieved. Once a costumer is assigned into a tier, he will remain in the same tier for 20 years.

Table 2.5 - Net Metering Tiers for Nevadans that Wish to Install Solar Panels

Net Metering Tier	Value of Bill Credits
Tier 1	95% of retail rate
Tier 2	88% of retail rate
Tier 3	81% of retail rate
Tier 4	75% of retail rate

As of July 2018, Nevadans are still being assigned into tier 1, therefore customers receive 95% of retail rate. The total applied and installed capacity so far is 68.8 MW. Once it reaches the 80-MW benchmark, all new customers will be assigned into tier 2, and so on. The 75% of retail rate is the lowest rate possibly reachable, and once in that tier, all customers will be fixed in the 75% retail rate (PUCN, 2017a).

2.7. Solar Energy and RPS Compliance in Arizona, California and Utah

Arizona adopted the RPS in 2006, agreeing that 15% of the retail electricity would come from renewable sources by 2025. The utility companies (AJO Improvement Company, Arizona Public Service Company, Duncan Valley Electric Coop, Mohave Electric Coop, Morenci Water and Electric, Navopache Electric Coop, Sulphur Springs Valley Electric Coop, Tucson Electric Power Company, Trico Electric Coop, UNS Electric) have been publishing yearly reports on how they are complying with the regulations and their plans for the future (Arizona Corporation Commission, n.d.-c).

The Arizona Corporation Commission has started programs, such as Arizona Goes Solar, to encourage the use of renewables for residential and commercial (also called non-residential) establishments. The utility companies listed above are responsible for implementing the program, offering upfront incentives (UFI) and performance-based incentives (PBI). Some companies, such as Trico Electric Cooperative (TEC), have offered those incentives in the past but no longer do (Arizona Corporation Commission, n.d.-a).

Ajo Improvement Company (AIC) offers upfront rebates for non-residential installations of $5.00 per watt (Watt DC-STC) for the first system application, $4.00 per watt for the second application received and $3.50/watt for all the following applications received. The ceiling value is $11,000.00 per customer and up to 60% of the system cost (Arizona Corporation Commission, n.d.-b).

Mohave Electric Cooperative (MEC) implemented the Sunwatts Renewable Energy Incentive Program, in which they give $0.05 per watt of installed solar energy nameplate capacity for systems up to 50 kW. The maximum amount paid is $2,500.00. If a system over generates power in a month, MEC will buy the excess for a certain amount per kWh, that will be discounted in the costumer’s bill for the following month. This rate varies by year, and for the year of 2018 they are paying $0.074171 per kWh (Mohave Electric Company, 2017).

In California, the California Public Utility Commission (CPUC) has created several RPS procurement program, for example, the RPS Feed-In Tariff Program: ReMAT, in which up to 493.6 MW of capacity are offered to qualified projects through a fixed-price standard contract to export electricity to California’s three major investor owned utilities (IOUs): Pacific Gas & Electric (PG&E), Southern California Edison (SCE) and San Diego Gas & Electric (SDG&E). This program targets small renewable generators with capacity less than 3 MW. All the electricity generated through ReMAT counts towards the RPS goals (California Public Utilities Commission, 2018b).

The IOUs mentioned above (SCE, PG&E and SDG&E) are also a part of Investor-Owned Utility Solar Photovoltaic (PV) Programs. Those companies are allowed to perform power purchase agreements (PPA) with independent power producers and also own and operate solar facilities for projects sizes from 1 MW to up to 20 MW depending on the company (California Public Utilities Commission, 2018a).

Utah has a voluntary RPS, aiming to have 25% of their total electricity coming from renewables until 2025. There are state incentives and there were utility incentives until 2012 (National Renewable Energy Laboratory, n.d.). For the state incentives there is the Renewable Energy System Tax Credit that can be applied to renewable technologies installed at commercial and residential establishments and also to large scale projects. This system is divided into two types: The Investment Tax Credit (ITC) and the Production Tax Credit (PTC) (Governor's Office of Energy Development, 2018).

The ITC applies for residential and commercial installations. The renewable technologies included are: biomass, wind, hydropower, geothermal, solar thermal and photovoltaic. The commercial tax credit is $50,000 or 10% of the qualified system cost, the lower value is always picked. The residential systems receive up to $2,000 or 25% of the total system cost, depending on which value is lower. The PTC are for systems of 600 kW or greater for the following renewable technologies: biomass, wind, PV and geothermal. Those systems receive $.0035/kWh for the first 48 months the commissioning of the project (Governor's Office of Energy Development, 2018).

Chapter 3 – Methodology

3.1.Research Approach

All daily power output data were obtained from Sunny Portal monitoring website (SMA Solar Technology, 2019) for five buildings (Student Union, Dayton Hall, CBC-C, Wright Hall and Beam Hall). Access to the data was obtained by collaboration with UNLV facilities (Mr. Whinery) and Nevada Energy. The data is in the form of power output and it varies according to the type of panel, sunlight incidence during the day, temperature of the panels, shading, wind speed, etc. To compute the impact of soiling on the panel operation, the expected efficiency has to be computed, taking into consideration all the factors mentioned earlier. Since some of the parameters necessary to calculate the efficiency of the panels are not measured by UNLV for each plant, a model for efficiency computation was developed using the National Renewable Energy Laboratory (NREL) software: SAM (System Advisory Model). In the model, it was necessary to add several parameters to the model including UNLV campus weather data, the manufacturer's specifications of the panels and inverters, the plane of array (POA), and cell temperatures.

Once the model was developed, the efficiency of the plant was computed. Next, the efficiency obtained for before and after rainfall periods was sorted for analysis. The goal was to determine, if possible, how much rain is necessary to clean the panels and what happens to the efficiency after rainfalls of different magnitudes.

A schematic drawing was made to better illustrate where each type of information came from. Figure 3.1 shows the source of information used in the research for the NREL model. The weather parameters of sunlight components (direct normal irradiance (DNI) and global horizontal irradiance (GHI)), temperature and wind speed, were obtained from the weather station located in the Center for Energy Research (CER) at UNLV. Those parameters, along with the manufacturer's specifications for the panels and the inverters were input in the SAM software. The outputs from the model were values for plane-of-array (POA) and the cell temperature, which were then used for the normalized efficiency calculations.

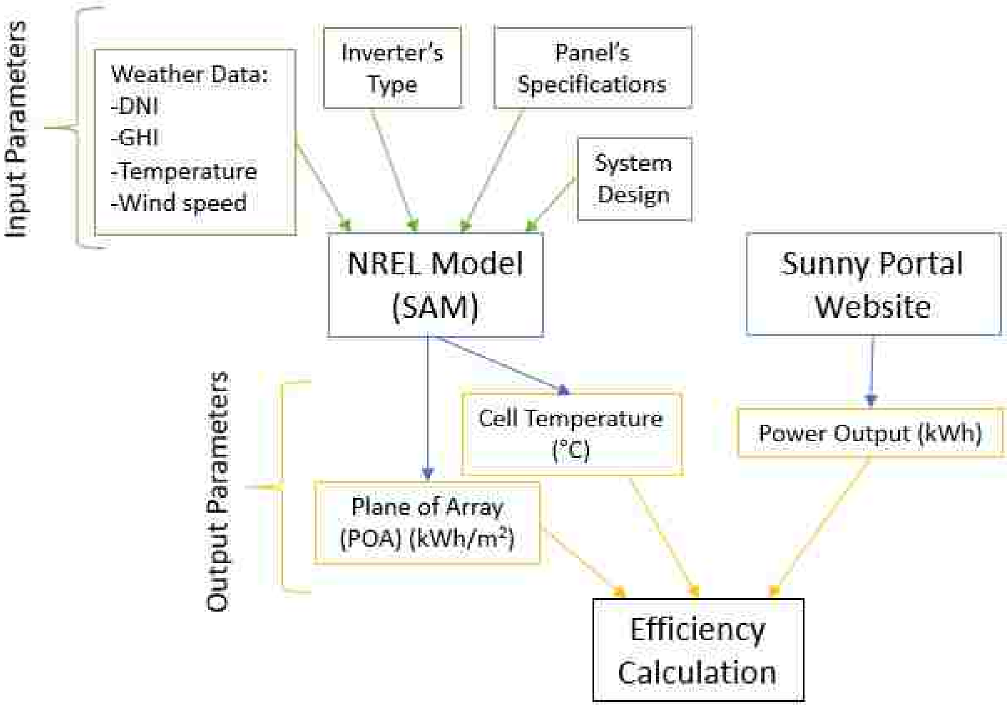


Figure 3.4 – Schematic Diagram with Steps for Model Inputs and Parameters Used for Efficiency Calculation

Rainfall data from 2014-2018 were obtained from a weather station near UNLV Desert Research Center (DRI) (latitude: 36° 06' 51" and longitude: 115° 08' 57"). The data were downloaded from the Community Environmental Monitoring Program website (CEMP, n.d.). The weather station is operated jointly by Desert Research Institute, WRCC, and the US Department of Energy. The gage used is Texas Electronics Rain Gauge Model #TE525, which is a tipping bucket gauge.

The dry periods (intervals between two rainfall events) were further analyzed to evaluate the rate of efficiency loss due to soiling. This analysis was conducted in three different ways: (a) comparison of the efficiency change from before and after one rainfall event; (b) comparison of the efficiency change between the end of one rainfall event and the start of the next; and (c) determination of the efficiency change between two rainfall events based on the slope of the efficiency trendline. The soiling losses were also calculated for the whole set of data for each solar plant studied.

To analyze the efficacy of washing, solar panels located on two different buildings at UNLV (Wright Hall and Student Union) were washed by a professional company. The increase in the panel's efficiency was computed and analyzed to determine whether it is worthwhile washing solar panels at the UNLV campus.

To compare the impacts of rainfall and mechanical washing in solar plant's efficiency Statistical analyses were performed using "t-Test: Paired Two Samples for Means" and "Linear Regression" with the Software Took Pak from Excel.

3.2. Power Output Data from UNLV Solar Panels

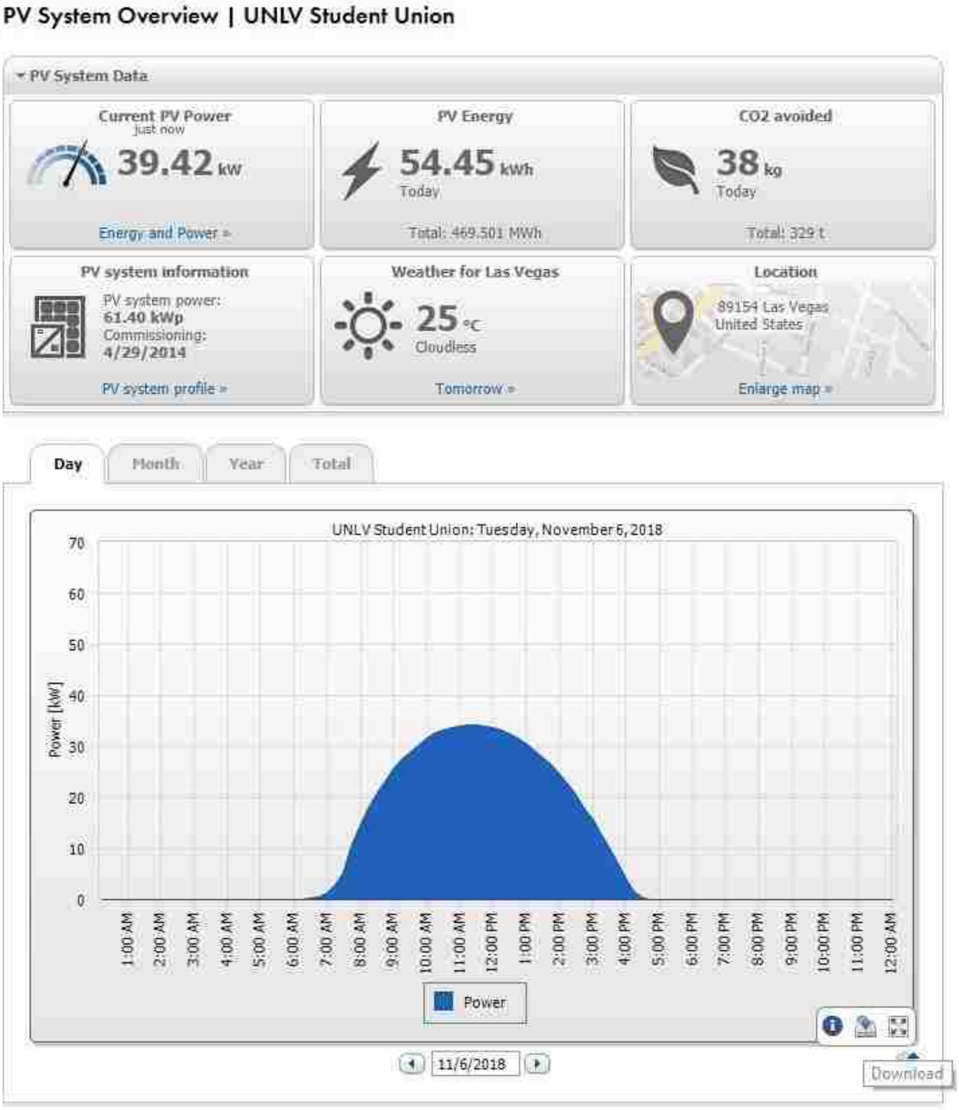
The solar power plants located at UNLV buildings are billed monthly based on the energy output. Table 3.1 below, shows the capacity of each plant, the start date of operation and costs associated with them.

Table 3.6 – Solar Energy Plants Located at the UNLV Campus Located on top of Different Buildings

Building	RLL1	RLL2	BEH	Dayton Hall	Student Union	WRI	CBC-C
Commissioning Date	4/30/2013	4/30/2014	5/1/2014	5/15/2014	4/29/2014	4/30/2014	5/1/2014
Size (kW)	59.28	61.40	61.40	61.40	61.40	61.40	61.40
Installed Cost	$349,868	$162,302	$162,302	$162,302	$162,302	$162,302	$162,302
NV Energy Rebates	$187,500	$140,000	$140,000	$140,000	$140,000	$140,000	$140,000
Net Cost for UNLV	$162,368	$22,302	$22,302	$22,302	$22,302	$22,302	$22,302

The AC power output data were obtained from the monitoring website Sunny Portal (SMA Solar Technology, 2019). This portal is owned by SMA America, LLC and access to the data was possible with the assistance of Mr. Whinery, the assistant director of facilities management at UNLV. An overview of the portal where the data were collected is shown in

Figure 3.2. The values for the power output (kW) for each day were downloaded from the website, directly into Excel. These data were available in 15-minute intervals.



PV System Overview | UNLV Student Union

PV System Data

Current PV Power just now 39.42 kW

PV Energy 54.45 kWh Today
Total: 469.501 MWh

CO2 avoided 38 kg Today
Total: 329 t

PV system information
PV system power: 61.40 kWp
Commissioning: 4/29/2014

Weather for Las Vegas
25 °C
Cloudless

Location
89154 Las Vegas
United States

Figure 3.5 – Example Sunny Portal Data Set

All data were adjusted to standard time and daylight savings were not taken into consideration. Only data from 11 a.m. to 1 p.m. were used in order to eliminate the effects of shading of the panels. This timeframe was selected because these hours were the closest to the solar noon (12 pm). Since power output data were available every 15-minute, the values between 11 a.m. and 1 p.m. were integrated to find the total kWh produced during that period. When the sun is further from solar noon, the effects of shading are more pronounced and the panels can be shaded by other panels in the arrays or by objects nearby. The solar noon for the UNLV campus is in the range from 12:24 pm to 12:54 pm (standard time, not considering daylight savings) depending on the time of the year (Time and Date AS, 2019).

3.3.Modeling

It is not possible to use only the power output data to compute efficiency, since temperature and solar irradiation vary from day to day and during different seasons of the year. However, some parameters needed for efficiency calculation were not available for this research and they had to be measured or computed. Therefore, a model was developed using the NREL software, SAM (version 2017.9.5 r4**)**, for each solar plant analyzed, to obtain the plane of array (POA) and solar cell temperature, since those parameters are not measured at the solar sites at UNLV.

In the software, the values of weather parameters (global horizontal, direct normal, dry bulb temperature and wind speed) were input. Those parameters were obtained from the weather station located at UNLV and downloaded from the Measurement and Instrumentation Data Center (MIDC) (NREL, 2019). The specifications of the panels and inverters for each system, as well as the number of panels and how they were connected were also input. This information was obtained from the electrical drawings and the data sheet of the solar panels, provided by the Facilities Management Department at UNLV. UNLV Facilities also provided the azimuth angle of the panels studied. There were a total of 212 panels and 4 inverters on each building. Table 3.2 shows how the panels were connected. In all of the buildings, the panels were connected the same way.

Table 3.7 – Arrangement of the Solar Panels on UNLV Buildings Showing Number of Panels per Array and Number of Inverters

Sub-array	Number of strings	Number of panels	Total # of panels in the sub-array	Inverter connected to
1	4	14 panels per string	56	1
2	4	14 panels per string	56	2
3	4	14 panels in 2 strings and 12 panels in 2 string[a]	52	3
4	4	12 panels per string	48	4

[a] This array was modeled as 4 strings of 13 panels per string, since the Software program can only model equal amounts of panels in a string.

Table 3.3 shows the input values used in the modeling. For all the other parameters, not listed in this table, the default values were used. In Appendix A, screenshots of the software are provided.

Table 3.8 – Input Parameters/Source of Data Used in the Software SAM

Catergories	Sub-Categories	Input
Location and Resource	Weather Data[a]	DNI[b]
		GHI[c]
		Temperature
		Windspeed
	Location	USA NV Las Vegas Mccarran Intl Ap (TMY3)
	Weather File Irradiance Data	DNI and GHI
Module	Solar Cell Model	SolarWorld SW270 Mono
	Temperature Correction	NOCT
	Mouting Standoff	Less than 0.5 in
	Array Height	Two story building height or higher
Inveter	Inverter Type	SMA America: STP15000-US-10 (480V) 480V [CEC 2013]
System Design	Modules per string	12-14[d]
	String in Parallel	4 or 8[d]
	Number of Inverters	1 or 2[d]
	Strings in Array	4 or 8[d]
	Tracking	Fixed
	Tilt (deg)	Varied from 2.84 to 7.48[e]
	Azimuth (deg)	176-179
	Ground Coverage Ratio	0.6956
Shading and Snow	Number of Modules Along Side of Row	1
	Number of Modules Along Bottom of Row	14-Dec
	Module Aspect Ratio[f]	1.75

[a] Weather data obtained from weather station located at UNLV (NREL, 2019)
[b] "Direct normal irradiance, sometimes called beam normal irradiance is the amount solar radiation per unit area that reaches a surface that is normal to the rays of solar radiation from the sun"
[c] "Global horizontal irradiance is the total solar radiation per unit area that reaches a horizontal surface"
[d] A model was developed for each of the 3 different string configurations presented in Table 3.2
[e] The tilt angles were manually measured for all the buildings modeled
[f] The ratio of the module length to module width

After inputting those parameters, the model was simulated and several output parameters were available. The POA and cell temperature were selected.

To be able to validate the model, the power output provided from the software was compared to the actual power output obtained from the Student Union solar plant. Since the model considered no soiling, two days were chosen for comparison when it is assumed that the panels had the least soiling: the sunny day after the panels were cleaned by the professional company (08/27/18) and the day after a 1.2 in rainfall that was considered to have cleaned the panels. These data can be found in Appendix B.

3.4.Efficiency Calculation

After all the parameters of POA and cell temperature were obtained from the modeling, it was possible to calculate the efficiency. The efficiency was calculated based on the method presented in Boeing (2018), which is described in equations 3.1 through 3.7.

$$\eta = \eta_{raw} + \eta_{raw} * \eta_t \qquad \text{Equation 3.4}$$

Where: η = normalized efficiency (%)

η_{raw} = raw efficiency (%)

η_t = efficiency correction for temperature (%)

$$\eta_{raw} = \frac{\int (P)}{\int (I) * A} \qquad \text{Equation 3.5}$$

Where: η_{raw} = raw efficiency (%)

P = power output of the solar panels (kW)

I = Plane of Array insolation (POA) (kWh/m^2)

A = area of (m^2)

$$\eta_t = \alpha * \Sigma_{day=1}^{N}(T - T_{avg}(day)) \qquad \text{Equation 3.6}$$

α = module temperature coefficient (%/°C)

N = number of days

T = average cell temperature for the whole data set (°C)

T_{avg} = daily average cell temperature from 11 p.m. to 1 a.m.

To integrate the power output and the POA, the trapezoidal rule was used as the integration method. The equations are described below.

$$\int (P) = \int_{t_0}^{t_{final}} P(t)dt = \Sigma_{i=1}^{i=8} \frac{P(t_{i-1})+P(t_i)}{2} * \Delta t$$ *Equation 3.7*

Where: t_0 = initial time (11 a.m.)

t_{final} = final time (1 p.m.)

Δt = time step (1/4 hour)

$$\int (I) = \int_{t_0}^{t_{final}} I(t)dt = \Sigma_{i=1}^{i=2} \frac{I(t_{i-1})+I(t_i)}{2} * \Delta t$$ *Equation 3.8*

Where: t_0 = initial time (11 a.m.)

t_{final} = final time (1 p.m.)

Δt = time step (1 hour)

The daily average cell temperature and the average cell temperature for the whole data set were calculated using Equation 9 and 10, respectively, presented below.

$$T_{avg}\,(day) = \frac{1}{3}\, \Sigma_{t=1}^{2} T(t_i)$$ *Equation 3.9*

Where: $T(t_i)$ = Cell temperature (°C) at the time t_i on a day

$$T = \frac{1}{N} \Sigma_{day=1}^{day=N} T_{avg}(day)$$ *Equation 3.10*

3.5.Rainfall Analyses

Rainfall data from 2014-2018 were obtained from the weather station located at the Desert Research Institute (DRI), at the intersection of Swenson and Flamingo Road, next to UNLV. This was the closest weather station to UNLV, therefore, it was the one chosen for this study. The data were downloaded from the Community Environmental Monitoring Program website (CEMP, n.d.). The rainfall data can be found in Appendix C.

Additional rainfall data for the years 1990-2013 were obtained from Community Environmental Monitoring Program website (CEMP, n.d.) and from Clark County Regional Flood Control District website (Clark County Regional Flood Control District (CCRFCD), n.d.), for rain gage “4484 – Tropicana Wash at Swenson”, which was closest location to

UNLV after the rain gage at DRI. Both places were used for data acquisition for the years of 1990-2013 because data from earlier years were not available at the DRI location.

Data from the DRI station and the CEMP and CCRFCD websites were combined in order to calculate the return periods for each rainfall depth. The rainfall events were organized from largest to smallest and ranked. The exceedance probability was calculated by the following equation:

$$Exceedance\ Probability\ (\%) = \left(\frac{m}{n+1}\right)x100 \qquad \textit{Equation 3.11}$$

Where m was the ranking number of a determined event and n was the total number of days with rainfall data (10591 days). The recurrence interval for a determined rainfall event was also calculated by the equation below:

$$Recurrence\ interval\ (years) = \frac{\left(\frac{n+1}{m}\right)x100}{365} \qquad \textit{Equation 3.12}$$

The data for the recurrence interval for the different rainfall events can be found in Appendix D.

3.5.1. Efficiency Change for Different Rainfall Events

From when the panels were installed (2014) until the end of 2018, rainfalls with a previous dry period of at least 20 days were analyzed. Rainfalls that occurred within a week were considered to be 1 event and only events with 3 or less rainfalls were selected. Also, only the events where there were 2 or more efficiency values for the week before and 2 or more efficiency values for the week after were taken into consideration. The efficiency change was investigated in three different ways. It was assumed that the panels were the dirtiest the week before the rainfall and the cleanest the week after. The process used was similar to the methodology described by Kimber et al. (2006).

To determine how much efficiency was recovered by a rainfall event, the average efficiency of the week before (η_b) and after (η_a) each rainfall event was calculated for all the buildings studied. To evaluate the efficiency loss/recovery after a rainfall, the normalized efficiency difference ($\Delta\eta_n$), or also percent change, was calculated using the following formula:

$$\Delta\eta_n\,(\%) = \frac{(\eta_a - \eta_b)}{\eta_a} x\ 100 \qquad \textit{Equation 3.13}$$

Where η_b = average efficiency of the week before a rainfall event

η_a = average efficiency of the week after a rainfall event

The rainfall events were divided into bins (0-0.1 in, 0.1-0.2 in, 0.2-0.3 in, 0.3-0.4 in and >0.4 in) following the classification presented by Kimber et al. (2006). If there was more than 1 rainfall during an event, the largest rain dictated the bin under which that rainfall event would fall. A linear regression was performed to evaluate the amount of rain necessary to restore some of the efficiency of the panels.

3.5.2. Determination of Soiling Rate

To calculate the soiling rate, a methodology similar to the one described by Mejia & Kleissl (2013) was used. The same criteria utilized in section 3.4.1 for selecting rainfall events was used to select the rainfall events for this section. In addition to those criteria, one more constraint was added. Only those rainfall events which were also ≥0.2 inches were considered. This additional constraint was based on the results obtained from the percent change ($\Delta\eta_n$), which will be discussed in the results. The soiling rate was calculated in three different ways.

I. In the first part, the average efficiency of the week before (η_b) and the week after (η_a), calculated in part 3.4.1, were used. The soiling losses (% efficiency lost/day) were calculated by the difference in the average efficiency ($\Delta\eta$) divided by the number of days of dry period (DP) before the rainfall event.

$$\Delta\eta\,(\%) = \eta_a - \eta_b \qquad \textit{Equation 3.14}$$

$$Soiling\ losses(\%/day) = \frac{\Delta\eta}{DP} \qquad \textit{Equation 3.15}$$

II. In the second part, to evaluate how much efficiency decrease there was between rainfall events, the average efficiency of the week following a rainfall (η_f) and the week previous (η_p) to the next rainfall was calculated. The soiling losses were calculated by the difference of η_f and η_p divided by the number of days during that dry period (following equation 3.10).

$$\Delta\eta\ (\%) = \eta_p - \eta_f \qquad \textit{Equation 3.16}$$

III. For the third part, also to analyze how much efficiency was lost due to soiling, the dry periods between two rainfall events (≥0.2 in) were analyzed. A trendline was plotted during the dry period and the slope of the line was considered to be the rate of efficiency loss due to soiling.

$$Soiling\ losses(\%/day) = \frac{Slope\ of\ trendline}{DP} \qquad \textit{Equation 3.17}$$

Figure 3.3 illustrates better the methodology for part 3.4.

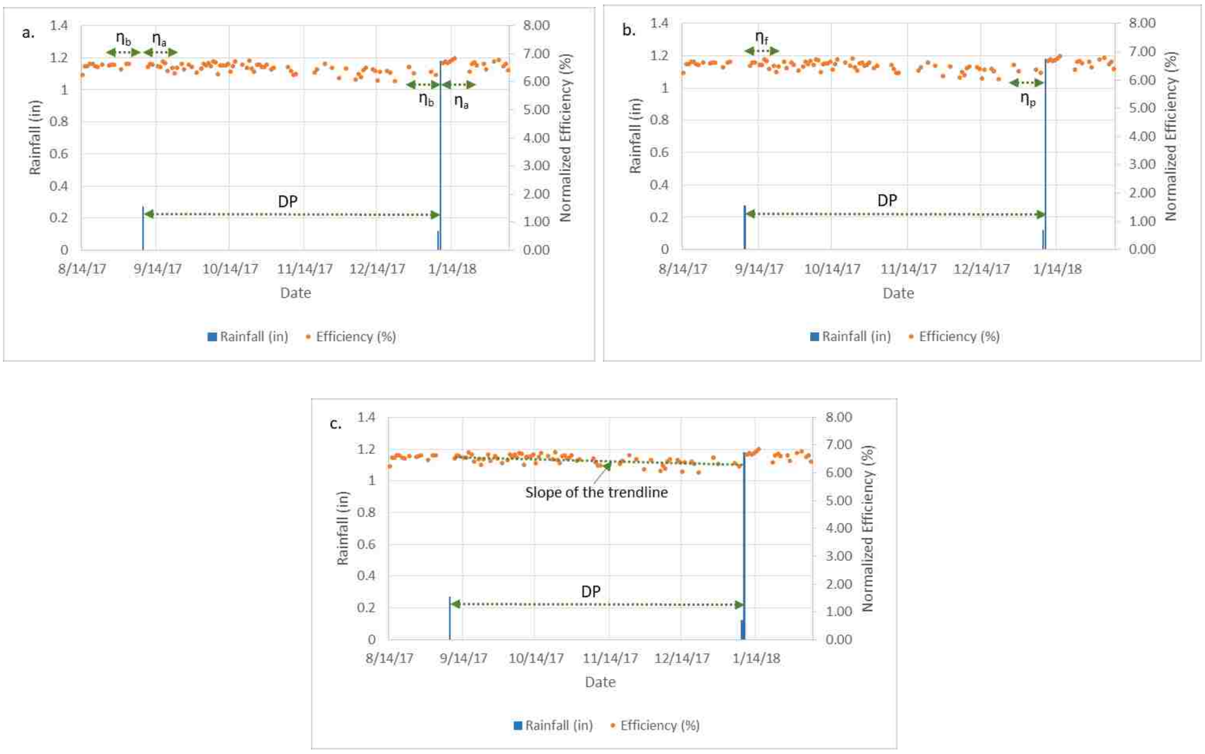


Figure 3.6 – (a), (b) and (c) illustrates the methodology for parts 3.4 I, II, III respectively (this image is not to scale, it is only illustrative)

3.6. Soiling Rates Losses Over the Years

The soiling rate was also calculated for each building following the methodology of unpublished research work by Aaron Sahm. The normalized efficiency was plotted over the years for each building. A trendline was added to the whole data set and the slope of that line was assumed to be the degradation rate of the solar panels. A new line, with same slope, was added passing through the point with higher efficiency (assumed to be when the panels were the cleanest). This point was determined by doing the average of the 30 highest efficiencies of the dataset. For the Student Union's panels, the ones that were washed, a line with the original slope was added, passing through the efficiency of the day after the panels were washed. New efficiency values were obtained from those new trendlines.

To figure out the soiling rate, the difference between the real and the new efficiencies were divided by the new efficiency and the values obtained were considered to be the soiling rate.

3.7. Evaluations of Washing Effects

3.7.1. Washing of UNLV's PV Panels On Student Union and Wright Hall Buildings

To better evaluate the effects of washing, a professional cleaning company was hired to wash Student Union's (SU) solar panels. The washing took place on 08/25/2018. The cost of washing was 6 dollars per panel, totaling $1,272.00 since there are 212 panels on that building. The company utilized treated tap water as the water source. A reverse osmosis (RO) system, connected to a faucet located on the building, was used to filter the water and bring the total dissolved solids (TDS) close to zero. The RO system was an nLite Hydropower by Unger model HP06T, with a resin bag inside and a water fed pole connected to it. The water is purified, and TDS levels are not more than 10 ppm. The specifications of the RO system are shown in Table 3.4 below.

Table 3.9 – RO system specifications (Unger, n.d.)

Model	HP06T
DI Resin Capacity	1 bag - 6.0L/0.21 cu.ft.
Power	Tap Pressure
Pump	NA
Working Hose Length	100 ft./30m plus
Water Production (Soft Water: TDS <100 ppm)	414 gal 1,570 L
Water Production (Medium Water: 100<TDS<250 ppm)	124 gal - 414 gal 470 L - 1,570 L
Water Production (Hard Water: 250<TDS<400 ppm)	69 gal - 124 gal 260 L - 270 L
Water Production (Very Hard Water: TDS>400 ppm)	<69 gal 260 L

Figure 3.7 – RO System Used by the Company to Clean Solar Panels (Unger, n.d.)

In Figure 3.4 it is shown the RO system used to clean the solar panels. It is composed of an N-lite hydropower DI which has a mixed bed ion exchange resin which removes TDS from water. There is a water pole connected to the system where water will flow and reach the brushes that are used to clean the solar panels.

The cleanliness of the panels was evaluated visually after the panels were washed. The panels had no dust or spots on them upon washing. The professional company hired also assured the panels were cleaned completely as per experience. Therefore, the evaluation was only visual, there was no measurement done or tool utilized to assess the cleanliness of the panels.

Another set of solar panels, the ones located on John S. Wright Hall (WRI), had been previously washed by the same company on 08/27/2016. However, there is no power output data available from 5/25/2016 to 9/22/2016, therefore, it was not possible to evaluate the effectiveness of washing for that building.

To evaluate if washing is worthwhile, the efficiency of the washed panels was analyzed using the same method presented in Section 3.6. An efficiency trendline was computed for all the data. A new line equation, with the same slope as the trendline, was found using a point of the efficiency after the panels were washed. New efficiencies were calculated from this new equation. These efficiencies were used to find the theoretical power output of the panels, as if they were always operating as when they were cleaned. The value for the extra energy produced was compared to the cost of washing.

Another method utilized was the comparison of the power output of the SU's panels (washed) to the panels located on Beam Hall, which is a building adjacent to Student Union that has solar panels with the same specifications and electrical connections as SU's. The kWh for both sites were calculated for the sunny day before and the sunny day after the washing. The change in output for the non-washed site was considered to be the baseline, taking into account weather variables which affect the output. The cleaned panels were also analyzed before and after the washing. Any additional change, compared to the baseline, was considered to be due to the cleaning.

3.7.2. Survey of Commercial Scale Solar Plants in Las Vegas Regarding Washing

As a tool to aid in examining the implication of soiling to energy loss in these plants, a survey was also conducted to analyze if non-residential establishments in the Las Vegas region with solar systems installed on their properties were washing their solar panels. The first step was to obtain a list with all the commercial establishments in Las Vegas, North Las Vegas and Henderson with solar panels installed on their properties (roofs, carports or grounds). Satellite imagery provided by Google Maps was used initially to identify those buildings. However, a more efficient method was later implemented. Since all buildings require permits to be able to install solar panels, acquiring the list of such permits would provide the locations of those sites.

The records of permits granted to commercial buildings for solar panel installation were requested from the Building Department of City of North Las Vegas, City of Las Vegas, Henderson and Clark County. The lists contained the permit’s number, establishment’s name and address, and capacity of the solar panels (kW). Once all the lists were obtained, only systems with capacity over 10 kW were selected.

A standard survey form with questions regarding the specifications of the panels and their washing schedule was generated. The survey form is presented in Appendix E. Subsequently, contact information was acquired via internet search and the form sent for completion. Some sites were also visited in person.

3.8. Statistical Analyses

Statistical analyses were performed to answer the following questions:

a) Is there a statistically significant difference in the change in efficiency from before and after rainfall events, therefore, showing that the rainfall events have impacts on the efficiency of the panels?

b) Is the soiling rate, i.e. the slope of the normalized efficiency trendline, statistically significant?

Statistical analyses were performed using a 95% confidence level. For the rainfall analysis part, to validate if there was a difference between the average efficiency before and after a rainfall event, the "t-Test: Paired Two Samples for Means", available in Excel from the Analysis ToolPak, was used. According to Navidi (2015), in a test for the difference between two means, the difference of means will be computed and if this difference is far from 0 then it can be concluded that the population means are different. If this difference is near 0, then it can be concluded that the population means could be the same.

This test can be a one-tailed or two-tailed test. The two-tailed t-test is used when the alternate hypothesis is two-sided, the mean of one group is different than zero (it could be greater or less than zero). In this case, both tails of the distribution contribute to the P-value. The one-tailed test is used when the alternate hypothesis is one-sided and specifies the expected direction of the results, the mean of the group is either more or less than the mean of the other group. In this case, only one extreme end, i.e. tail, of the distribution contributes to the P-value. (Boeing, 2018; Walpole & Myers, 1989)

For the two-tailed test, the null hypothesis is H_0: $\mu_x - \mu_y = 0$ and the alternate hypothesis is H_1: $\mu_x - \mu_y \neq 0$. For the one-tailed test, the null hypothesis is the same, however, the alternate hypothesis is either H_1: $\mu_x - \mu_y > 0$ or H_1: $\mu_x - \mu_y < 0$. If the p-values are less than 0.05 then the null hypothesis can be rejected, and it is concluded that there is a statistically significant difference of efficiency before and after a rainfall event.

For the parts where a trendline was added, a “Linear Regression” analysis was performed which was also available in Excel from the Analysis ToolPak. The null hypothesis was that the slope (β) of that line was zero, H_0: $\beta = 0$. The alternate hypothesis was that the slope of that line is different than zero (H_0: $\beta \neq 0$), therefore, there would be a significant change in efficiency during the period analyzed. According to Walpole & Myers (1989), the null hypothesis basically says that the variations in the results (Y) happen by chance or random fluctuations and are independent of the values of X. The “Significance F” obtained from the ANOVA analysis of linear regression was studied and the p-values for both coefficients of the linear trendline were studied as well. Both values should be less than 0.05 to achieve a confidence level of 95%.

Chapter 4 – Results and Discussions

4.1. Rainfall Analyses

4.1.1. Analysis of the PV Plant Efficiency Variation With Different Rainfall Events

To evaluate how the efficiency of the solar plants is impacted by different rainfall intensities and to try to determine a minimum amount of rainfall needed to restore part of the panel's efficiency, different rainfall events were analyzed and the plant's efficiency before and after a rainfall period was compared.

Even though data were downloaded for five plants (Student Union, Wright Hall, Beam Hall, CBC-C and Dayton Hall), only 3 plants (Student Union, CBC-C and Dayton Hall) were used for this analysis. The reason is there were many periods during which the power output was not recorded for Beam Hall. For Wright Hall there were also some periods with no power output data, in addition, for the solar periods selected for the analysis, there was shading of the panels during the winter time during the time of the day selected (from 11 am to 1pm). Therefore, it was not possible to construct a model for these two plants to calculate the normalized efficiency.

The rainfall events selected for the analyses following methodology 3.4.1 are listed in Table 4.1. This table shows the dates the events occurred, the rainfall that were combined into the same event, and the rainfall's depth in inches. Each row contains information for one rainfall event. When there was more than one rainfall in an event, the largest one was considered to be the rainfall amount for that event. The rainfall amount for each event is shown in the "Control Rain" column. Not all these events could be analyzed for all the plants because for some of them either there was no data for some periods, or there was not more than one efficiency value available for the week before and/or after the event so it was not possible to calculate an average.

Table 4.10 - Rainfall Events Selected for the Analyses of Impacts of Rainfall on the Efficiency of the Solar Plants at UNLV

Date	Rainfall (in)	Date	Rainfall (in)	Date	Rainfall (in)	Control Rain (in)	Number of days prior with no rain
9/7/14	0.02	9/8/14	0.32			0.32	27
11/1/14	0.01					0.01	36
2/22/15	0.12	2/23/15	0.39			0.39	22
4/25/15	0.16					0.16	54
6/13/15	0.01	6/14/15	0.15			0.15	26
8/7/15	0.02					0.02	32
9/15/15	0.03					0.03	32
10/5/15	0.25					0.25	20
1/4/16	0.01	1/5/16	0.26			0.26	49
4/8/16	0.04	4/9/16	0.67	4/10/16	0.09	0.67	67
6/11/16	0.03					0.03	35
8/4/16	0.02					0.02	33
9/29/16	0.01					0.01	38
10/23/16	0.01	10/24/16	0.17			0.17	24
12/22/16	0.41	12/23/16	0.02	12/24/16	0.26	0.41	59
3/27/17	0.02					0.02	36
5/7/17	0.06					0.06	34
7/11/17	0.06					0.06	65
9/8/17	0.27					0.27	28
1/8/18	0.12	1/9/18	1.18			1.18	122
3/10/18	0.11	3/11/18	0.07			0.18	60
5/1/18	0.09					0.09	39
8/11/18	0.06					0.06	23
10/3/18	0.02					0.02	53
11/29/18	0.23					0.23	39

The average plant efficiencies of the week before and after each of those rainfall events, for each plant, are shown in Appendix F. It is possible to notice that CBC-C's normalized efficiency was lower than the efficiencies from Dayton Hall and Student Union. That was due to the fact that CBC-C's plant was yielding less power than the other two plants. The reason of such difference in power production is not known, especially since all the plants have the same type of solar panels, inverters, electrical connections and they have the same capacity and same commissioning date. UNLV Facilities was contacted and did not know why the power output for CBC-C was much lower than the other buildings. One of the possibilities for the lower output of the CBC-C array could be due to afternoon shadowing of the solar panels by the tall CBC-B building located immediately west of CBC-C. The percent change ($\Delta\eta_n$) was used to analyze how much efficiency was recovered by the rainfall event. The difference in efficiency ($\Delta\eta$) was used to compute the plant's soiling rate. The percent efficiency changes obtained from all the three plants (Student Union, Dayton Hall and CBC-C) were combined and plotted together (Figure 4.1).

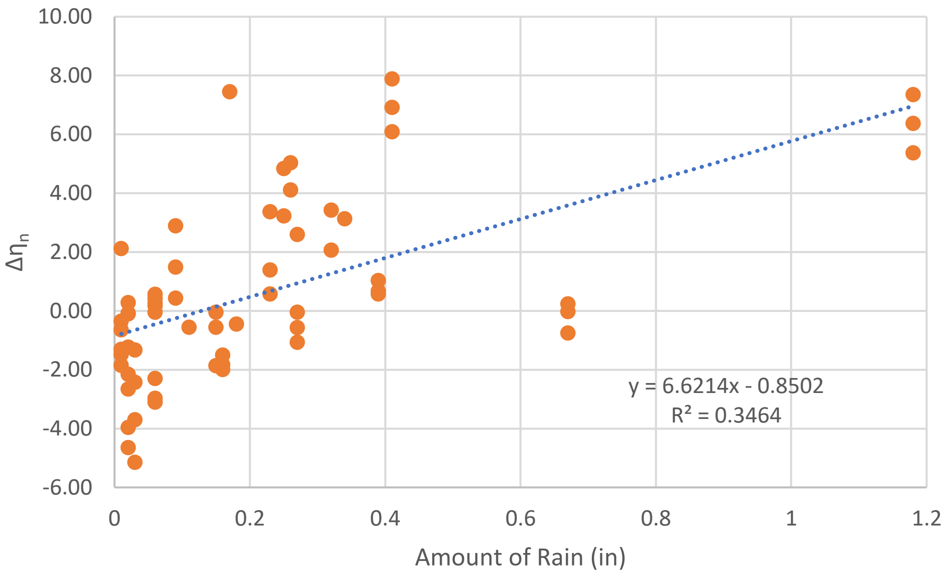


Figure 4.8 - Percent Change in Efficiency for Different Rainfall Events

Figure 4.1 shows that the percent efficiency recovered with rainfall varies much and the data are scattered; however, it is possible to observe a linear trend in the values indicating that the larger the rainfall event, the greater the recovery of the plants' efficiencies. When a least-square linear regression was performed, using Excel ToolPak, it showed that the obtained regression data is statistically significant since both p-values of the regression coefficients and significance F are less than 0.05. However, there is not such good fit for the trendline (R^2 is low: 0.3464), as was expected due to the large scatter. However, R^2 only reports the goodness of fit, in other words, what percentage of your data can be explained by the linear regression equation. To analyze if the results of the regression model are statistically significant and if the results are reliable and not only happening by chance, it is important to look at the p-values of the coefficient of regression and the significance F value. Table 4.2 shows all the values for the linear regression statistical analysis.

Table 4.11 – "Regression" Analysis Performed Using the Values of the Percent Change in Efficiency ($\Delta\eta_n$) as the Y Input and the Amount of Rain as the X Input

Regression Statistics	
Multiple R	0.5885
R Square	0.3464
Adjusted R Square	0.3358
Standard Error	2.4891
Observations	64

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	203.56	203.56	32.86	3.14E-07
Residual	62	384.13	6.20		
Total	63	587.69			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-0.8502	0.4031	-2.1092	3.90E-02
Total Rain	6.6214	1.1552	5.7320	3.14E-07

Since R^2 is low, it is possible to determine that predicted data (linear regression) does not have a good correlation to the actual data, meaning that this regression is not very good at making accurate predictions for the efficiency change depending on the rain depth values. Therefore, the regression explains a significant portion of the variance but not all variance in the data. However, the p-values and significance F are lower than 0.05 which means the null hypothesis can be rejected, meaning that rain does have an impact on the efficiency of the panels but since R^2 is low, it is not possible to determine the exact change that will happen based on rainfall alone.

The rainfall events were combined into bins based on their depth following the classification presented in Kimber et al. (2006). What dictated the depth of an event, to determine in which bin they would fall under, was the largest rainfall in that event, which is shown as the control rain in Table 4.1. When the rainfall events were combined into bins, it was possible to see more clearly the correlation of the amount of rainfall and the normalized efficiency difference (Table 4.3). Table 4.3 shows the rainfall size bin, and the average, maximum and minimum percent change in normalized efficiency. The average values for the normalized efficiency is the average efficiency differences for all the rainfall events that fall under that determined bin. For example, there were nine rainfall events that fell under category 2, therefore there were nine values of efficiency change ($\Delta\eta_n$). An average of all those values was calculated to determine the average (%) for that classification. The maximum and minimum values in each category are also reported. The correlation of the average % change in efficiency and the rainfall level can be seen in Figure 4.2.

Table 4.12 – Categories of Rainfall Events Classified According to the Rain Depth, Average Percent Change for Different Rainfall Categories and the Maximum and Minimum Values Obtained in Each Category and the Standard Deviation

Rainfall Level (in)	Category	Average (%)	Max. (%)	Min. (%)	Standard Deviation (%)
0-0.1	1	-1.13	2.89	-5.15	1.97
0.1-0.2	2	-0.15	7.45	-1.99	2.94
0.2-0.3	3	2.13	5.04	-1.07	2.19
0.3-0.4	4	1.82	3.42	0.58	1.25
>0.4	5	4.38	7.88	-0.76	3.51

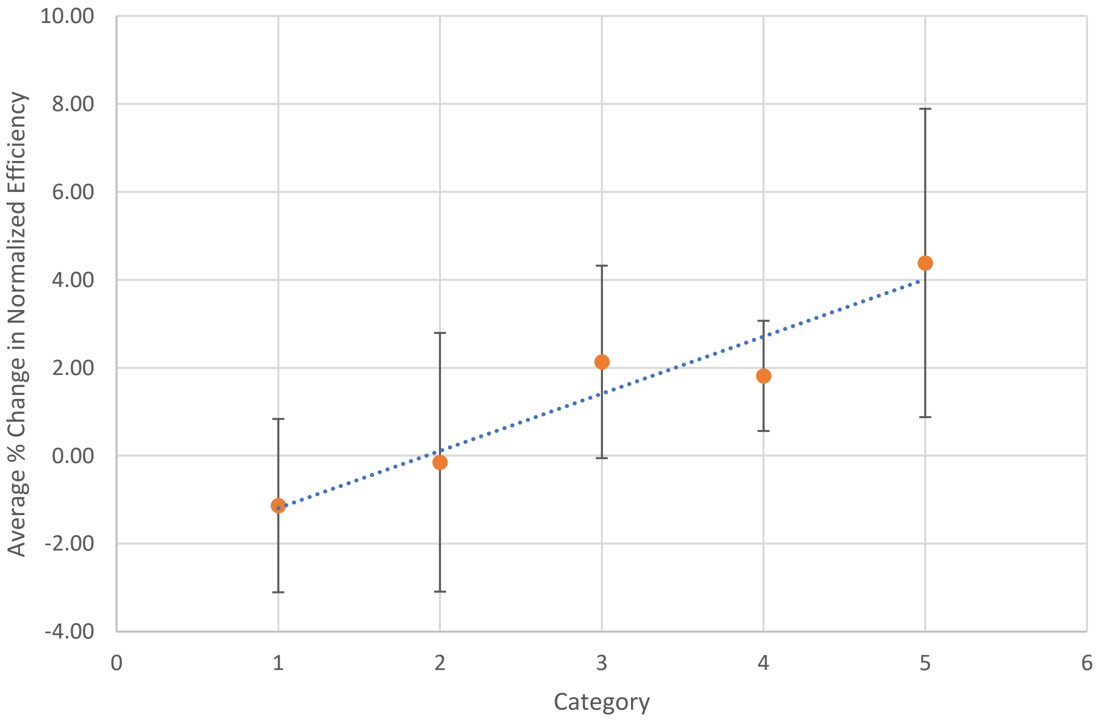


Figure 4.9 – Average Percent Change in Normalized Efficiency for Different Rainfall Categories and the Standard Deviation for Each Average Value. Each Rainfall Event was Classified Under a Category Depending According to the Most Intense Rainfall in the Event

A least square linear regression analysis was performed using the values of the average percent change in efficiency and the rainfall categories, presented in Figure 4.2 and Table 4.3. The results are presented in Table 4.4. Similarly, to the previous analysis, the purpose was to determine if the values found for the average percent change had a good correlation to the rainfall depth and if they were statistically significant or happening by chance.

Table 4.13 – Linear Regression Analysis for the Average Percent Change in Efficiency According to the Different Categories (Bins)

Regression Statistics	
Multiple R	0.9575
R Square	0.9169
Adjusted R Square	0.8892
Standard Error	0.7145
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	16.89418274	16.89418274	33.09175	1.04E-02
Residual	3	1.531576355	0.510525452		
Total	4	18.4257591			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-2.4892	0.7494	-3.3216	4.50E-02
Rainfall level (in)	1.2998	0.2259	5.7525	1.04E-02

The value of R^2 is 0.9169 which means that 91.69% of the variations in averages of normalized efficiency differences of the week before and after can be explained by the rainfall category. The high R^2 was expected since an averaged/smoothed data was used. The results of the regression model indicated statistically significant data, with p-values of the regression coefficients and significance F values are less than 0.05. Therefore, the difference in efficiency is not happening by chance, and it is affected by the different rainfall levels and since the R^2 is high, it is possible to predict the change in averaged normalized efficiency, depending on which of those categories a rainfall falls under.

Since the values of normalized efficiency for the solar panels on CBC-C were relatively lower than those obtained from Student Union's and Dayton's plants, the average % change in the normalized efficiency for the CBC-C panels was also evaluated separately to observe if there was a significant difference in the correlation with the rainfall amount. Figure 4.2 was replotted separating the data from CBC-C's plant.

Figure 4.3 shows the average % change in normalized efficiency only using the data obtained from CBC-C's plant and Figure 4.4 shows the average % change in normalized efficiency using data from Dayton Hall and Student Union combined. A linear regression and statistical analysis were performed for both plots and the results are shown after each figure, on Table 4.5 and 4.6.

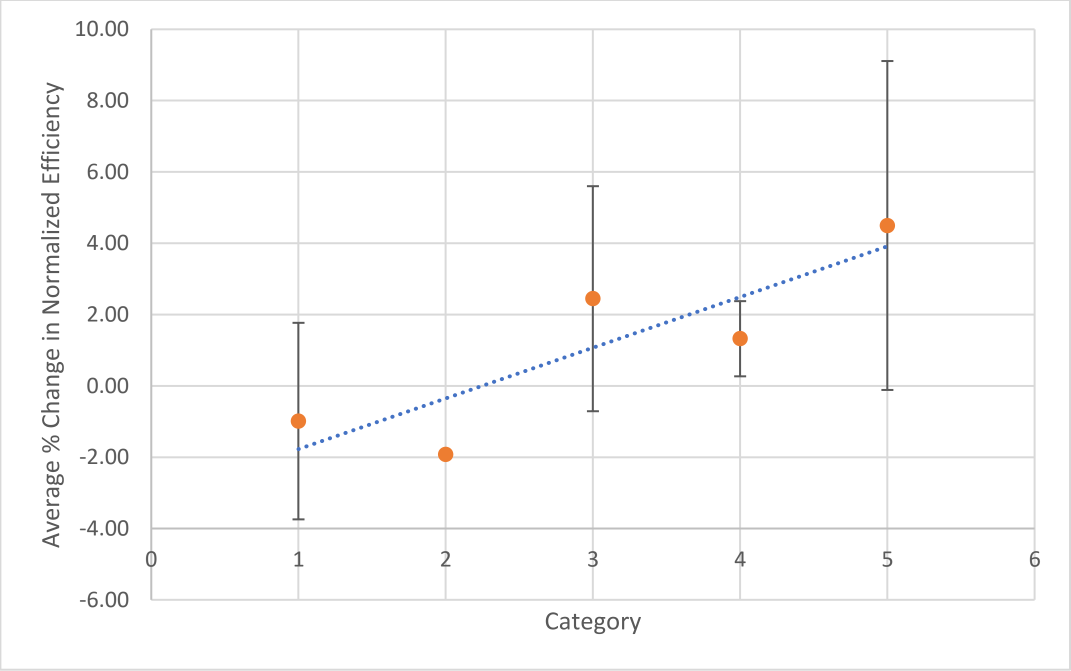


Figure 4.10 - Average Percent Change in Normalized Efficiency for Different Rainfall Categories and the Standard Deviation for Each Average Value Using the Normalized Efficiencies Values from Only CBC-C' Plant

Table 4.14 - Linear Regression Analysis for the Average Percent Change in Efficiency According to the Different Categories (Bins) Using the Data from Only CBC-C's Plant

Regression Statistics	
Multiple R	0.8668
R Square	0.7513
Adjusted R Square	0.6684
Standard Error	1.4939
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	20.22064925	20.22064925	9.061093	0.057
Residual	3	6.69477184	2.231590613		
Total	4	26.91542109			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-3.1960	1.5668	-2.0398	0.134
X Variable 1	1.4220	0.4724	3.0102	0.057

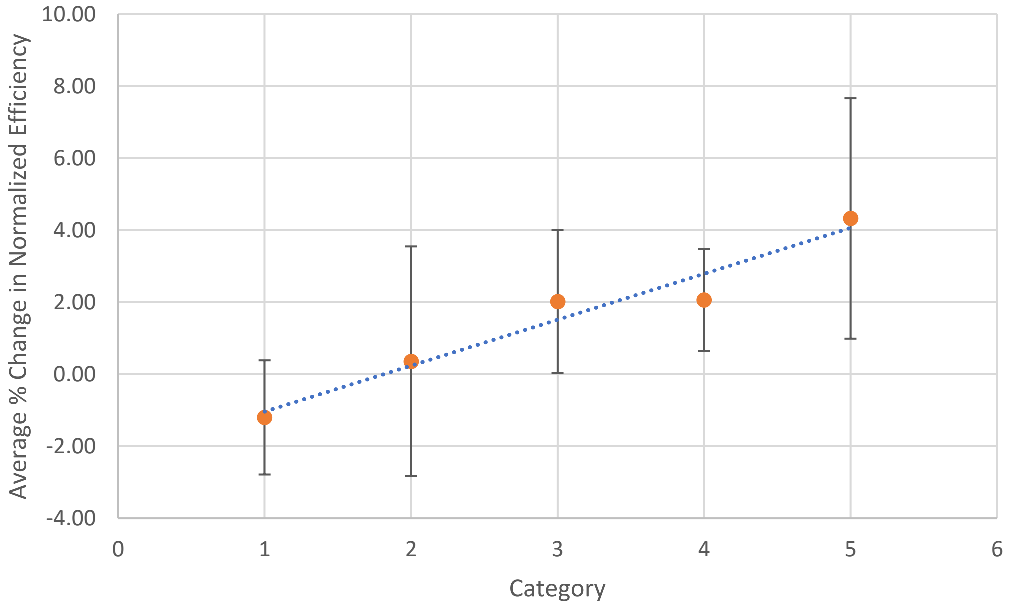


Figure 4.11 - Average Percent Change in Normalized Efficiency for Different Rainfall Categories and the Standard Deviation for Each Average Value Using the Normalized Efficiencies Values from Dayton Hall's and Student Union's Plants

Table 4.15 - Linear Regression Analysis for the Average Percent Change in Efficiency According to the Different Categories (Bins) Using the Data from Dayton Hall's and Student Union's Plants

Regression Statistics	
Multiple R	0.9737
R Square	0.9482
Adjusted R Square	0.9309
Standard Error	0.5444
Observations	5

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	16.26409297	16.26409297	54.87992	5.09E-03
Residual	3	0.88907336	0.296357787		
Total	4	17.15316633			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-2.3127	0.5710	-4.0505	2.71E-02
Category	1.2753	0.1722	7.4081	5.09E-03

It is possible to observe that the CBC-C's linear regression was not statistically significant at a $p < 5\%$ confidence level (computed p-values for slope and intercept and significance F are higher than 0.05). Therefore, one must accept the null hypothesis that a relationship between efficiency change and rainfall depth category did not exist for the CBC-C panels over the study period. A potential reason for that observation is that there are a smaller number of data points analyzed in each rainfall depth category. When evaluating the combined data from Dayton Hall and Student Union, it is possible to reject the null hypothesis of no significant relationship and accept the alternative hypothesis and that there is a significant relationship between rainfall depth category and the increase in efficiency. This might occur because when large amounts of data points are used for the regression, the impacts of outliers on the average value could be lessened compared to a data set with a small number of data points.

For the evaluations that follow on the rainfall amount necessary to clean the panels, the combined data from the Student Union and Dayton Hall buildings combined were used since they were statistically significant.

From Figure 4.4 it is possible to visually note that at least a 0.2 inch rainfall event was necessary for the panels to recover at least part of their previous efficiencies. To statistically analyze if there is a decrease or no change in efficiency after rainfall events less than 0.2 inches and an increase in efficiency after rainfall events greater than 0.2 inches, a Student's t-test analysis was performed for the case of Paired Two Samples for Means from Excel Tool Pak. The data input were all the efficiency values from before and after rainfall events ("Mean efficiency 1 week before" and "Mean efficiency 1 week after" - values shown in Appendix F). The test was performed in two groups, one for rainfall events less than 0.2 inches and the other for rainfall events greater than 0.2 inches. The one-tailed test, which takes into consideration the expected direction of the results, was used and the null and alternate hypothesis are specified below.

For the group with rainfall events less than 0.2 inches, the null hypothesis was H_0: $\mu_x - \mu_y = 0$ and the alternate hypothesis, H_1: $\mu_x - \mu_y < 0$. For the group with rainfall events more than 0.2 inches, the null hypothesis was also H_0: $\mu_x - \mu_y = 0$ and the alternate hypothesis, H_1: $\mu_x - \mu_y > 0$. The results are shown in Table 4.7.

Table 4.16 - Results from “t-Test: Paired Two Samples for Means” (a) For Rainfall Events <0.2 in; (b) for Rainfall Events >0.2 in

(a) t-Test: Paired Two Sample for Means for Rainfall Events <0.2 in

	Mean efficiency 1 week before	*Mean efficiency 1 week after*
Mean	10.9199	10.8289
Variance	8.3697	8.2871
Observations	38	38
Pearson Correlation	0.9965	
Hypothesized Mean Difference	0	
df	37	
t Stat	2.3221	
P(T<=t) one-tail	0.0129	
t Critical one-tail	1.6871	
P(T<=t) two-tail	0.0258	
t Critical two-tail	2.0262	

(b) t-Test: Paired Two Sample for Means for Rainfall Events >0.2 in

	Mean efficiency 1 week after	*Mean efficiency 1 week before*
Mean	11.0775	10.7535
Variance	9.8162	9.2503
Observations	25	25
Pearson Correlation	0.9950	
Hypothesized Mean Difference	0	
df	24	
t Stat	5.0409	
P(T<=t) one-tail	1.87E-05	
t Critical one-tail	1.7109	
P(T<=t) two-tail	3.75E-05	
t Critical two-tail	2.0639	

When analyzing the results from the regression analysis, for the data to be statistically significant, the computed Student’s t-Stat should be higher than critical t-value for the number or degrees of freedom. The associated probability value, p, should be less than 0.05. Therefore, the null hypothesis can be rejected, and the alternate hypothesis can be accepted. There is a statistically significant difference in the efficiency before and after rainfall events. This means that, for the group of rainfall events less than 0.2 inches, the average efficiency of the week before the rainfall is higher than the average efficiency of the week after the rainfall. And for the group of rainfall events greater than 0.2 inches, the average efficiency of the week before the rainfall is lower than the average efficiency of the week after the rainfall. Therefore, it can be concluded that at least 0.2 inches of rainfall is necessary to restore part of the panels efficiency and that is why only rainfall events over 0.2 inches were considered for the analyses of the dry periods between rainfall events in Section 4.1.2.

Light rainfall made the panels dirtier in most of the cases. This is similar to the effect one observes when a light rainfall hits the windshield of cars; because the rainfall is not sufficient to create a washing runoff, it creates a surface where the dust is accumulated more in areas that do not receive rainfall droplets. There is little information in the literature regarding this observation. In this study, the majority of the rainfalls with depth of less than 0.2 inches resulted in decreased efficiency of the panels. In a review by Sayyah et al. (2014), it is stated that light rainfall decreased the performance of the panels, as it might increase the dust deposition on the panels. However, the authors do not mention the amount of rainfall that was classified as light. They also acknowledge the fact that heavy rainfalls can fully restore the efficiency of the panels as the data of this research also indicated.

Kimber et al. (2006) conducted research on 250 solar systems located throughout California. They found that a 0.2-inch rainfall event was insufficient to clean one of the systems in Northern California, and a 0.82-inch rainfall event was needed to increase the efficiency by 40%. The authors also calculated the average efficiency of the week before and after a rainfall event for different systems, in Southern California, Northern California, California Central Valley and Southwest U.S. Desert. Overall, they were not able to find a clear amount necessary to clean the panels, as their values varied greatly, and they were not able to find a direct correlation between the rainfall amount and efficiency recovery. Conversely, in the research performed for this thesis, a direct correlation between the size of the rainfall and efficiency recovery was found for panels located in Las Vegas. Because soiling is caused by different types and size of particles and that humidity and other factors impact how they attach to the surface of the panels, one expects rainfall intensity needed to wash them to be different (Boeing, 2018; Qasem et al., 2014; Xu et al., 2017). In areas where soiling has a bigger impact, light rainfalls have been reported to restore efficiency at least partially. Schil et al. (2011) reported that there was a 20% loss of the original efficiency in solar panels located in Grand Canaria, Spain. The authors observed that, for panels completely covered by dust, a minor rainfall event was able to partially clean the panel, however, the amount of rainfall was not reported.

The angle of the panels is also an important parameter when looking into the amount of rain necessary to clean. Cano (2011) stated that modules with tilt angles less than 15° had higher water retention on the panels, which combined with the dust produced a "sticky matter" that besides not being able to be blown off by wind, also resulted in the accumulation of more dust particles. The solar panels used in this research had tilt angles less than 10°, therefore it is possible that this effect may happen during light rainfall.

The rainfall events in Las Vegas, near UNLV, were analyzed over the last 29 years. The recurrence intervals for each rainfall event size are shown in Appendix D.

It was observed that a 0.2 in rainfall event occurs approximately every 52 days. Therefore, it is expected that the solar panels will recover, at least partial, efficiency around every 52 days.

The objective of this part of the research was to evaluate how rainfall impacts the efficiency of the panels. The results showed that rainfall events smaller than 0.2 inches can decrease the efficiency and the events larger than 0.2 inches can recover part of the efficiency. The larger the rainfall event, the higher is the efficiency recovery. Other authors had investigated the impact of rainfall, but in most cases they were not able to identify a direct correlation between the size of rain and the efficiency recover (A. Kimber et al., 2006). In other regions, less rainfall amount (0.04 inches) was sufficient to clean the panels. Therefore, the rainfall threshold amount is dependent on the location and setting of the panels because soiling is influenced by the characteristics of the dust particles and weather conditions (Caron & Littmann, 2013; Zorrilla-Casanova et al., 2011).

4.1.2. Determination of the Plant Efficiency Loss due to Soiling

In order to calculate the efficiency loss of the solar panels during the period between rainfall events (dry periods), rainfall events greater than 0.2 inches were considered, since this was the threshold found in the previous section to improve the plant's efficiency.

For the calculation of the efficiency loss, the rainfall events selected are shown in Table 4.8. Not all those events could be analyzed for all the buildings because for some of them either there was no data for some periods, or there was not more than one efficiency value for the week before and/or after.

Table 4.17 – Rainfall Events Used to Calculate Soiling Rates During a Dry Period Using the Efficiency of the Week Before (η_b) and the Week After (η_a) a Rainfall Event

Event #	Date	Rainfall (in)	Date	Rainfall (in)	Date	Rainfall (in)	Total Rain	Number of days prior with no rain >0.2 in
1	8/3/14	0.33					0.33	156
2	9/8/14	0.32					0.32	36
3	1/11/15	0.43					0.43	125
4	2/23/15	0.39					0.39	43
5	8/13/15	0.77					0.77	171
6	10/5/15	0.25					0.25	53
7	10/17/15	0.22					0.22	12
8	11/4/15	0.2					0.2	18
9	1/5/16	0.26					0.26	62
10	4/9/16	0.67					0.67	95
11	4/28/16	0.46	4/30/16	0.86	5/7/16	0.2	0.86	19
12	7/1/16	0.25					0.25	55
13	12/22/16	0.41	12/24/16	0.26			0.41	174
14	1/20/17	0.26	1/22/17	0.46			0.46	27
15	2/18/17	0.64					0.64	27
16	8/4/17	0.26					0.26	167
17	9/8/17	0.27					0.27	35
18	1/9/18	1.18					1.18	123
19	7/9/18	0.43					0.43	181
20	11/29/18	0.23					0.23	143

Using the average efficiency of the week before (η_b) and the week after (η_a), presented in methodology 3.4.2(I), the efficiency losses were calculated and the results are shown in Table 4.9. The value of $\Delta\eta$ was calculated by the difference between η_b and η_a (η_b -

η_a). The average efficiency loss for each plant, which was the average of all the values of efficiency loss were computed and are shown it the last row of Table 4.9.

Table 4.18 – Efficiency Losses for Different Rainfall Events for Different UNLV Solar Plants Calculated Using the Efficiency of the Week Before (η_b) and the Week After (η_a) a Rainfall Event Using Method I

Event #	**Student Union**		**Dayton Hall**		**CBC-C**	
	$\Delta\eta$ (%)	**Efficiency Loss (% / day)**	**$\Delta\eta$ (%)**	**Efficiency Loss (% / day)**	**$\Delta\eta$ (%)**	**Efficiency Loss (% / day)**
2	-0.529	-1.47E-02	-0.480	-1.33E-02	-	-
3	-0.108	-8.62E-04	0.087	6.92E-04	0.044	3.53E-04
4	-0.117	-2.71E-03	-0.176	-4.08E-03	-0.055	-1.27E-03
5	-0.157	-9.17E-04	-0.138	-8.08E-04	-	-
6	-0.534	-1.01E-02	-0.441	-8.33E-03	-	-
7	0.188	1.57E-02	0.086	7.18E-03	0.071	5.88E-03
8	-0.057	-3.17E-03	-0.051	-2.82E-03	-0.028	-1.53E-03
9	-0.543	-8.75E-03	-0.369	-5.96E-03	-0.356	-5.74E-03
10	-0.003	-3.22E-05	-0.023	-2.38E-04	0.043	4.53E-04
11	-0.094	-4.95E-03	-0.077	-4.07E-03	-0.095	-5.03E-03
12	0.202	3.68E-03	-	-	0.281	5.12E-03
13	-0.787	-4.52E-03	-0.963	-5.53E-03	-0.533	-3.06E-03
14	-0.346	-1.28E-02	-0.279	-1.03E-02	-0.094	-3.47E-03
15	-0.017	-6.14E-04	0.167	6.19E-03	0.231	8.57E-03
16	-0.195	-1.17E-03	-0.180	-1.08E-03	-0.107	-6.41E-04
17	0.071	2.01E-03	0.050	1.44E-03	0.070	2.01E-03
18	-0.970	-7.89E-03	-0.751	-6.11E-03	-0.429	-3.48E-03
19	-0.288	-1.59E-03	-0.178	-9.82E-04	-0.130	-7.17E-04
Average		**-2.97E-03**		**-2.83E-03**		**-1.71E-04**

The calculations of the efficiency loss using the second method, presented in methodology 3.4.2(II), are presented in Table 4.10. The efficiency loss was $\Delta\eta$/DP and $\Delta\eta$ in this method was calculated by the difference in the average efficiency of a week following a rainfall event and the average efficiency of the week previous to the next rainfall event.

Table 4.19 - Efficiency Losses for Different Rainfall Events for Different UNLV Solar Plants Calculated Using the Efficiency of the Week Following (η_f) a Rainfall Event and the Week Previous (η_p) to the Next Rainfall Event Using Method II

From Event #	**To Event #**	**DP**	**Student Union**		**Dayton Hall**		**CBC-C**	
			Δη (%)	**Efficiency Loss (% / day)**	**Δη (%)**	**Efficiency Loss (% / day)**	**Δη (%)**	**Efficiency Loss (% / day)**
1	2	36	-0.136	-3.78E-03	-0.186	-5.16E-03	-	-
2	3	125	-0.001	-6.55E-06	0.568	4.55E-03	-0.039	-3.15E-04
3	4	43	-0.261	-6.06E-03	-0.402	-9.35E-03	-0.052	-1.21E-03
4	5	171	-0.584	-3.41E-03	-0.804	-4.70E-03	-	-
5	6	53	-0.133	-2.51E-03	0.035	6.66E-04	-	-
8	9	62	-1.200	-1.94E-02	-0.615	-9.91E-03	-0.309	-4.99E-03
9	10	95	0.224	2.36E-03	-0.302	-3.18E-03	0.036	3.81E-04
11	12	55	-0.006	-1.10E-04	-	-	0.100	1.81E-03
12	13	174	-0.118	-6.76E-04	-	-	-0.129	-7.44E-04
13	14	27	-0.586	-2.17E-02	-0.399	-1.48E-02	-0.189	-6.99E-03
14	15	27	-0.280	-1.04E-02	-0.170	-6.30E-03	0.092	3.41E-03
15	16	167	-0.455	-2.72E-03	-0.619	-3.70E-03	-0.073	-4.37E-04
16	17	35	0.224	6.39E-03	0.262	7.49E-03	0.079	2.24E-03
17	18	123	-0.098	-7.98E-04	-0.005	-3.96E-05	-0.266	-2.17E-03
18	19	181	-0.965	-5.33E-03	-1.239	-6.85E-03	-0.299	-1.65E-03
19	20	143	-	-	0.104	7.31E-04	-0.434	-3.04E-03
Average				**-4.54E-03**		**-3.61E-03**		**-1.05E-03**

The efficiency loss due to soiling, calculated according methodology 3.4.2(III), are shown in Table 4.11. The values of the efficiency loss were the same value as the slopes for the efficiency trendline between those determined rainfall events. All the graphs, and their trendlines with the equations, are shown in Appendix G. For all the graphs there was a poor fit of the trendline, R^2 varied from 0.0002 to 0.7609. This poor fit was due to the large variation on efficiency values from one day to the other. That is why the average loss was calculated; to have a better estimate of the overall loss when comparing different methods and different sites.

Table 4.20 – Efficiency Losses for Different Rainfall Events for Different UNLV Solar Plants Calculated Using the Efficiency Trendline Slope Using Method III

From Event #	To Event #	DP	Student Union	Dayton Hall	CBC-C
			Efficiency Loss (% / day)	**Efficiency Loss (% / day)**	**Efficiency Loss (% / day)**
1	2	36	-4.50E-03	-1.80E-03	-
2	3	125	1.00E-03	2.20E-03	-2.70E-03
3	4	43	-1.06E-02	-1.47E-02	-7.00E-04
4	5	171	-3.20E-03	-4.20E-03	-1.60E-03
5	6	53	-2.00E-04	4.20E-03	-
8	9	62	-2.58E-02	-1.41E-02	-8.70E-03
9	10	95	2.40E-03	-3.40E-03	-1.40E-03
11	12	55	-1.40E-03	-	6.00E-04
12	13	174	2.00E-04	2.80E-03	-5.00E-04
13	14	27	-2.86E-02	-1.97E-02	-8.60E-03
14	15	27	-1.39E-02	-1.01E-02	3.90E-03
15	16	167	-4.10E-03	-5.30E-03	-1.50E-03
16	17	35	1.07E-02	8.40E-03	2.20E-03
17	18	123	-1.50E-03	1.00E-04	-2.90E-03
18	19	181	-4.30E-03	-6.40E-03	-1.30E-03
19	20	143	-	4.00E-03	-1.30E-03
Average			**-5.59E-03**	**-3.87E-03**	**-1.75E-03**

The data in Table 4.11 indicate that, although the efficiency loss varies within the different dry periods, the average loss is very similar for all the solar plants studies in all the different ways calculated. This was expected because each dry period has different characteristics. Only rainfalls over 0.2 inches were analyzed in this part, however, there were rainfall events that may have occurred and were less than 0.2 inches and influenced the soiling/cleaning of the plants.

There is also a variance in the efficiency loss values when the same rainfall is analyzed by different methods. One of the reasons could be because each method has its own assumptions. The method using the efficiency of the week before (η_b) and the week after (η_a) a rainfall event assumes that the panels were equally clean on the start of the dry period and after the rainfall event and uses smaller amount of data. The method using the efficiency of the week following (η_f) a rainfall event and the week previous (η_p) to the next rainfall event also uses a smaller amount of data and assumes that following a rainfall event the panels would be clean. Finally, the method using linear regression also assumes that the panels are clean after a rainfall event and it takes into consideration the predicted values of efficiency by the trendline which did not describe the actual efficiency very well due to the low values of R^2.

The average efficiency loss for each plant using the different methods are summarized in Table 4.12. An overall average efficiency loss was calculated for each plant by using the values of efficiency loss obtained through the different methods (shown in column Overall Loss).

Table 4.21 – Summary of Efficiency Loss Values Found Using the Different Methods and the Overall Efficiency Loss for Each Plant

	Method: η_b **and** η_a	**Method:** η_p **and** η_f	**Method: Slope**	**Overall Loss (% / day)**
	Average Loss (% / day)	**Average Loss (% / day)**	**Average Loss (% / day)**	
SU	-2.97E-03	-4.54E-03	-5.59E-03	-4.36E-03
Dayton	-2.83E-03	-3.61E-03	-3.87E-03	-3.44E-03
CBC-C	-1.71E-04	-1.05E-03	-1.75E-03	-9.91E-04

Average losses were -0.00436%/day, -0.00344 and -0.000991 respectively for SU, Dayton, and CBC-C plants. Only the average efficiency loss for CBC-C plant, calculated using η_b and η_a, was an order of magnitude lower than the averages found for the other two plants.

The results also show that soiling did not seem to have a great impact on the efficiency of the panels when the efficiency of each system was plotted over time. During the dry periods, there was not a visible decrease in efficiency, showing that soiling does not impact the efficiency significantly, contrary to what was presented in Kimber et al. (2006) for the plants she studied. The efficiency data can be found in Appendix H. When comparing to solar panels located in the Middle East, the soiling efficiency loss observed in this study was much lower. Soiling has a greater impact in the efficiency loss in the Middle East since there is higher humidity, high occurrence of dust storms and higher dust intensity in that region when compared to Nevada, United States (Maghami et al., 2016; Rehman & El-Amin, 2012). Some studies conducted in the Middle East found up to 89% reduction in efficiency due to soiling (Rajput & Sudhakar, 2013).

The efficiency losses due to soiling, in the range from -0.000171/day to 0.00559/day, were relatively higher than the ones found in a study conducted by Mejia et al. (2013) in California. They found an average loss of 0.0005/day and 26% of the systems had losses higher than 0.1/ day. However, most sites had solar panels with tilt angles higher than 5°. For the sites where the tilt angle was 5° or lower, the mean soiling losses were around 0.0018/day which is similar to the losses found in this study. There is larger dust deposition with lower tilt angles as it has been demonstrated in previous study (Cano, 2011). Lower tilt angles favor the accumulation of dust on the panels. One of the reasons is that one of the parameters that influence the dust accumulation is the gravitational effect (Qasem et al., 2014). For the panels with tilt <5°, 50% of the sites had soiling higher than 0.1/day, which is much higher than the losses found in this study. None of the sites studied had soiling losses as high as 0.1/day. Even with higher losses, the authors determined that it was not economically worthwhile washing those solar systems (Cano, 2011).

The objective of the part of the research described above was to calculate how much efficiency was lost due to soiling during the dry periods. It was noticed that the efficiency loss varied within different building and depeding on the method used to calculate. However, in all the cases the average loss of efficiency was not very high. For the plant in Student Union the average overall loss was about 0.0044%/day. Similarly, the overall loss for the plant in Dayton Hall was 0.0034%/day. CBC-C’s plant was the one that showed the lesser overall loss of only 0.00099%/day. Comparing to solar plants located in California with similar tilt angles, the values obtained were close (Mejia et al., 2013).

4.2. Soiling Rate over the Years

To evaluate the performance of the plants assuming they were always operating at their optimal efficiency and to better observe how the rainfall events impacted the soiling rates, the expected efficiency of the panels (as if they were always clean) was calculated (Figure 4.5). Data from 4.5 years and three plants were used. The dotted line (blue) is the efficiency trendline over the years and its slope, which represents the overall decrease in efficiency, was assumed to be the degradation of the panels over time. The 30 highest efficiency points were selected, and an average was calculated. This method was chosen as a way to eliminate any outliers and to give a more representative value than the single highest efficiency point. And another line with the same slope as the trendline, was found using the average efficiency data point computed. That line was plotted (red/dashed line). The predicted efficiency of the plants, assuming they were operating in their best condition and always as clean as when they started operating, was assumed to be near that new trendline. The soiling of the panels was considered to be the difference between the new efficiency and the real efficiency. The same process was used to find the solid line (yellow). However, the point used to find the equation for that line was the efficiency of the period after the intense rainfall (1.18 in) that occurred on 01/09/18. Figure 4.5 shows the real efficiency of the panels and the calculated new trendlines for the Student Union Plant. The global horizontal irradiance was also plotted to observe the variations thought out the years and how that may have also impacted the change in efficiency.

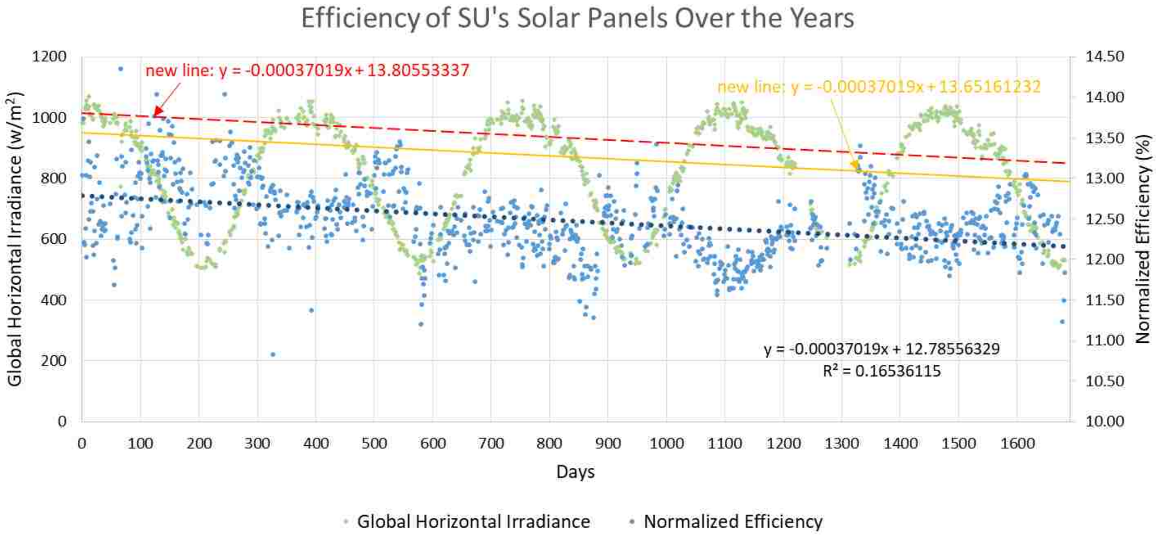


Figure 4.12 – Normalized Efficiency of Student Union's Panels and its Trendlines and Global Horizontal Irradiance. All Trendlines are Based on the Normalized Efficiency

Since both new trendlines are close to each other, the rainfall on 01/09/18 restored, almost completely, the efficiency of the panels. The soiling rates, computed as the difference between the theoretical efficiency and the real efficiency, are shown in Figure 4.6 below.

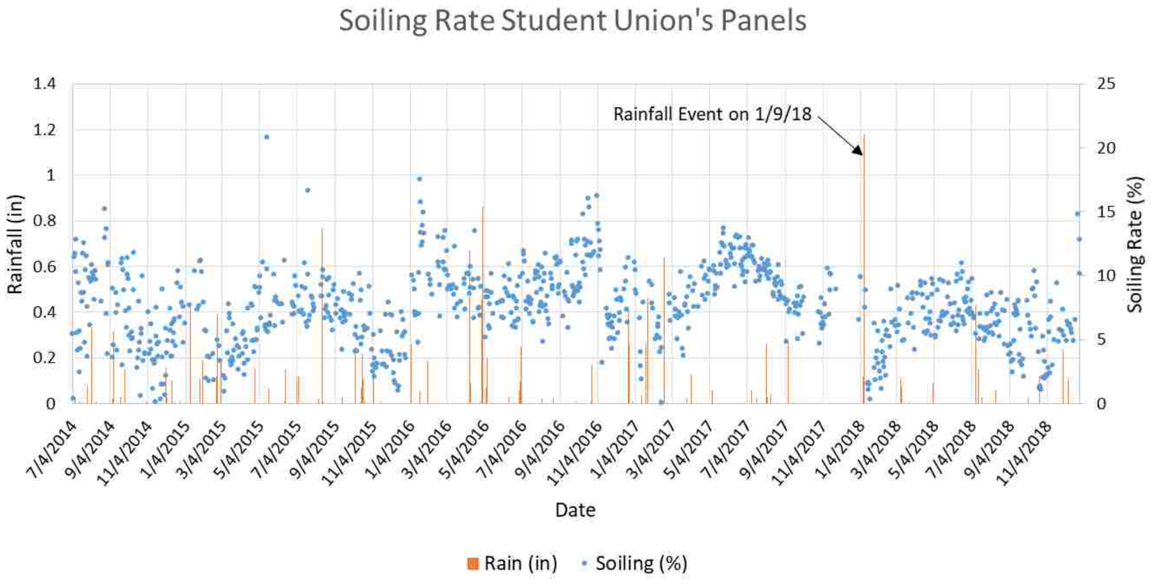


Figure 4.13 – Soiling Rate of Student Union's Panels

It is possible to observe that the soiling rates were as high as 20% at one point. However, throughout the year the 80% of the soiling rates were in the range from 0 to 10%. The average soiling rate when all the points were taken into account was about 7.5%.

The same process was followed for the solar panels on Dayton Hall and CBC-C. Figures 4.7 and 4.8 show the efficiency and soiling rates, respectively, for CBC-C.

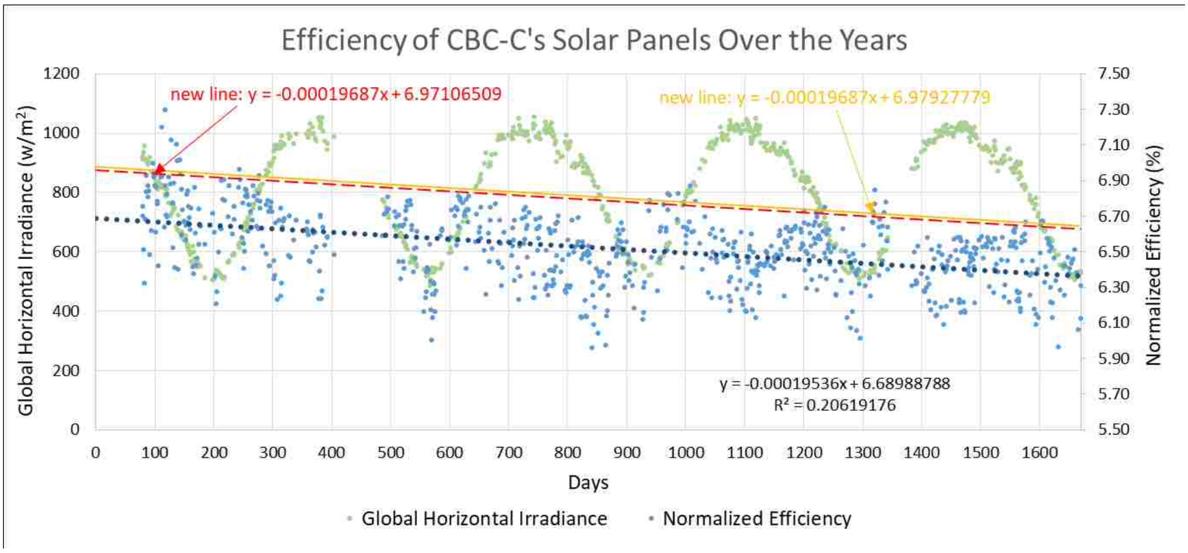


Figure 4.14 – Normalized Efficiency of CBC-C's Panels and its Trendlines and Global Horizontal Irradiance. All Trendlines are Based on the Normalized Efficiency

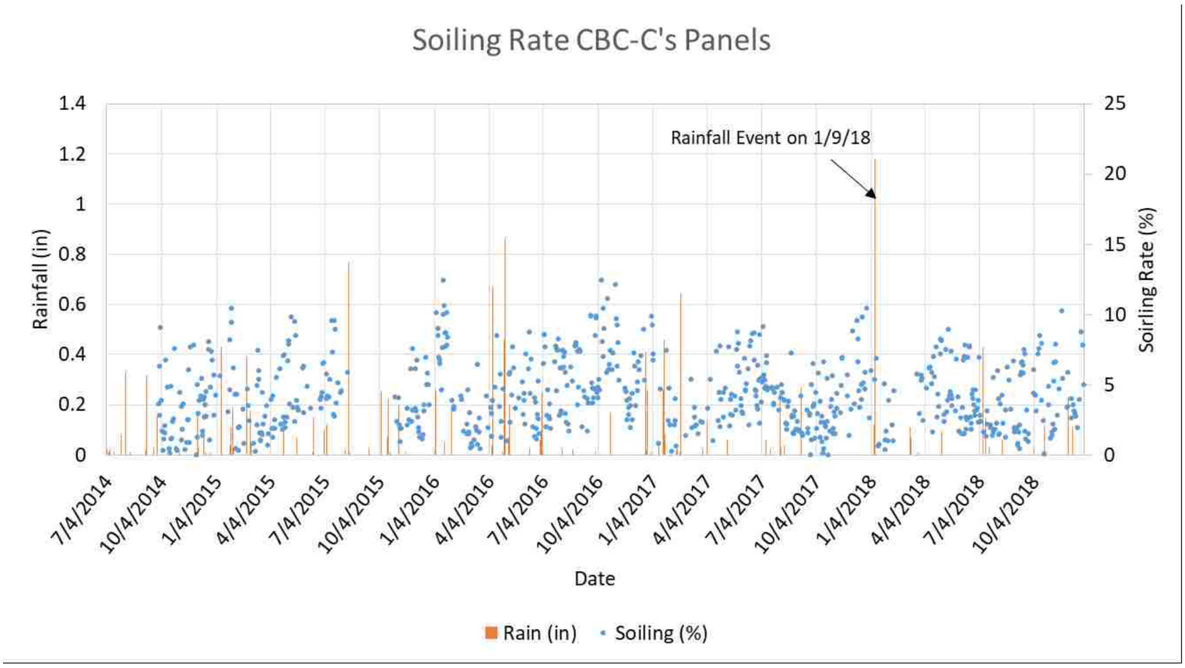


Figure 4.15 – Soiling Rate of CBC-C's Panels

Figures 4.9 and 4.10 show the efficiency and soiling rates, respectively, for Dayton Hall' PV panels.

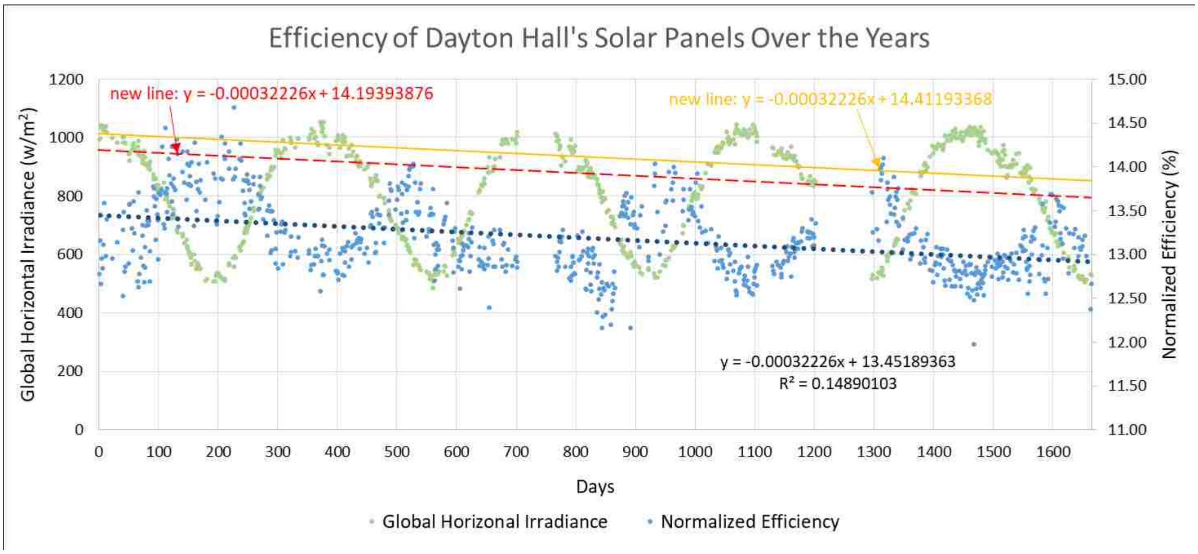


Figure 4.16- Normalized Efficiency of Dayton Hall's Panels and its Trendlines and Global Horizontal Irradiance. All Trendlines are Based on the Normalized Efficiency

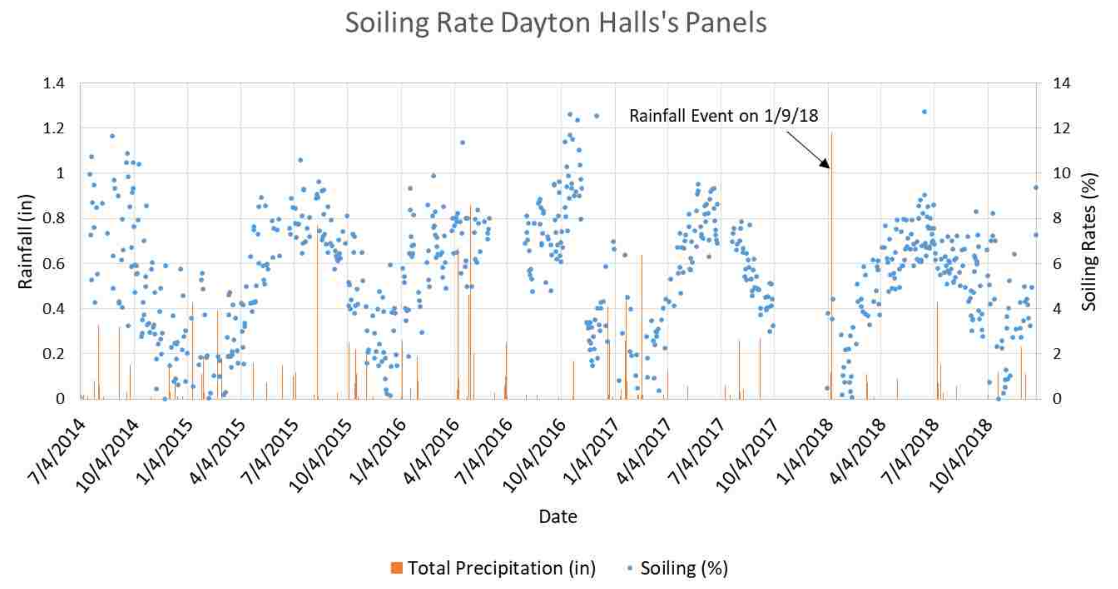


Figure 4.17 - Soiling Rate of Dayton Hall's Panels

For Figures 4.5, 4.7 and 4.9, all trendlines are based on the normalized efficiency. The black line is based on calculated efficiency, the yellow line and red line are alternative projected efficiencies from different days when panels were considered clean.

For CBC-C's plant, the soiling rates reached up to 12% in a few of the days, however only 1% of the time, the soiling rate was higher than 10%. The average soiling rate was about

4.1% for this plant. When looking into Dayton Hall's data, 98% of the time the soiling rates were in the range from 0-10%, and the average was about 5.3%.

Those values of soiling rates are higher than expected because the actual efficiency is being compared to a theoretical efficiency calculated based on ideal cleanliness. The higher rates are also due to the fact that the tilt angle of the panels are very low in all the plants, which is prone to more soiling. Cano (2011) investigated the effects of the tilt angles on solar panels and determined that smaller angles caused higher losses due soiling.

It is possible to observe a pattern; in most of the cases the soiling rate decreases after a rainfall event (Figures 4.6, 4.8 and 4.10). The 1.2-inch rainfall event that happened on 1/9/18 shows this effect most clearly. The soiling rates dropped close to zero after this rainfall, but they start building up right after the rainfall.

However, it is not possible to attribute the change in efficiency only to soiling losses. Even though the normalized efficiency was calculated to try to eliminate all the other parameters influencing the change in efficiency, it seems that there are still impacts from other factors on the normalized efficiency.

One of the factors contributing to the change of efficiency seems to be seasonal effects. As it is possible to observe in Figures 4.5, 4.7 and 4.9, the global horizontal irradiance varies throughout the year. Solar irradiation is dependent on the sun's position during the day and also over the year. How much solar energy reaches a surface area is dependent upon the angle of the Earth's surface in relation to the Sun. During summer months, the irradiation is higher because the Sun is located directly overhead, reaching the Earth closer to a 90° elevation above the horizon (Nelson & Starcher, 2016b). Although the calculated efficiency aimed to remove the seasonal differences in irradiance, it seems that there were still some seasonal effects taking place, as the normalized efficiency varies during summer and winter along with irradiance.

Another factor that could also be influencing the observed variations in the normalized efficiency is the fact that the sensors in the UNLV weather station, from which the weather data were obtained (direct normal irradiance (DNI) and global horizontal irradiance (GHI), temperature and wind speed), were not maintained and cleaned regularly. Consequently, it is possible that those values are not completely accurate, leading to a different calculated value for the normalized efficiency.

Therefore, some of the efficiency decrease can be attributed to soiling losses but not all of it. In this research, it was not possible to separate only the soiling from other factors.

4.3. Evaluation of Washing Effects

4.3.1. Cost Evaluation and Analysis of the Impact of Panel Washing on the Efficiency of the UNLV Student Union Solar Plant

The economic feasibility of washing the panels of a solar plant depends on the cost of washing the panels, the loss in energy due to soiling, the price of electricity, and net metering rates. In this portion of the research, the impact and cost of panel washing on solar energy generation recovery was investigate. To accomplish this objective, The UNLV Student Union solar plant has been was washed on 8/27/18. The last significant rainfall (>0.2 in) occurred 49 days prior to the washing. Figure 4.11 shows the solar panels on Student Union on the day that they were washed.

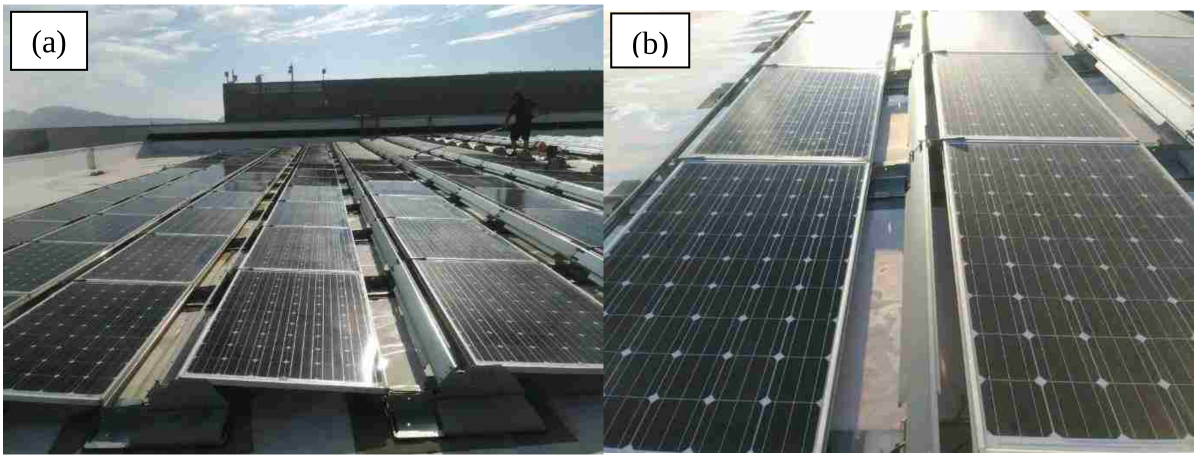


Figure 4.18 – (a) Solar Panels on Student Union Being Washed by a Professional Cleaning Company; (b) Solar Panels that Were Washed (left) Compared to the Unwashed Panels (right)

To evaluate if washing is worthwhile in terms of cost, two types of analyses were performed. The first one was the comparison of the power output increase of the Student Union's plant from the day before and after the washing. Since power output varies daily and is dependent on several factors such as temperature and sun irradiation, a control source was used. The control was the power output from the solar panels locates on Beam Hall which is adjacent to SU. Those panels had the same specifications and electrical connections as SU's. However, the panels in Beam Hall were not washed. Figures 4.12 and 4.13 show the power output for both sites for the sunny day before and after nearest to the washing date.

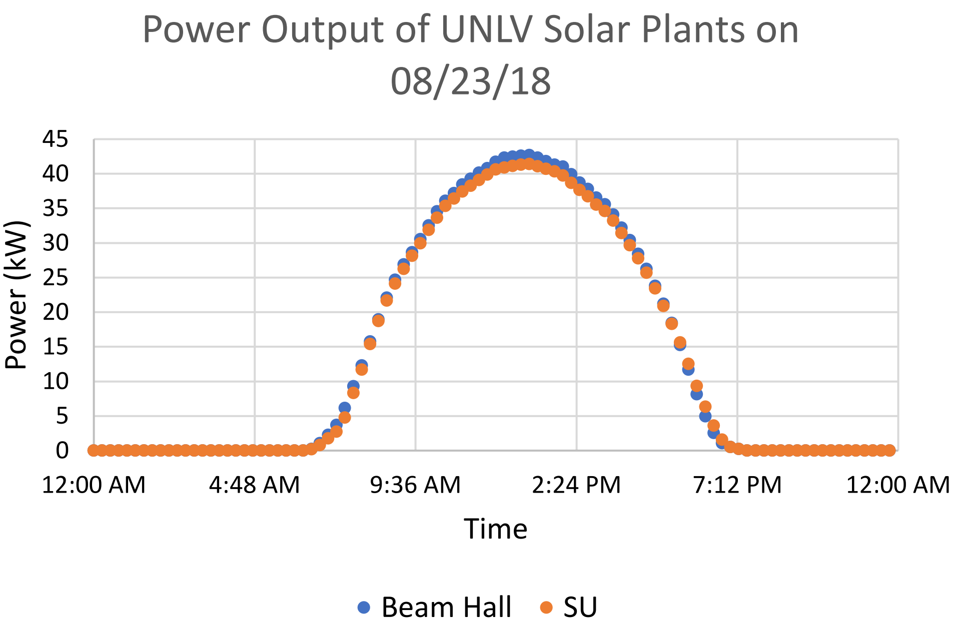


Figure 4.19 – Power Output for the Panels Located on Beam Hall and SU on the Nearest Sunny Day Before the Washing

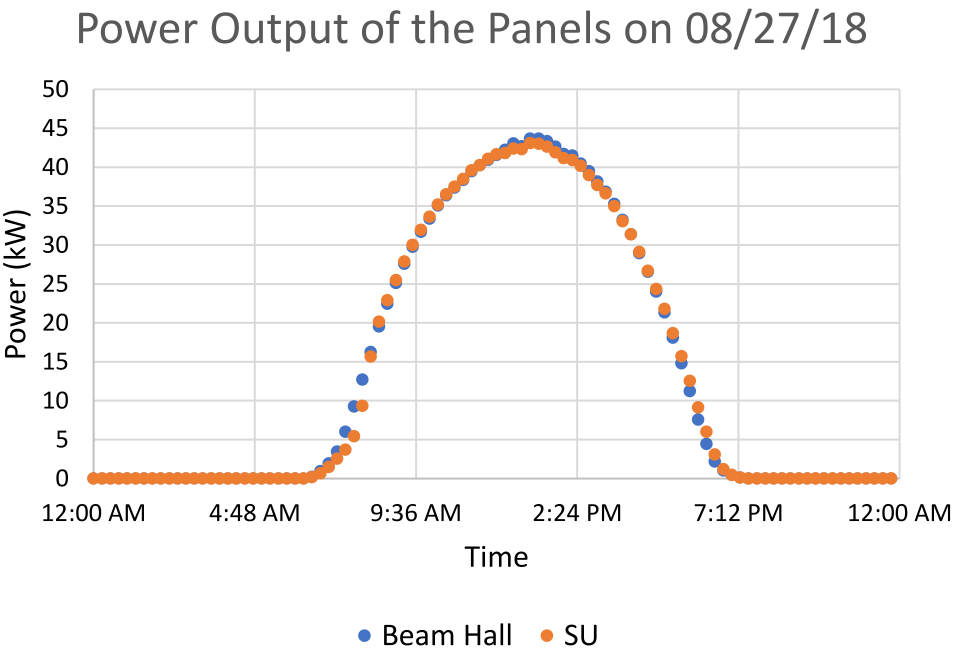


Figure 4.20 - Power Output for the Panels Located on Beam Hall and SU on the Nearest Sunny Day After the Washing

Visually, it is possible to observe the slightest decrease in the difference between the panels on SU and Beam Hall after the ones on SU were washed. This difference was computed in order to observe the actual increase in power output due to washing the panels. The results are shown in Table 4.13

Table 4.22 – Increase in Power Output in SU by Analyzing the Power Output from the Panels on SU and Comparing to the Panels on Beam Hall

	kWh Produced		**Percent Difference**	**Additional Power Obtained in SU**
	8/23/2018	**8/27/2018**		
Beam Hall	331.87	337.23	1.62%	1.82%
Student Union	324.23	335.36	3.43%	

There was only an increase of 1.82% in the power output for the solar panels in Student Union. If taken into consideration the amount of energy that the panels produced on 8/23/18, this would mean an increase in about 5.90 kWh. Figure 4.14 shows the price for the kWh in Southern Nevada.

Southern Nevada

Residential: **$0.11171** / kWh

Small Business: **$0.06934** / kWh

Effective: 4/1/2019 - 6/30/2019

Figure 4.21 – Price of Energy in Southern Nevada (NV Energy, 2019)

This increase in power output would result in only $0.40 cents a day. In a scenario where the solar panels would remain as clean as they were when washed and the increase in power output would be constant all the time, it would take over 3,000 days to pay off the cost of washing ($1,272.00). However, the panels start getting soiled immediately and it is expected to have lower and lower efficiencies until the next rainfall event, therefore it is likely that this increase in power output will only happen in the next few days after washing. The panels will then start getting soiled again and the power production will decrease.

It was found earlier in this research that a rainfall of 0.2 inches or more would partially restore efficiency of the panels. The solar panels on Student Union had a 49-day dry period (without rainfall over 0.2 inches) prior to the date of washing. While this does not seem like a long time for soil build-up, there were not found to be many periods with more than 49 days without a 0.2-inch rainfall in Las Vegas. From the rainfall events analyzed from the time period studied (2014-2018), the probability of a rainfall larger than 0.2 inches occurring within 49 days is 70%. The average dry period between rainfall events of 0.2 inches or larger is about 42 days, for the rainfall events analyzed. Therefore, it is likely that within 42 days, the efficiency would be partially restored by rainfall.

When the last 29 years (1990-2018) of rainfall data were taken into consideration, the return period calculated for a rainfall depth of 0.2 inches or higher was approximately 52 days. Which means that in Las Vegas area near UNLV, it is expected that every 52 days there will be a rainfall event of at least 0.2 inches depth. Therefore, this is considered to be the longest period for soiling buildup on the solar panels and every 52 days some of the efficiency of the panels are expected to be recovered.

The other method used to evaluate the effects of washing on the solar panels was to analyze the efficiency in the whole data set, as it was performed on Part 4.2. The trendline for the efficiency data set was found and a new line equation was computed with the same slope as the trendline but passing through the efficiency point of the day after the panels were washed. Considering that the panels would always be as clean as that day, new efficiency values we obtained from the new line (Figure 4.15).

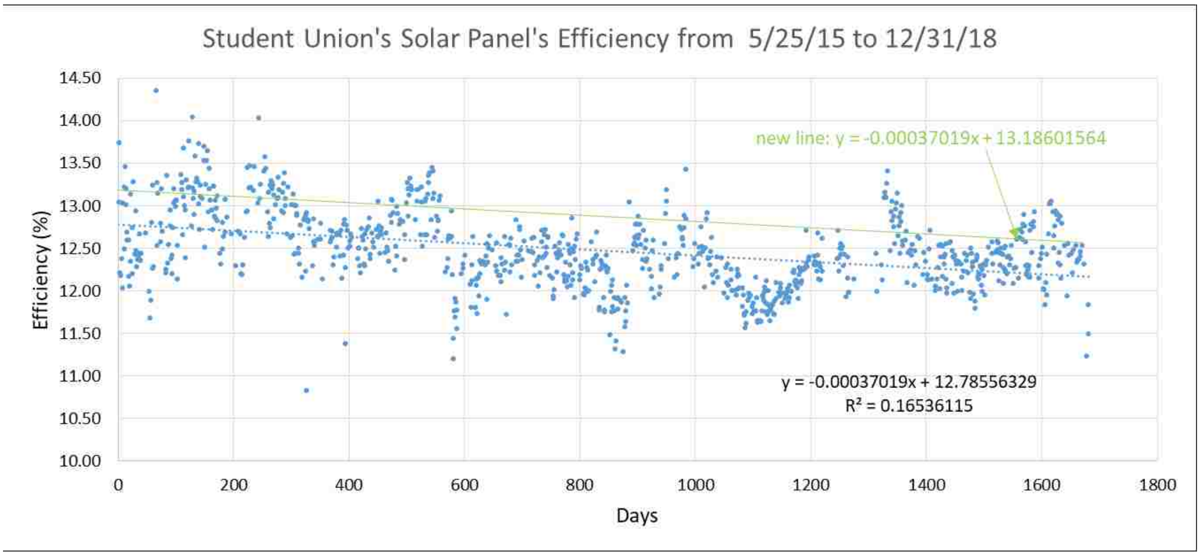


Figure 4.22 – New Trendline Obtained Considering the Panels were Always as Clean as the Day After They Were Washed

The theoretical efficiencies were converted into power output values, using the parameters of POA and cell temperature (following equations presented under methodology for the efficiency calculations). These theoretical power output values were obtained for the whole data set (since the panels were installed on 05/25/14 to 12/31/18). The average increase on power output between the theoretical and actual power output were ~6%. The value found here was slightly higher than the one found using the previous method (~2%). One of the reasons could be due to the fact that, in this method, the power output analyzed was only from 11am to 1 pm, when there is the largest production. The difference between the theoretical and actual power output would probably be lower if the whole day was taken into consideration. The values found for soiling losses in power output are similar to the ones predicted by the model developed by Kimber (2007), of over 4% in the Desert Southwest/Las Vegas.

Other authors have performed research on the impacts of panel washing on solar energy efficiency in the Southwest of the United States. Some authors found that tit is not worthwhile washing solar panels. Kimber (2007) analyzed three sets of solar panels located in Southern California, and each one had a capacity of around 100 kW (the ones at UNLV have a capacity around 60 kW). The cost of washing each of their systems was $800 dollars compared to $1,272.00 which was the cost to wash the UNLV system with a total capacity of 61 kW. The author determined that washing was not worthwhile at the current energy cost.

On areas were dust deposition is higher, in the Middle East for example, it is recommended cleaning of the panels. Al-Sabounchi et al. (2013) recommended monthly cleaning on solar panels located in Abu Dhabi, for reasonable performance. In Cyprus, authors recommend cleaning on a 2-3 week basis due to high losses in performance caused by soiling (Kalogirou et al., 2013).

The goal of the evaluation discussed above was to evaluate if washing the panels from UNLV's solar plants was worthwhile. There was not a significant increase in power production when the panels were washed by a professional company. The extra power output obtained was not enough to offset the washing cost of six dollars per panel. Similar studies conducted in the southwest of the United States also observed that it is not worthwhile washing solar panels (Adrianne Kimber, 2007; F. A. Mejia & Kleissl, 2013b).

4.3.2. Results on the Survey Conducted on Small Scale Solar Plants in Las Vegas

A total of 166 establishments were identified to have solar panels installed on their properties. However, it was only possible to obtain response from 96 establishments. The plants' capacity varied from 8.875 kW to 1,122 kW.

The major interest was to find out if small scale solar plants have been washing their panels. Figure 4.16 shows what those establishments answered.

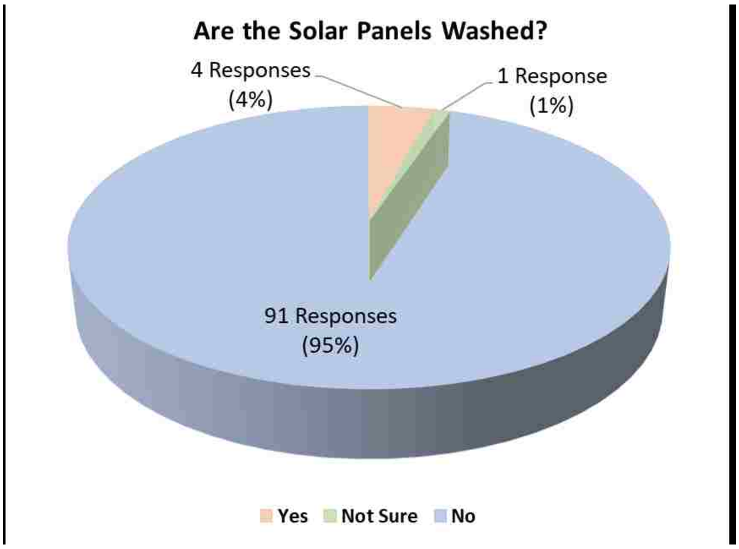


Figure 4.23 – Answers from Survey Regarding the Cleaning of Solar Panels

Among the four plants that do wash their solar panels, two of them answered that they wash once a year, one of them said they wash bi-annually and another said they only washed once. Two of the plants that wash their panels hires a professional company to clean them, the other two of them just use in house staff to hose down the panels with tap water.

It was also noticed that most places that has solar panels installed, the maintenance is responsibility of a third party hired to take care of the panels.

The City of Las Vegas manages solar panels installed on 40 different buildings across the city, with a total capacity of 6,118 kW. A person that was responsible for the solar plants' planning and construction, and also responsible for their maintenance, was the one that answered the questionnaire for those plants.

When asked if they had ever washed the panels of their solar plants, the following answer was obtained:

"No. We contracted an Engineering Firm for the attached retro-commissioning and report of the City's solar installations. CLV Operations and Maintenance staff use the maintenance recommendations detailed in the report (WPCF excluded, as well as a few installations that the installer maintains as a part of a PPA). It was recommended that cleaning the panels was not a cost-effective ongoing use of funds – any change in performance would be negligible. We've also had a few other University of Nevada and UNLV researchers look into cleaning panels and the conclusion was again that there was no need to do additional cleaning in an effort to improve performance – when it does rain, that's just as effective at cleaning panels as hosing them down.".

Chapter 5 – Conclusions, Limitations and Recommendations for Future Research

5.1. Conclusions

This study aimed to use the solar panels located on building rooftops at the University of Nevada, Las Vegas, as a case study to observe the efficiency loss due to soiling in rooftop PV systems. The efficiency change of the solar panels after a rainfall event was also analyzed to determine the minimum amount of rain necessary to at least partially recover PV panel efficiency. To better evaluate the effects of washing PV systems, a professional cleaning company was hired to wash the solar panels, and a cost analyses was performed.

The objectives of this research were a) to evaluate the effects of rainfall in the efficiency of solar panels and try to determine how much rainfall is necessary to recover, at least partial, efficiency of the panels b) to estimate the soiling rates during different dry periods in Las Vegas and observe how much efficiency was lost due to soiling; and c) to examine if it is worthwhile to wash distributed generation solar plants, taking the cost of washing into consideration. UNLV solar plants, from Student Union, Dayton Hall, CBC-C and Beam Hall, were used as a case study to address the objectives above. The following can be concluded from the results obtained:

1) When the efficiency of the plants was analyzed before and after rainfall events, it was possible to notice that small rainfalls (less than 0.2 inches) made the panels lose efficiency, on average. Rainfall events greater than 0.2 inches recovered part of the efficiency; the larger the rainfall event, the greater the increase in efficiency. The amount of rainfall necessary for efficiency recovery varies from region to region, as it is dependent on several factors, including the weather, amount of dust on the panels, dust characteristics, and tilt angle. In regions where the panels become completely covered with dust, for example in

the Middle East where there are dust storms that generate higher dust deposition rates, different rainfall magnitudes may be needed to recover efficiency.

Rainfall data were also analyzed from the last 29 years near UNLV. A median (50th percentile) recurrence interval of 52 days was found for rainfall events of depth of 0.2 inches or higher. Therefore, it is expected that approximately, every 52 days there will be a rainfall depth that is large enough to be able to restore some of the solar panel's efficiency.

2) The efficiency loss due to soiling was calculated by three different methods for three UNLV solar plants. The average efficiency loss for each plant were: Student Union: -0.0044%/day, CBC-C: -0.00099%/day, and Dayton Hall: -0.0034%/day. The efficiency loss for the UNLV solar plants was similar to that found for solar plants located in desert areas in California, with the same tilt angles as the ones at UNLV. However, the efficiency change of could not be attributed only to the soiling of the panels because there seemed to be other factors impacting it, the major one being the seasonal effects.

3) For one of the UNLV solar plants (Student Union) washed by a professional panel cleaning company, when the the efficiencies of the sunny day before and after the SU's plant were compared to that of an unwashed plant (Beam Hall), there was only an increase of 1.82% of the power output from the SU's plant after it was washed. A prediction of the power output is that, if the solar panels always operated in the conditions as when they were cleaned, showed a 6% increase from the real power ouput. It was then determined that the revenue increase from an increase in generate power as a result of washing the solar panels does not offset the five dollar washing cost per panel.

However, in the future, there might be an increase in the price of energy or an increase in the efficiency of solar cells, resulting in higher revenue or a decrease in the costs of washing per panel water resulting in lower cost, resulting in a revised economic analysis indicating that it might be worthwhile to wash the panels. Additionally, when a survey was conducted in Las Vegas on all commercial establishemnts that have solar panels installed, the majority (95% of the places) stated that they do not wash their solar systems at the present time.

5.2. Limitations of the Research

There were some limitations to this research. One of the limitations was that the parameters necessary to calculate the normalized efficiency for the solar panels (plane of array and cell temperature) were not measured on site. Therefore, a software package was used to model those parameters. However, there could be errors associated with those calculations that would not be present if the needed parameters had been measured.

Another limitation was the fact that, even though normalized efficiency was calculated, it did not seem possible to atribute the change in efficiency only to soiling. When evaluating the efficiency data throughout the years, it was possible to notice seasonal effects infuencing the obtained values.

In this research, the soiling load (g/m^2) on the solar panels were not measured. In addition, there was no particle characterization (determination of size, shape, color, etc.). Therefore, it was not possible to correlate the efficiency losses to the soiling load. Those are important parameters to be measured due to the reason that dust loadings can vary greatly from location to location, as they are dependent on factors such as construction activities, wind blown dust from disturbed vacant lands, and roadway particulate emissions. Consequently, it is important to know where the dust on the panels is primarly coming from, which was not determined in this research.

This research also did not employ a set of solar panels that could be used as a control set. A control set of solar panels would help minimize the seasonal effects and give more exact information on soiling losses.

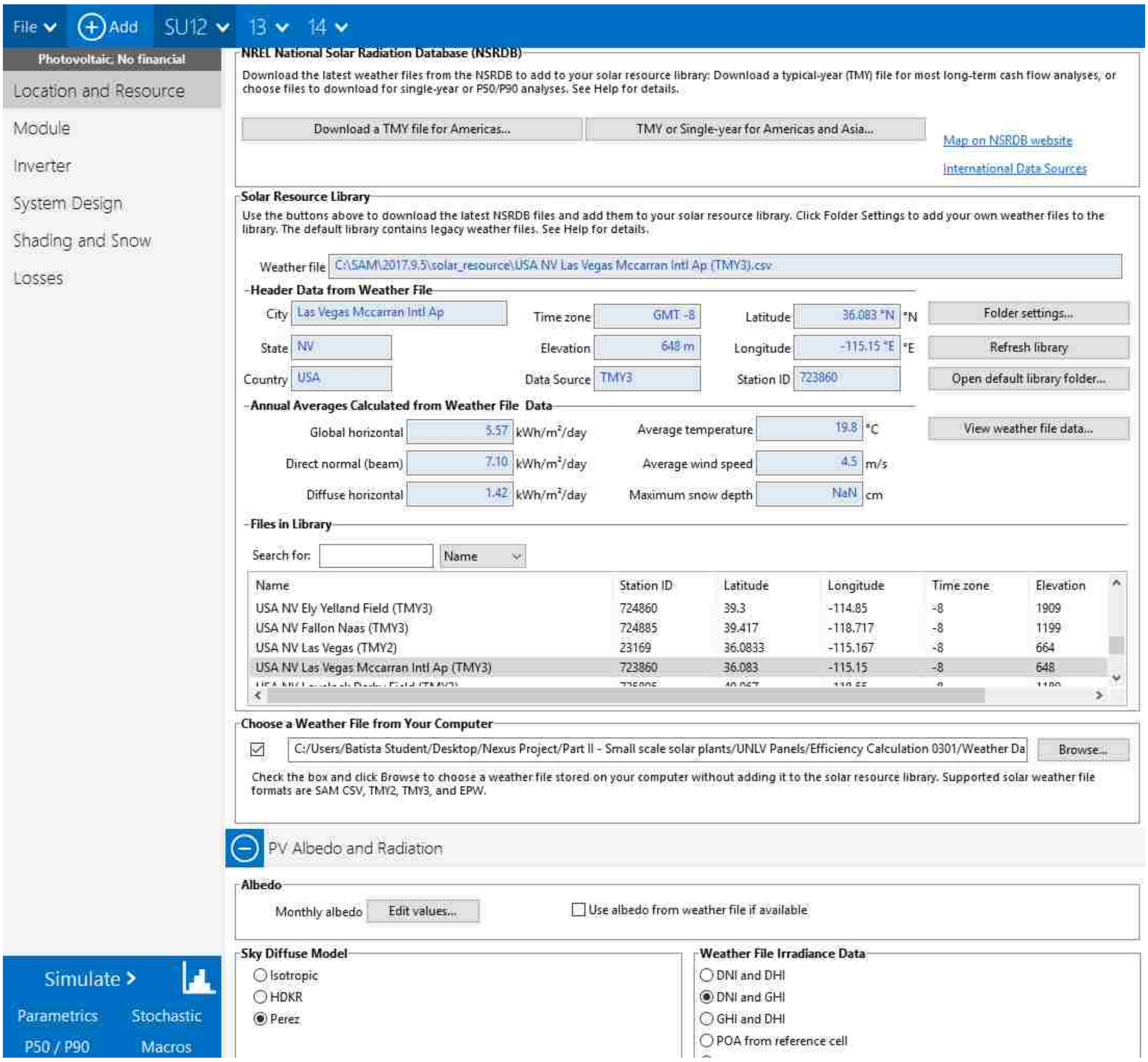
5.2. Recommendations for Future Research

This research only studied solar panels located in one part of Las Vegas. For future work, it would be interesting to analyze the rainfall effects on efficiency recovery on solar panels located in other places that have a climate similar to Las Vegas but might have different dust deposition rates or different critical rainfall depth recurrence intervals. In such research, it would be possible to observe what is the threshold necessary to restore at least a partial efficiency gain, and to determine if the critical rainfall depth is similar to the 0.2 inches observed for this area.

In future research, in order to minimize errors, it is highly recommended that all the parameters needed for the efficiency calculations should be measured on site. Also, having a set of solar panels that are always cleaned, to be used as a control, is also recommended. This way, it is possible to have a more exact estimate of soiling losses. When both sets (experimental and control) are identical and submitted to the same weather variations, but one is clean and the other is getting naturally soiled, then the difference in efficiency can be solely attributed to soiling.

Appendix A

Screenshots taken from the modeling program SAM. The screenshot presented were from the modeled panels of Student Union. For the other sites the same program was used and the only parameters that varied were the tilt angle of the panels and the azimuth angle, since those were different for each site. The panels on all building were electrically connected the same way, therefore there was no need to modify the other parameters.



NREL National Solar Radiation Database (NSRDB)

Download the latest weather files from the NSRDB to add to your solar resource library: Download a typical-year (TMY) file for most long-term cash flow analyses, or choose files to download for single-year or P50/P90 analyses. See Help for details.

Solar Resource Library

Use the buttons above to download the latest NSRDB files and add them to your solar resource library. Click Folder Settings to add your own weather files to the library. The default library contains legacy weather files. See Help for details.

Weather file: C:\SAM\2017.9.5\solar_resource\USA NV Las Vegas Mccarran Intl Ap (TMY3).csv

Header Data from Weather File

City: Las Vegas Mccarran Intl Ap
State: NV
Country: USA
Time zone: GMT -8
Elevation: 648 m
Data Source: TMY3
Latitude: 36.083 °N °N
Longitude: -115.15 °E °E
Station ID: 723860

Annual Averages Calculated from Weather File Data

Global horizontal: 5.57 kWh/m²/day
Direct normal (beam): 7.10 kWh/m²/day
Diffuse horizontal: 1.42 kWh/m²/day
Average temperature: 19.8 °C
Average wind speed: 4.5 m/s
Maximum snow depth: NaN cm

Files in Library

Search for: Name

Name	Station ID	Latitude	Longitude	Time zone	Elevation
USA NV Ely Yelland Field (TMY3)	724860	39.3	-114.85	-8	1909
USA NV Fallon Naas (TMY3)	724885	39.417	-118.717	-8	1199
USA NV Las Vegas (TMY2)	23169	36.0833	-115.167	-8	664
USA NV Las Vegas Mccarran Intl Ap (TMY3)	723860	36.083	-115.15	-8	648

Choose a Weather File from Your Computer

☑ C:/Users/Batista Student/Desktop/Nexus Project/Part II - Small scale solar plants/UNLV Panels/Efficiency Calculation 0301/Weather Da

Check the box and click Browse to choose a weather file stored on your computer without adding it to the solar resource library. Supported solar weather file formats are SAM CSV, TMY2, TMY3, and EPW.

Albedo

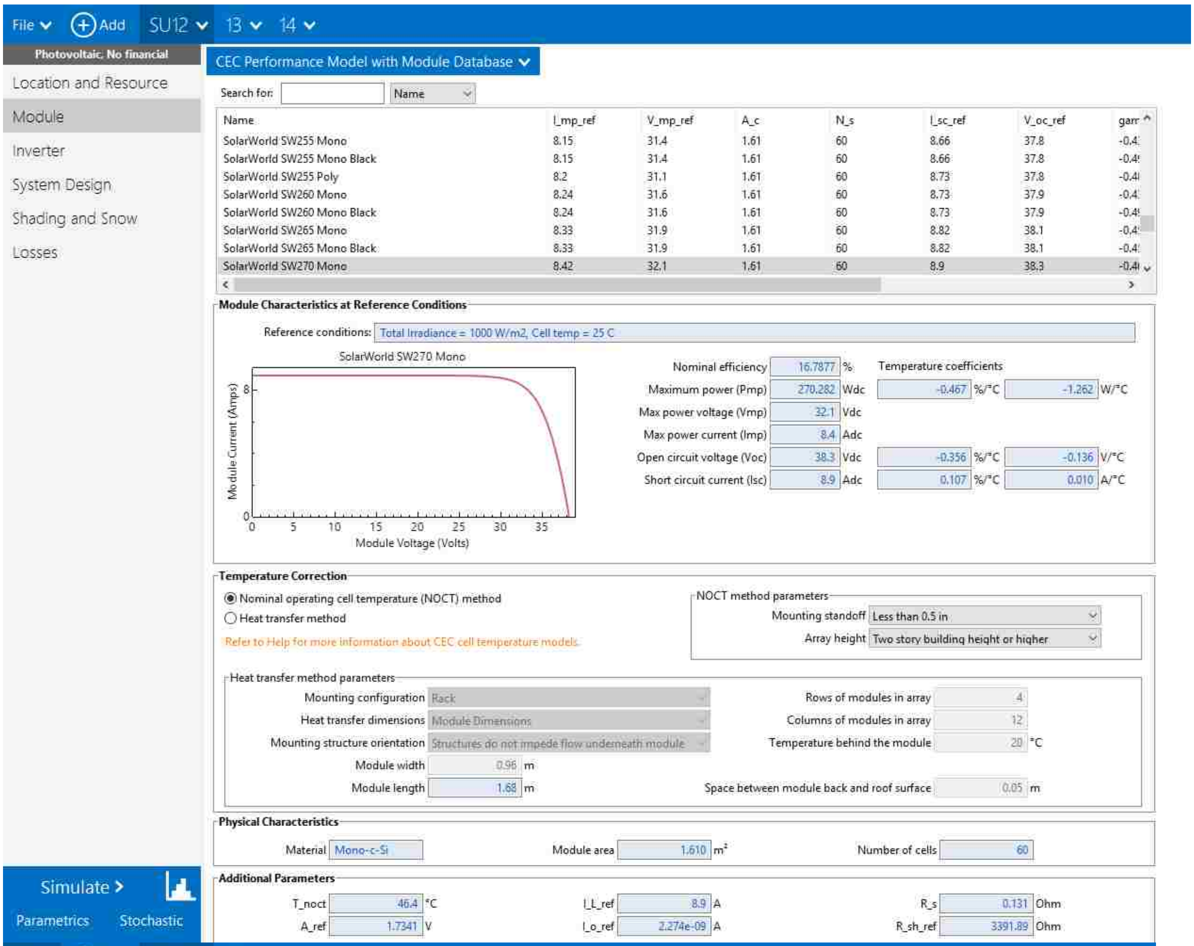
Monthly albedo
☐ Use albedo from weather file if available

Sky Diffuse Model

○ Isotropic
○ HDKR
● Perez

Weather File Irradiance Data

○ DNI and DHI
● DNI and GHI
○ GHI and DHI
○ POA from reference cell



CEC Performance Model with Module Database

Search for: Name

Name	I_mp_ref	V_mp_ref	A_c	N_s	I_sc_ref	V_oc_ref	garr
SolarWorld SW255 Mono	8.15	31.4	1.61	60	8.66	37.8	-0.4
SolarWorld SW255 Mono Black	8.15	31.4	1.61	60	8.66	37.8	-0.4
SolarWorld SW255 Poly	8.2	31.1	1.61	60	8.73	37.8	-0.4
SolarWorld SW260 Mono	8.24	31.6	1.61	60	8.73	37.9	-0.4
SolarWorld SW260 Mono Black	8.24	31.6	1.61	60	8.73	37.9	-0.4
SolarWorld SW265 Mono	8.33	31.9	1.61	60	8.82	38.1	-0.4
SolarWorld SW265 Mono Black	8.33	31.9	1.61	60	8.82	38.1	-0.4
SolarWorld SW270 Mono	8.42	32.1	1.61	60	8.9	38.3	-0.4

Module Characteristics at Reference Conditions

Reference conditions: Total Irradiance = 1000 W/m2, Cell temp = 25 C

			Temperature coefficients			
Nominal efficiency	16.7877	%				
Maximum power (Pmp)	270.282	Wdc	-0.467	%/°C	-1.262	W/°C
Max power voltage (Vmp)	32.1	Vdc				
Max power current (Imp)	8.4	Adc				
Open circuit voltage (Voc)	38.3	Vdc	-0.356	%/°C	-0.136	V/°C
Short circuit current (Isc)	8.9	Adc	0.107	%/°C	0.010	A/°C

Temperature Correction

● Nominal operating cell temperature (NOCT) method
○ Heat transfer method

Refer to Help for more information about CEC cell temperature models.

NOCT method parameters

Mounting standoff: Less than 0.5 in
Array height: Two story building height or higher

Heat transfer method parameters

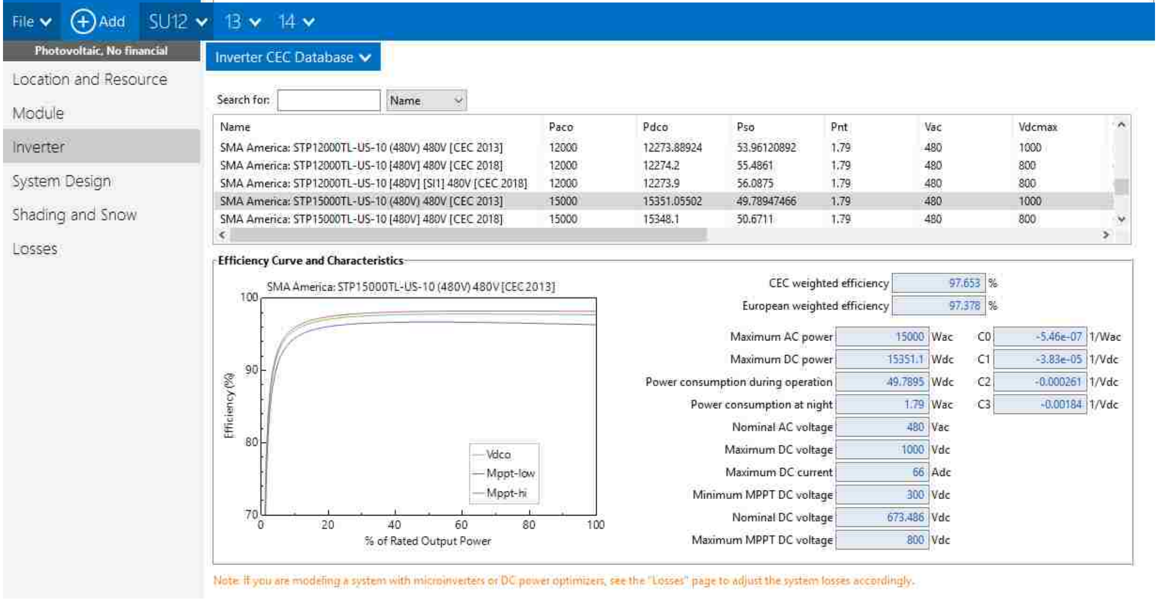
Mounting configuration: Rack
Heat transfer dimensions: Module Dimensions
Mounting structure orientation: Structures do not impede flow underneath module
Module width: 0.96 m
Module length: 1.68 m
Rows of modules in array: 4
Columns of modules in array: 12
Temperature behind the module: 20 °C
Space between module back and roof surface: 0.05 m

Physical Characteristics

Material: Mono-c-Si
Module area: 1.610 m²
Number of cells: 60

Additional Parameters

T_noct: 46.4 °C
A_ref: 1.7341 V
I_L_ref: 8.9 A
I_o_ref: 2.274e-09 A
R_s: 0.131 Ohm
R_sh_ref: 3391.89 Ohm



Inverter CEC Database

Search for: Name

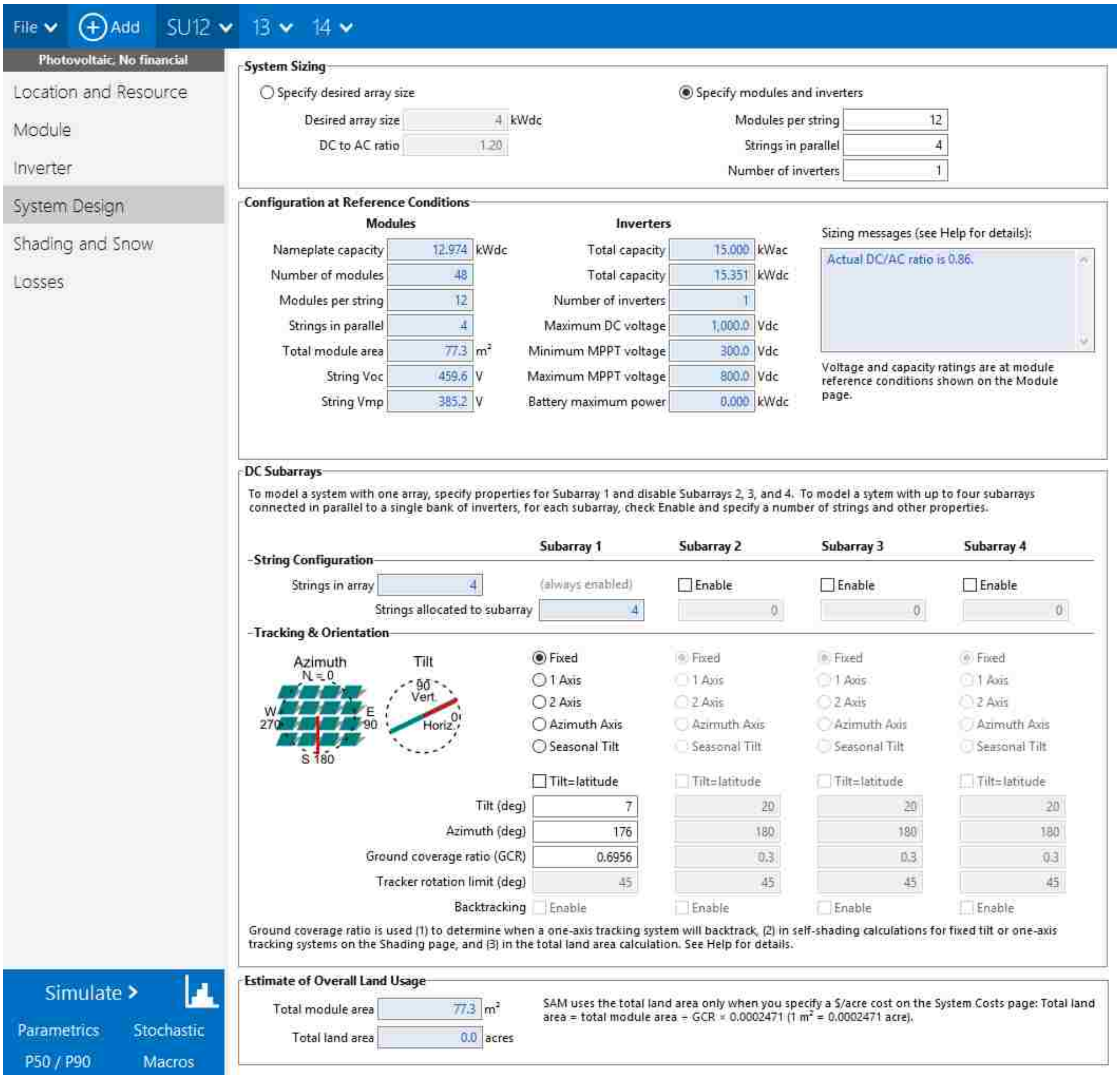
Name	Paco	Pdco	Pso	Pnt	Vac	Vdcmax
SMA America: STP12000TL-US-10 (480V) 480V [CEC 2013]	12000	12273.88924	53.96120892	1.79	480	1000
SMA America: STP12000TL-US-10 [480V] 480V [CEC 2018]	12000	12274.2	55.4861	1.79	480	800
SMA America: STP12000TL-US-10 [480V] [SI1] 480V [CEC 2018]	12000	12273.9	56.0875	1.79	480	800
SMA America: STP15000TL-US-10 (480V) 480V [CEC 2013]	15000	15351.05502	49.78947466	1.79	480	1000
SMA America: STP15000TL-US-10 [480V] 480V [CEC 2018]	15000	15348.1	50.6711	1.79	480	800

Efficiency Curve and Characteristics

CEC weighted efficiency: 97.653 %
European weighted efficiency: 97.378 %

Maximum AC power	15000	Wac	C0	-5.46e-07	1/Wac
Maximum DC power	15351.1	Wdc	C1	-3.83e-05	1/Vdc
Power consumption during operation	49.7895	Wdc	C2	-0.000261	1/Vdc
Power consumption at night	1.79	Wac	C3	-0.00184	1/Vdc
Nominal AC voltage	480	Vac			
Maximum DC voltage	1000	Vdc			
Maximum DC current	66	Adc			
Minimum MPPT DC voltage	300	Vdc			
Nominal DC voltage	673.486	Vdc			
Maximum MPPT DC voltage	800	Vdc			

Note: If you are modeling a system with microinverters or DC power optimizers, see the "Losses" page to adjust the system losses accordingly.



System Sizing

○ Specify desired array size

Desired array size	4	kWdc
DC to AC ratio	1.20	

● Specify modules and inverters

Modules per string	12
Strings in parallel	4
Number of inverters	1

Configuration at Reference Conditions

Modules			Inverters		
Nameplate capacity	12.974	kWdc	Total capacity	15.000	kWac
Number of modules	48		Total capacity	15.351	kWdc
Modules per string	12		Number of inverters	1	
Strings in parallel	4		Maximum DC voltage	1,000.0	Vdc
Total module area	77.3	m^2	Minimum MPPT voltage	300.0	Vdc
String Voc	459.6	V	Maximum MPPT voltage	800.0	Vdc
String Vmp	385.2	V	Battery maximum power	0.000	kWdc

Sizing messages (see Help for details):

Actual DC/AC ratio is 0.86.

Voltage and capacity ratings are at module reference conditions shown on the Module page.

DC Subarrays

To model a system with one array, specify properties for Subarray 1 and disable Subarrays 2, 3, and 4. To model a sytem with up to four subarrays connected in parallel to a single bank of inverters, for each subarray, check Enable and specify a number of strings and other properties.

String Configuration

Strings in array: 4

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	(always enabled)	☐ Enable	☐ Enable	☐ Enable
Strings allocated to subarray	4	0	0	0

Tracking & Orientation

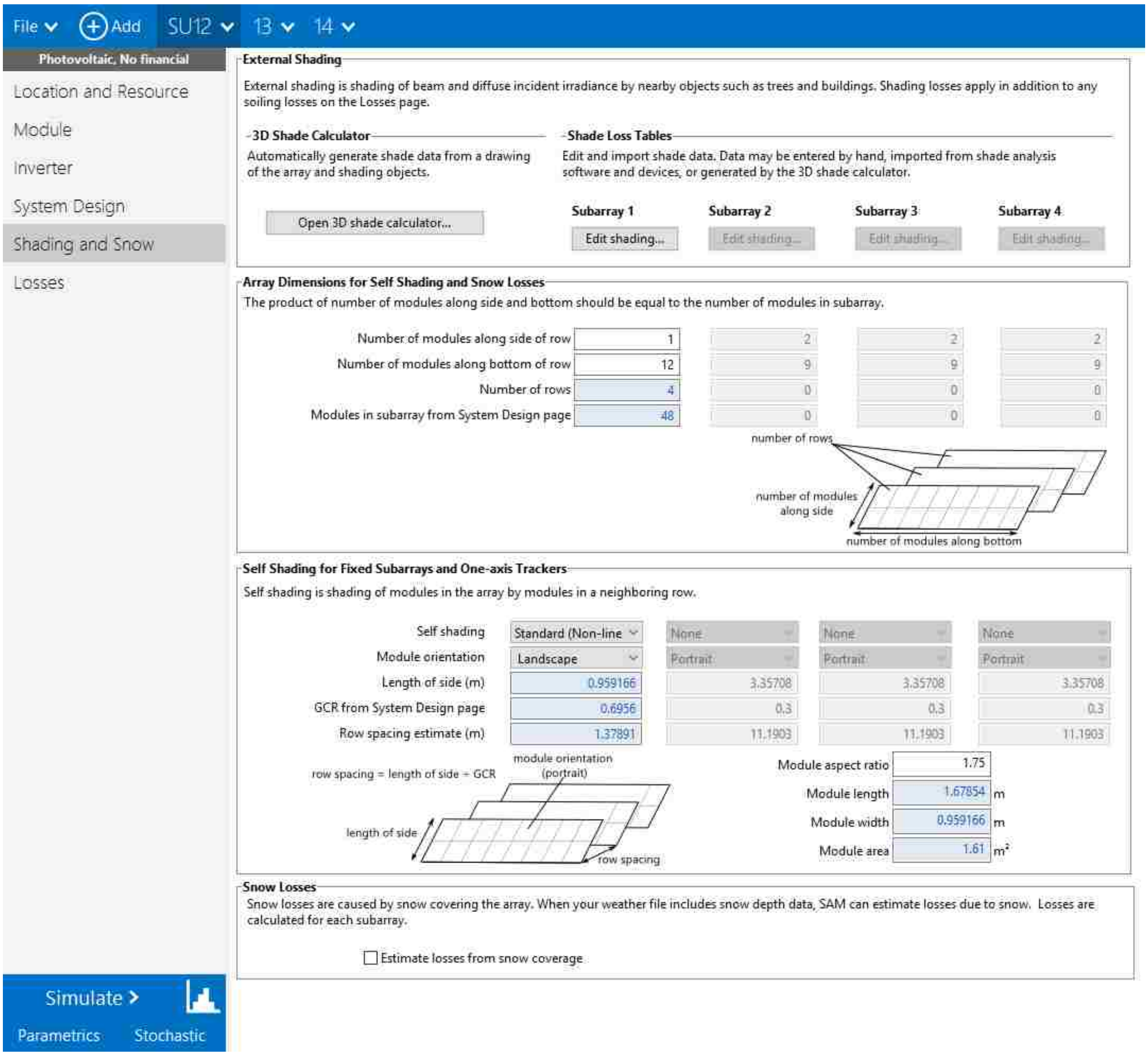
	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	● Fixed	● Fixed	● Fixed	● Fixed
	○ 1 Axis	○ 1 Axis	○ 1 Axis	○ 1 Axis
	○ 2 Axis	○ 2 Axis	○ 2 Axis	○ 2 Axis
	○ Azimuth Axis	○ Azimuth Axis	○ Azimuth Axis	○ Azimuth Axis
	○ Seasonal Tilt	○ Seasonal Tilt	○ Seasonal Tilt	○ Seasonal Tilt
	☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude
Tilt (deg)	7	20	20	20
Azimuth (deg)	176	180	180	180
Ground coverage ratio (GCR)	0.6956	0.3	0.3	0.3
Tracker rotation limit (deg)	45	45	45	45
Backtracking	☐ Enable	☐ Enable	☐ Enable	☐ Enable

Ground coverage ratio is used (1) to determine when a one-axis tracking system will backtrack, (2) in self-shading calculations for fixed tilt or one-axis tracking systems on the Shading page, and (3) in the total land area calculation. See Help for details.

Estimate of Overall Land Usage

Total module area	77.3	m^2
Total land area	0.0	acres

SAM uses the total land area only when you specify a $/acre cost on the System Costs page: Total land area = total module area ÷ GCR × 0.0002471 (1 m^2 = 0.0002471 acre).



External Shading

External shading is shading of beam and diffuse incident irradiance by nearby objects such as trees and buildings. Shading losses apply in addition to any soiling losses on the Losses page.

3D Shade Calculator

Automatically generate shade data from a drawing of the array and shading objects.

Shade Loss Tables

Edit and import shade data. Data may be entered by hand, imported from shade analysis software and devices, or generated by the 3D shade calculator.

Array Dimensions for Self Shading and Snow Losses

The product of number of modules along side and bottom should be equal to the number of modules in subarray.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Number of modules along side of row	1	2	2	2
Number of modules along bottom of row	12	9	9	9
Number of rows	4	0	0	0
Modules in subarray from System Design page	48	0	0	0

Self Shading for Fixed Subarrays and One-axis Trackers

Self shading is shading of modules in the array by modules in a neighboring row.

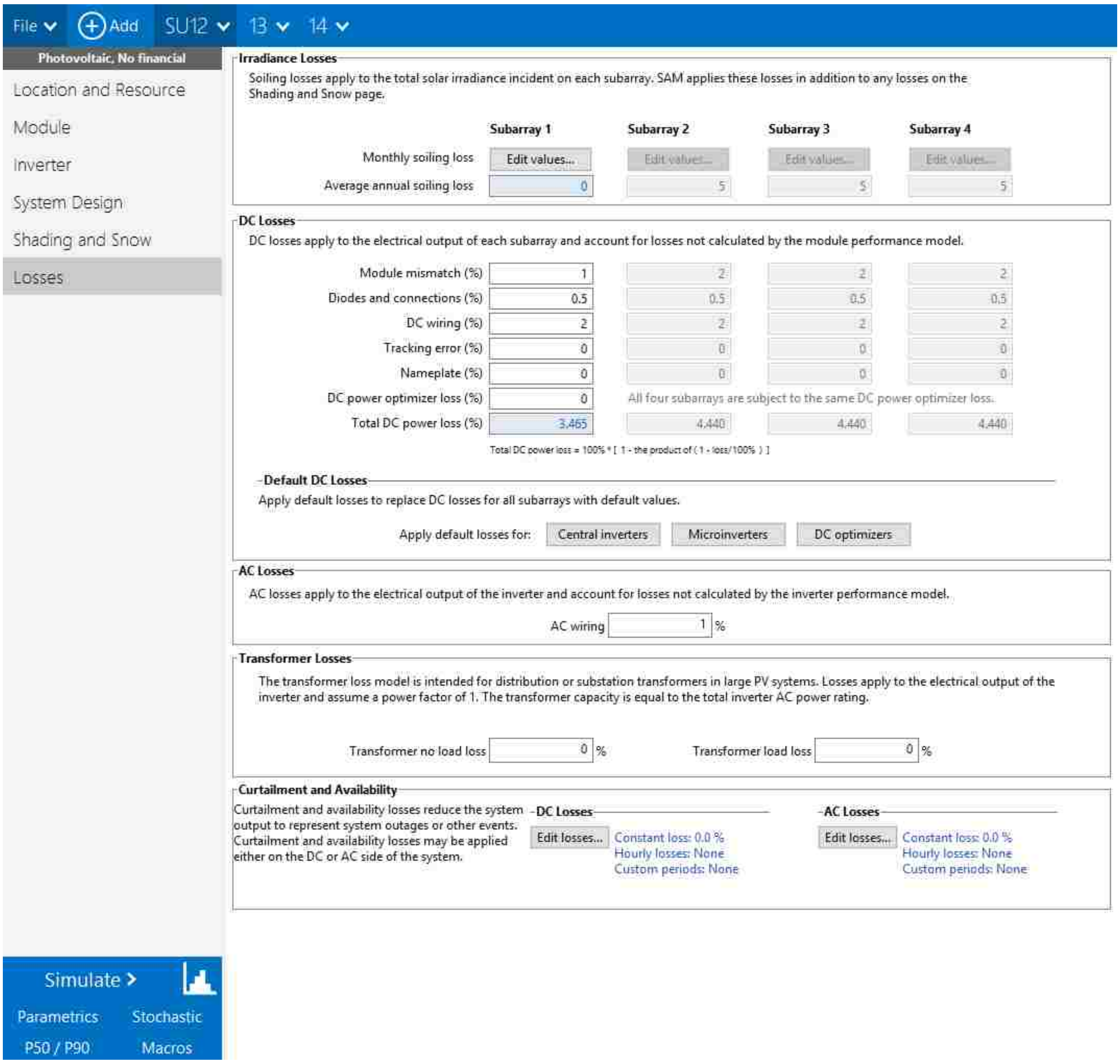
Self shading	Standard (Non-line	None	None	None
Module orientation	Landscape	Portrait	Portrait	Portrait
Length of side (m)	0.959166	3.35708	3.35708	3.35708
GCR from System Design page	0.6956	0.3	0.3	0.3
Row spacing estimate (m)	1.37891	11.1903	11.1903	11.1903

Module aspect ratio	1.75	
Module length	1.67854	m
Module width	0.959166	m
Module area	1.61	m²

Snow Losses

Snow losses are caused by snow covering the array. When your weather file includes snow depth data, SAM can estimate losses due to snow. Losses are calculated for each subarray.

☐ Estimate losses from snow coverage



Irradiance Losses

Soiling losses apply to the total solar irradiance incident on each subarray. SAM applies these losses in addition to any losses on the Shading and Snow page.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Monthly soiling loss	Edit values...	Edit values...	Edit values...	Edit values...
Average annual soiling loss	0	5	5	5

DC Losses

DC losses apply to the electrical output of each subarray and account for losses not calculated by the module performance model.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
Module mismatch (%)	1	2	2	2
Diodes and connections (%)	0.5	0.5	0.5	0.5
DC wiring (%)	2	2	2	2
Tracking error (%)	0	0	0	0
Nameplate (%)	0	0	0	0
DC power optimizer loss (%)	0	All four subarrays are subject to the same DC power optimizer loss.		
Total DC power loss (%)	3.465	4.440	4.440	4.440

Total DC power loss = 100% * [1 - the product of (1 - loss/100%)]

Default DC Losses

Apply default losses to replace DC losses for all subarrays with default values.

Apply default losses for:

AC Losses

AC losses apply to the electrical output of the inverter and account for losses not calculated by the inverter performance model.

AC wiring 1 %

Transformer Losses

The transformer loss model is intended for distribution or substation transformers in large PV systems. Losses apply to the electrical output of the inverter and assume a power factor of 1. The transformer capacity is equal to the total inverter AC power rating.

Transformer no load loss 0 %

Transformer load loss 0 %

Curtailment and Availability

Curtailment and availability losses reduce the system output to represent system outages or other events. Curtailment and availability losses may be applied either on the DC or AC side of the system.

DC Losses

Constant loss: 0.0 %
Hourly losses: None
Custom periods: None

AC Losses

Constant loss: 0.0 %
Hourly losses: None
Custom periods: None

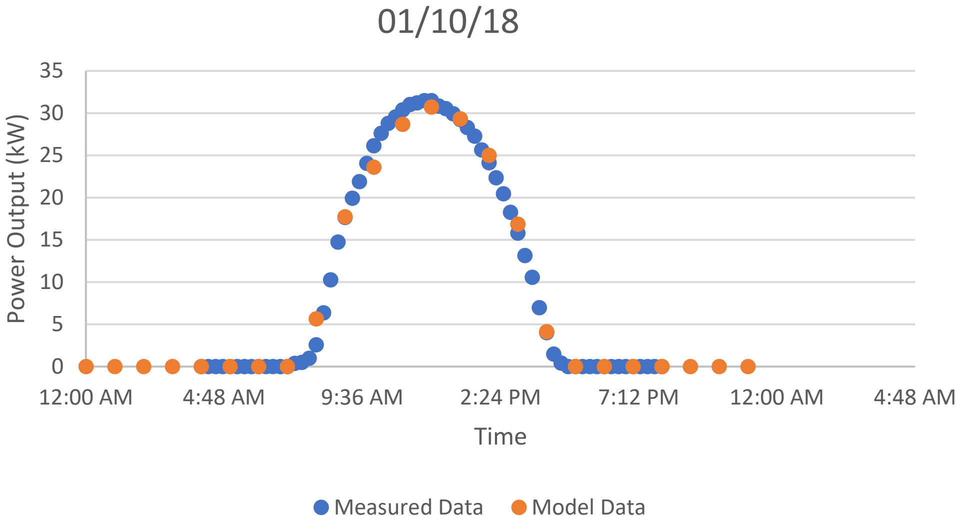
Figure A.24 – Screenshots of the Software SAM that was Used for Modeling of Paramenters

Appendix B

The Table B.1 and Figure B.1 below compares the energy outputs obtained from the model and the measured data from Student Union. These two days were considered when the panels were the cleanest and had the least amount of soiling (close to no soiling). The modeled and measured total power outputs for each day were compared. The differences in total power are shown in the table below. There was a very small difference in the energy produced by the solar panels when they are considered clean and the energy from the SAM model. On 01/10/18, where there was a big rainfall (1.18 in) that was considered to clean the panels, the model and the real data only showed a difference of 0.03%. On the date when the panels were washed (08/27/18), the difference between the total energy produced by the panels and model was 0.47%.

Table B.23 - Comparison of Modeled and Measured Student Union PV Array Daily Generated Energy Outputs

	kWh Produced		**Percent**
	Model	**SU Measured Data**	**Difference**
1/10/2018	181.69	181.64	0.03%
8/27/2018	336.95	335.36	0.47%



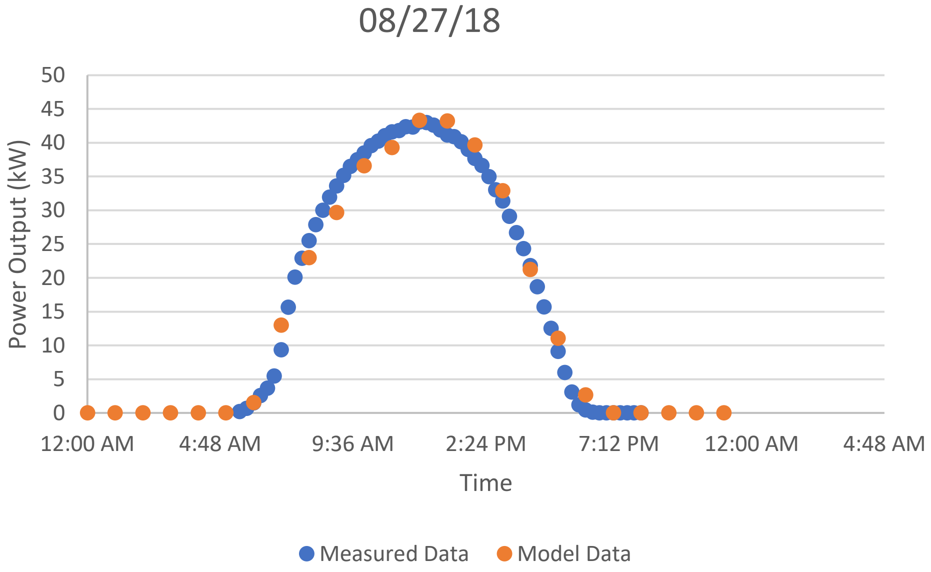


Figure B.25 - Comparison of Modeled and Measured Student Union PV Array Diurnal Generated Energy Variations for Different Days When Solar Panels were Considered Clean

Appendix C

Table C.1 shows the rainfall events obtained from the Community Environmental Monitoring Program website (CEMP, n.d.), that were combined with the DRI rainfall gauge data.

Table C.24 - Chronological Listing of Consolidated Dataset Used for Rainfall Return Period Calculations

Date	Total Precipitation (in)
12/25/18	0.09
12/07/18	0.11
11/29/18	0.23
10/21/18	0.12
10/03/18	0.02
08/11/18	0.06
07/19/18	0.03
07/14/18	0.15
07/10/18	0.07
07/09/18	0.43
05/01/18	0.09
03/23/18	0.01
03/22/18	0.01
03/11/18	0.07
03/10/18	0.11
01/09/18	1.18
01/08/18	0.12
09/08/17	0.27
08/11/17	0.04
08/05/17	0.03
08/04/17	0.26
07/19/17	0.02
07/11/17	0.06
05/07/17	0.06
04/03/17	0.13
03/27/17	0.02
02/19/17	0.02
02/18/17	0.64
02/17/17	0.01
02/12/17	0.02
02/11/17	0.02
01/23/17	0.08
01/22/17	0.46
01/20/17	0.26
01/13/17	0.04
01/12/17	0.01
12/30/16	0.01
12/24/16	0.26
12/23/16	0.02
12/22/16	0.41
10/24/16	0.17
10/23/16	0.01
09/29/16	0.01
08/22/16	0.02
08/04/16	0.02
07/02/16	0.01
07/01/16	0.25
06/30/16	0.10
06/28/16	0.06
06/11/16	0.03
05/07/16	0.20
05/06/16	0.07
04/30/16	0.86
04/28/16	0.46
04/25/16	0.01
04/10/16	0.09
04/09/16	0.67
04/08/16	0.04
02/01/16	0.08
01/31/16	0.19
01/19/16	0.05
01/05/16	0.26
01/04/16	0.01
11/16/15	0.01
11/04/15	0.20
10/21/15	0.01
10/18/15	0.11
10/17/15	0.22
10/16/15	0.07
10/05/15	0.25
09/15/15	0.03
08/14/15	0.01
08/13/15	0.77
08/07/15	0.02
07/06/15	0.12
07/02/15	0.10
06/14/15	0.15
06/13/15	0.01
05/18/15	0.07
04/25/15	0.16
03/02/15	0.05
03/01/15	0.18
02/23/15	0.39
02/22/15	0.12
01/31/15	0.03
01/30/15	0.19
01/27/15	0.11
01/26/15	0.04
01/11/15	0.43
12/25/14	0.01
12/16/14	0.01
12/12/14	0.10
12/04/14	0.03
12/02/14	0.16
11/01/14	0.01
09/26/14	0.15
09/20/14	0.03
09/08/14	0.32
09/07/14	0.02
08/11/14	0.01
08/04/14	0.06
08/03/14	0.33
07/27/14	0.08
07/15/14	0.01
07/08/14	0.02
07/07/14	0.01
07/04/14	0.02
02/28/14	0.27

Date	Total Precipitation (in)
12/04/13	0.01
11/23/13	0.19
11/22/13	0.29
11/21/13	0.74
10/10/13	0.03
09/11/13	0.22
09/09/13	0.20
09/08/13	0.05
09/04/13	0.01
09/03/13	0.01
08/30/13	0.04
08/26/13	0.05
08/19/13	0.01
08/18/13	0.24
08/16/13	0.20
07/20/13	0.35
04/08/13	0.04
03/08/13	0.16
01/27/13	0.04
01/26/13	0.28
01/25/13	0.04
12/14/12	0.20
12/13/12	0.24
10/11/12	1.02
10/10/12	0.04
09/11/12	2.09
08/22/12	0.94
08/21/12	0.16
08/12/12	0.04
08/01/12	0.24
07/13/12	0.04
03/17/12	0.16
02/14/12	0.04
12/18/11	0.04
12/14/11	0.04
12/12/11	0.08

Date	Total Precipitation (in)
11/04/11	0.04
10/06/11	0.04
10/05/11	0.12
10/04/11	0.04
10/03/11	0.08
09/24/11	0.12
09/14/11	0.20
09/13/11	0.08
09/11/11	0.12
08/13/11	0.08
07/31/11	0.04
07/10/11	0.20
07/09/11	0.35
07/05/11	0.04
07/03/11	0.35
05/18/11	0.04
02/20/11	0.04
02/19/11	0.04
12/23/10	0.08
12/22/10	1.06
12/21/10	0.24
12/20/10	0.39
12/17/10	0.04
12/06/10	0.08
10/22/10	0.04
10/20/10	0.39
10/18/10	0.04
10/17/10	0.12
10/02/10	0.24
08/08/10	0.04
04/22/10	0.43
03/07/10	0.20
02/27/10	0.08
02/22/10	0.20
02/09/10	0.20
02/06/10	0.47

Date	Total Precipitation (in)
01/27/10	0.28
01/22/10	0.04
01/21/10	0.83
01/20/10	0.47
01/19/10	0.43
01/18/10	0.04
12/12/09	0.04
12/07/09	0.28
06/24/09	0.16
02/16/09	0.08
02/09/09	0.04
02/08/09	0.04
02/07/09	0.63
12/25/08	0.12
12/19/08	0.04
12/18/08	0.39
12/17/08	0.35
12/15/08	0.28
11/27/08	0.20
11/26/08	0.35
09/08/08	0.24
08/07/08	0.16
05/23/08	0.04
03/16/08	0.04
02/20/08	0.04
01/27/08	0.43
01/05/08	0.04
12/01/07	0.08
11/30/07	0.43
09/22/07	0.35
09/21/07	0.31
08/27/07	0.75
08/01/07	0.04
07/24/07	0.04
07/23/07	0.08
04/16/07	0.12

Date	Total Precipitation (in)
02/13/07	0.12
01/05/07	0.04
12/28/06	0.08
12/17/06	0.04
10/14/06	0.59
10/13/06	0.08
10/06/06	0.16
10/05/06	0.24
08/03/06	0.04
07/18/06	0.08
07/17/06	0.12
06/07/06	0.04
03/28/06	0.08
03/21/06	0.12
02/28/06	0.08
10/25/05	0.04
10/18/05	1.02
10/17/05	0.39
08/14/05	0.20
07/28/05	0.04
07/24/05	0.43
03/23/05	0.20
03/22/05	0.04
03/19/05	0.08
03/04/05	0.28
02/23/05	0.04
02/22/05	0.31
02/21/05	0.59
02/19/05	0.04
02/18/05	0.39
02/17/05	0.04
02/12/05	0.08
02/11/05	0.71
01/29/05	0.08
01/28/05	0.20
01/27/05	0.04
01/26/05	0.20
01/11/05	0.08
01/10/05	0.08
01/09/05	0.16
01/07/05	0.24
01/04/05	0.20
01/03/05	0.59
12/29/04	1.18
12/28/04	0.87
11/22/04	0.28
11/21/04	0.79
11/08/04	0.08
11/07/04	0.51
10/27/04	0.16
10/22/04	0.04
10/20/04	0.35
09/09/04	0.08
08/16/04	0.12
08/12/04	0.28
04/08/04	0.04
04/03/04	0.28
04/02/04	0.59
03/02/04	0.16
03/01/04	0.04
02/26/04	0.24
02/24/04	0.04
02/23/04	0.12
02/22/04	0.55
02/21/04	0.16
02/20/04	0.08
02/03/04	0.04
12/30/03	0.28
12/25/03	0.35
12/11/03	0.35
11/16/03	0.08
11/12/03	0.43
09/02/03	0.24
08/26/03	0.12
08/19/03	0.16
08/16/03	0.47
07/31/03	0.28
07/25/03	0.04
07/24/03	0.16
07/19/03	0.20
07/16/03	0.04
04/15/03	0.16
04/14/03	0.31
03/17/03	0.04
03/16/03	0.16
03/15/03	0.04
03/01/03	0.04
02/28/03	0.24
02/27/03	0.08
02/26/03	0.20
02/25/03	0.63
02/13/03	0.12
02/12/03	0.63
11/30/02	0.16
10/27/02	0.12
10/26/02	0.04
09/11/02	0.24
07/17/02	0.04
03/24/02	0.04
12/14/01	0.08
11/24/01	0.08
11/07/01	3.82
08/09/01	0.16
07/06/01	0.20
03/07/01	0.08
03/06/01	0.04
02/28/01	0.39
02/27/01	0.67

Date	Total Precipitation (in)
02/26/01	0.51
02/25/01	0.24
02/13/01	0.12
01/27/01	0.20
01/26/01	0.08
01/11/01	0.16
01/09/01	0.12
01/08/01	0.12
10/30/00	0.12
10/27/00	0.39
10/23/00	0.20
10/04/00	0.04
08/30/00	0.08
08/29/00	0.28
08/26/00	0.16
08/25/00	0.08
03/08/00	0.16
03/05/00	0.04
02/27/00	0.04
02/24/00	0.04
02/23/00	0.24
02/21/00	0.94
02/20/00	0.04
02/16/00	0.39
02/12/00	0.04
02/11/00	0.04
09/22/99	0.16
09/18/99	0.04
09/12/99	0.12
08/10/99	0.20
07/27/99	0.04
07/16/99	0.04
07/15/99	0.20
07/14/99	0.63
07/12/99	0.24
07/08/99	1.38

Date	Total Precipitation (in)
07/07/99	0.04
06/04/99	0.04
06/02/99	0.04
04/30/99	0.24
04/29/99	0.08
04/25/99	0.04
04/12/99	0.04
02/04/99	0.04
12/06/98	0.08
11/28/98	0.08
11/12/98	0.04
11/08/98	0.04
10/30/98	0.20
09/11/98	0.51
09/08/98	0.63
09/04/98	0.08
08/30/98	0.08
08/15/98	0.04
07/23/98	0.04
07/20/98	0.63
06/08/98	0.04
05/13/98	0.12
04/25/98	0.20
04/01/98	0.04
03/28/98	0.24
03/26/98	0.35
03/25/98	0.28
03/14/98	0.04
02/24/98	0.67
02/23/98	0.20
02/20/98	0.59
02/17/98	0.59
02/14/98	0.16
02/07/98	0.04
02/06/98	0.59
02/04/98	0.08

Date	Total Precipitation (in)
02/03/98	0.24
01/10/98	0.04
01/09/98	0.12
12/07/97	0.04
11/26/97	0.04
11/13/97	0.04
11/10/97	0.08
09/25/97	0.67
09/04/97	0.24
09/03/97	0.28
09/01/97	0.55
08/17/97	0.04
08/10/97	0.04
08/09/97	0.12
08/08/97	0.04
07/28/97	0.28
07/22/97	0.08
04/02/97	0.08
01/13/97	0.20
01/05/97	0.08
12/09/96	0.16
11/26/96	1.06
10/30/96	0.08
10/07/96	0.20
07/28/96	0.31
07/15/96	0.04
06/26/96	0.04
05/29/96	0.04
05/26/96	0.12
05/24/96	0.04
03/04/96	0.08
02/21/96	0.04
02/20/96	0.04
01/31/96	0.08
08/22/95	0.16
05/24/95	0.35

Date	Total Precipitation (in)
05/23/95	0.08
03/23/95	0.04
03/21/95	0.08
03/11/95	0.20
03/06/95	0.04
03/05/95	0.16
02/28/95	0.08
01/25/95	0.63
01/24/95	0.35
01/21/95	0.08
01/15/95	0.04
01/13/95	0.04
01/11/95	0.04
01/10/95	0.39
01/07/95	0.35
01/05/95	0.08
01/04/95	0.71
01/03/95	0.24
12/30/94	0.12
12/29/94	0.28
12/25/94	0.83
12/24/94	0.12
12/23/94	0.04
11/26/94	0.04
11/11/94	0.28
09/20/94	0.08
09/19/94	0.20
07/23/94	0.04
07/18/94	0.35
03/25/94	0.12
02/17/94	0.04
02/08/94	0.08
02/07/94	0.08
02/04/94	0.28
01/25/94	0.04
01/05/94	0.04
12/15/93	0.16
12/14/93	0.04
11/12/93	0.04
11/11/93	0.04
08/07/93	0.16
08/06/93	0.08
08/05/93	0.04
08/02/93	0.08
06/05/93	0.16
03/28/93	0.08
03/26/93	0.16
02/28/93	0.20
02/27/93	0.31
02/26/93	0.39
02/19/93	0.16
02/18/93	0.12
02/09/93	0.08
02/08/93	1.42
01/31/93	0.04
01/18/93	0.79
01/16/93	0.31
01/15/93	0.04
01/14/93	0.12
01/13/93	0.16
01/12/93	0.12
01/10/93	0.08
01/08/93	0.04
01/07/93	0.08
01/06/93	0.28
12/30/92	0.04
12/29/92	0.04
12/28/92	0.39
12/27/92	0.20
12/08/92	0.08
12/07/92	0.75
12/04/92	0.24
10/28/92	0.08
10/24/92	1.22
08/30/92	0.08
06/02/92	0.20
05/30/92	0.04
05/08/92	0.12
03/31/92	0.28
03/30/92	0.59
03/29/92	0.04
03/27/92	0.91
03/26/92	0.04
03/23/92	0.12
03/22/92	0.24
03/20/92	0.04
03/08/92	0.87
03/07/92	0.67
03/02/92	0.39
02/15/92	0.12
02/13/92	0.16
02/12/92	0.63
02/10/92	0.04
02/07/92	0.39
01/05/92	0.43
01/03/92	0.04
12/30/91	0.16
12/11/91	0.12
11/15/91	0.31
11/14/91	0.16
10/30/91	0.04
09/05/91	0.04
08/11/91	0.04
08/10/91	0.59
07/31/91	0.55
07/08/91	0.04
06/01/91	0.24
05/21/91	0.28

Date	Total Precipitation (in)
05/03/91	0.08
03/27/91	0.67
03/20/91	0.16
03/19/91	0.12
03/01/91	0.35
02/28/91	0.55
02/27/91	0.12
01/08/91	0.04
01/04/91	0.12
01/03/91	0.08
11/02/90	0.04
10/19/90	0.08
09/21/90	0.08
07/26/90	0.04
07/16/90	0.04
07/15/90	0.04
07/14/90	0.04
06/10/90	1.38
06/09/90	0.20
04/20/90	0.08
02/19/90	0.24
02/17/90	0.16
01/18/90	0.55
01/17/90	0.71

Appendix D

Table D.1 shows the recurrence values calculated for different storm events in Las Vegas from 1990 to 2018.

Table D.25 – Calculated Recurrence Periods for Different Rainfall Events in Las Vegas

Total Precipitation (in)	Ranking	Exceedance Probability	Recurrence Interval (days)	Recurrence Interval (yr)
3.82	1	0.009%	10592.00	29.02
2.09	2	0.019%	5296.00	14.51
1.42	3	0.028%	3530.67	9.67
1.38	5	0.047%	2118.40	5.80
1.22	6	0.057%	1765.33	4.84
1.18	8	0.076%	1324.00	3.63
1.06	10	0.094%	1059.20	2.90
1.02	12	0.113%	882.67	2.42
0.94	14	0.132%	756.57	2.07
0.91	15	0.142%	706.13	1.93
0.87	17	0.160%	623.06	1.71
0.86	18	0.170%	588.44	1.61
0.83	20	0.189%	529.60	1.45
0.79	22	0.208%	481.45	1.32
0.77	23	0.217%	460.52	1.26
0.75	25	0.236%	423.68	1.16
0.74	26	0.245%	407.38	1.12
0.71	29	0.274%	365.24	1.00
0.67	35	0.330%	302.63	0.83
0.64	36	0.340%	294.22	0.81
0.63	44	0.415%	240.73	0.66
0.59	53	0.500%	199.85	0.55
0.55	58	0.548%	182.62	0.50
0.51	61	0.576%	173.64	0.48
0.47	64	0.604%	165.50	0.45
0.46	66	0.623%	160.48	0.44
0.43	75	0.708%	141.23	0.39
0.41	76	0.718%	139.37	0.38
0.39	90	0.850%	117.69	0.32
0.35	105	0.991%	100.88	0.28
0.33	106	1.001%	99.92	0.27
0.32	107	1.010%	98.99	0.27
0.31	114	1.076%	92.91	0.25
0.29	115	1.086%	92.10	0.25
0.28	135	1.275%	78.46	0.21
0.27	137	1.293%	77.31	0.21

Total Precipitation (in)	Ranking	Exceedance Probability	Recurrence Interval (days)	Recurrence Interval (yr)
0.26	141	1.331%	75.12	0.21
0.25	143	1.350%	74.07	0.20
0.24	167	1.577%	63.43	0.17
0.23	168	1.586%	63.05	0.17
0.22	170	1.605%	62.31	0.17
0.20	204	1.926%	51.92	0.14
0.19	207	1.954%	51.17	0.14
0.18	208	1.964%	50.92	0.14
0.17	209	1.973%	50.68	0.14
0.16	246	2.323%	43.06	0.12
0.15	249	2.351%	42.54	0.12
0.13	250	2.360%	42.37	0.12
0.12	290	2.738%	36.52	0.10
0.11	294	2.776%	36.03	0.10
0.10	297	2.804%	35.66	0.10
0.09	300	2.832%	35.31	0.10
0.08	369	3.484%	28.70	0.08
0.07	374	3.531%	28.32	0.08
0.06	379	3.578%	27.95	0.08
0.05	383	3.616%	27.66	0.08
0.04	519	4.900%	20.41	0.06
0.03	527	4.975%	20.10	0.06
0.02	540	5.098%	19.61	0.05
0.01	564	5.325%	18.78	0.05

Appendix E

Survey form used to collect data from establishments with solar panels.

UNLV
Howard R. Hughes
College of
ENGINEERING

Interview Questions

Name of Survey Respondent: ____

E-mail: ____

Name of Establishment: ____

Address: ____

About the Solar Panels

1) What company installed the panels? ____

2) When did they start operating? ____

3) What is the total capacity? ____

4) How many panels are there? ____

5) Do you wash the solar panels? ____

If yes to question 5, please answer questions 5.1 through 5.6

5.1) How often do you wash the solar panels? ______________________________

5.2) Do you hire a company to wash? If so, what company? __________________

____

5.3) What is the cost for cleaning them? _________________________________

5.4) What is the source of water used to wash the panels? __________________

____

5.5) What is the amount of water used to wash all the panels? ________________

____

Appendix F

Table F.26 - Calculations of the Average Efficiency of a Week Before and After Rainfall Events for the Buildings: Student Union, Dayton Hall and CBC-C [a]

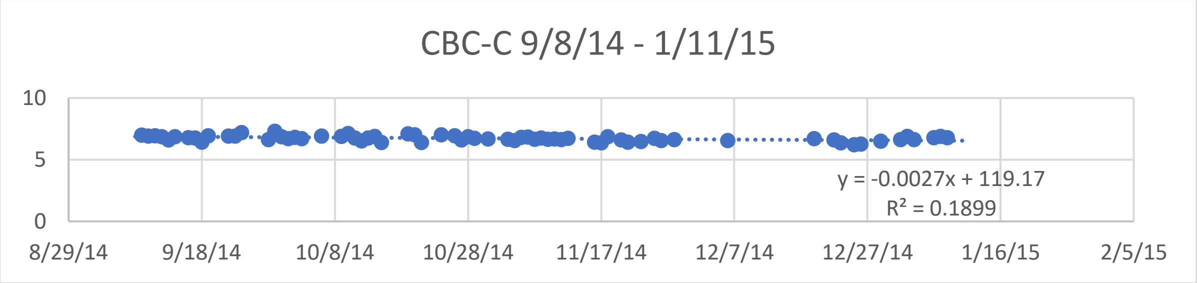
Date	Rain	Date	Rain	Date	Rain	Total Rain	Number of days prior with no rain	Number of days with no rain after	Mean efficiency 1 week before (%)	Mean efficiency 1 week after (%)	% Change ($\Delta\eta_n$)
11/1/2014	0.01					0.01	36	31	13.9798	13.9307	-0.35
9/29/2016	0.01					0.01	38	24	12.6453	12.4604	-1.48
11/1/2014	0.01					0.01	36	31	13.2562	13.0153	-1.85
9/29/2016	0.01					0.01	38	24	11.8750	11.7213	-1.31
11/1/2014	0.01					0.01	36	31	6.7604	6.7170	-0.65
9/29/2016	0.01					0.01	38	24	6.1654	6.2991	2.12
8/7/2015	0.02					0.02	32	6	13.0329	13.0221	-0.08
10/3/2018	0.02					0.02	53	18	13.2412	13.0795	-1.24
8/7/2015	0.02					0.02	32	6	12.6040	12.5918	-0.10
8/4/2016	0.02					0.02	33	18	12.3085	11.9905	-2.65
3/27/2017	0.02					0.02	36	7	12.2446	12.2797	0.29
10/3/2018	0.02					0.02	53	18	12.9303	12.3567	-4.64
8/4/2016	0.02					0.02	33	18	6.4221	6.2864	-2.16
10/3/2018	0.02					0.02	53	18	6.6148	6.3628	-3.96
9/15/2015	0.03					0.03	32	20	13.4083	13.2322	-1.33
9/15/2015	0.03					0.03	32	20	12.9516	12.6444	-2.43
6/11/2016	0.03					0.03	35	17	12.4497	12.0055	-3.70
6/11/2016	0.03					0.03	35	17	6.6143	6.2902	-5.15
5/7/2017	0.06					0.06	34	65	13.0032	12.7113	-2.30
8/11/2018	0.06					0.06	23	53	12.8916	12.8860	-0.04
5/7/2017	0.06					0.06	34	65	12.1695	11.8030	-3.11
7/11/2017	0.06					0.06	65	8	11.9627	11.9832	0.17
8/11/2018	0.06					0.06	23	53	12.3368	12.3684	0.26
5/7/2017	0.06					0.06	34	65	6.5445	6.3553	-2.98
7/11/2017	0.06					0.06	65	8	6.4330	6.4602	0.42
8/11/2018	0.06					0.06	23	53	6.4493	6.4861	0.57
5/1/2018	0.09					0.09	39	69	12.8525	12.9088	0.44
5/1/2018	0.09					0.09	39	69	12.2435	12.4288	1.49
5/1/2018	0.09					0.09	39	69	6.2391	6.4249	2.89
3/10/2018	0.11	3/11/2018	0.07			0.11	60	11	12.4743	12.4049	-0.56
3/10/2018	0.11	3/11/2018	0.07			0.11	60	11	13.1601	13.1014	-0.45
6/13/2015	0.01	6/14/2015	0.15			0.15	26	18	12.9814	12.9095	-0.56
6/13/2015	0.01	6/14/2015	0.15			0.15	26	18	12.5866	12.5813	-0.04
6/13/2015	0.01	6/14/2015	0.15			0.15	26	18	6.5739	6.4537	-1.86

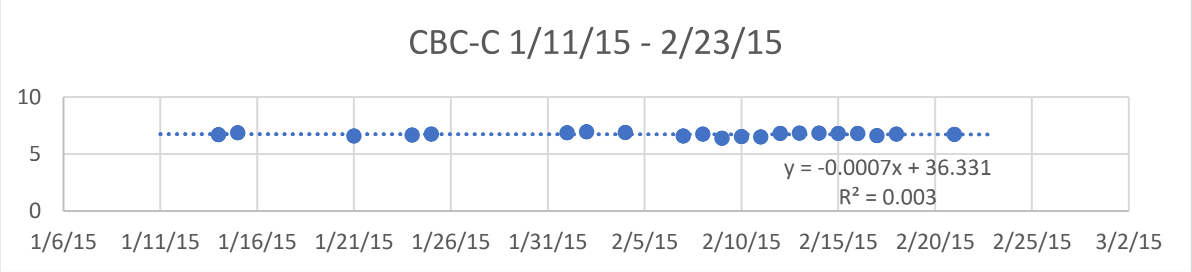
4/25/2015	0.16					0.16	54	23	13.2677	13.0708	-1.51
4/25/2015	0.16					0.16	54	23	12.7966	12.5672	-1.83
4/25/2015	0.16					0.16	54	23	6.6804	6.5500	-1.99
10/23/2016	0.01	10/24/2016	0.17			0.17	24	59	11.8053	12.7561	7.45
11/29/2018	0.23					0.23	39	8	13.0191	13.2026	1.39
11/29/2018	0.23					0.23	39	8	12.3082	12.3799	0.58
11/29/2018	0.23					0.23	39	8	6.1269	6.3403	3.37
10/5/2015	0.25					0.25	20	11	13.2170	13.6584	3.23
10/5/2015	0.25					0.25	20	11	12.5137	13.1494	4.83
1/4/2016	0.01	1/5/2016	0.26			0.26	49	14	11.7590	12.2637	4.11
1/4/2016	0.01	1/5/2016	0.26			0.26	49	14	6.2720	6.6046	5.04
1/4/2016	0.01	1/5/2016	0.26			0.26	49	14	13.0432	13.3913	2.60
9/8/2017	0.27					0.27	28	122	13.2354	13.2295	-0.04
9/8/2017	0.27					0.27	28	122	12.3887	12.3182	-0.57
9/8/2017	0.27					0.27	28	122	6.6382	6.5680	-1.07
9/7/2014	0.02	9/8/2014	0.32			0.32	27	12	12.7603	13.2127	3.42
9/7/2014	0.02	9/8/2014	0.32			0.32	27	12	6.7262	6.8682	2.07
9/7/2014	0.02	9/8/2014	0.32			0.32	27	12	13.1667	13.5921	3.13
2/22/2015	0.12	2/23/2015	0.39			0.39	22	6	13.7045	13.8472	1.03
2/22/2015	0.12	2/23/2015	0.39			0.39	22	6	13.0875	13.1756	0.67
2/22/2015	0.12	2/23/2015	0.39			0.39	22	6	6.7480	6.7872	0.58
12/22/2016	0.41	12/23/2016	0.02	12/24/2016	0.26	0.41	59	6	12.1405	12.9275	6.09
12/22/2016	0.41	12/23/2016	0.02	12/24/2016	0.26	0.41	59	6	6.2274	6.7602	7.88
12/22/2016	0.41	12/23/2016	0.02	12/24/2016	0.26	0.41	59	6	12.9506	13.9133	6.92
4/8/2016	0.04	4/9/2016	0.67	4/10/2016	0.09	0.67	67	15	13.0327	13.0296	-0.02
4/8/2016	0.04	4/9/2016	0.67	4/10/2016	0.09	0.67	67	15	12.4461	12.4763	0.24
4/8/2016	0.04	4/9/2016	0.67	4/10/2016	0.09	0.67	67	15	6.5982	6.5487	-0.76
1/8/2018	0.12	1/9/2018	1.18			1.18	122	60	12.2201	13.1900	7.35
1/8/2018	0.12	1/9/2018	1.18			1.18	122	60	6.3017	6.7303	6.37
1/8/2018	0.12	1/9/2018	1.18			1.18	122	60	13.2247	13.9761	5.38

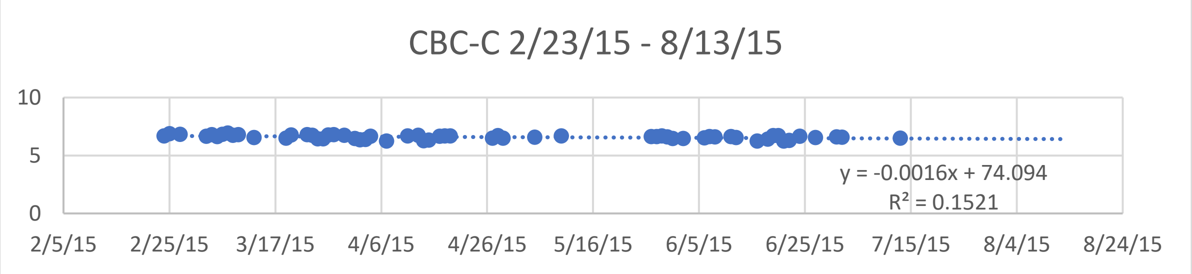
a. All the buildings are combined into the same table

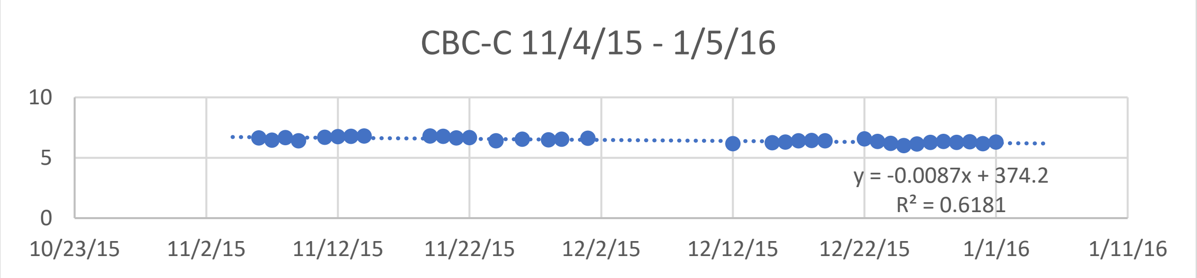
Appendix G

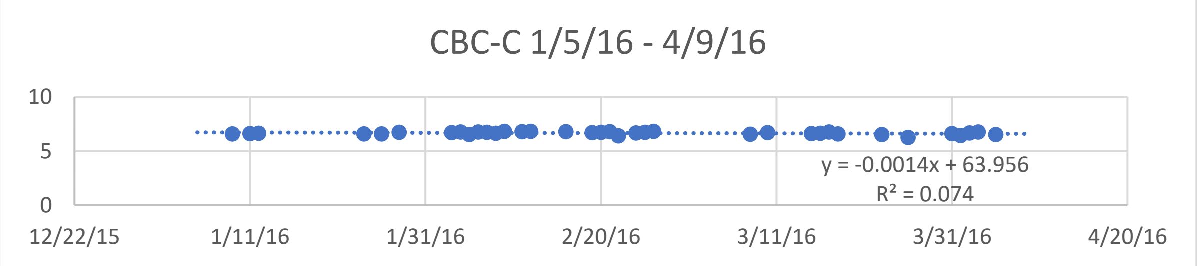
Graphs of dry periods for all the building analyzed. It is shown the efficiency during the dry period, its trendline as well as the equation of the line. In the x-axis it is shown the efficiency (%) and the y-axis the date. The title of the graph specifies the building to which it belongs to and the dry period date.

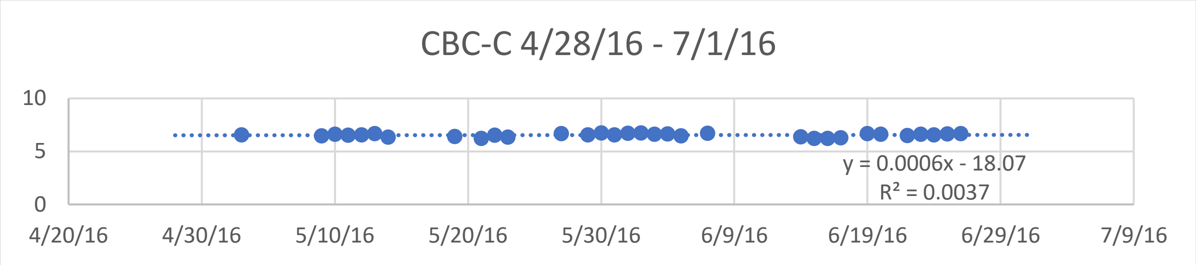


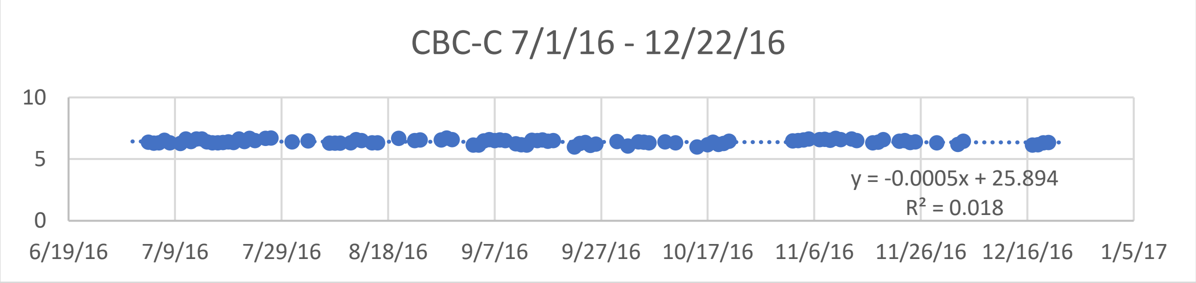


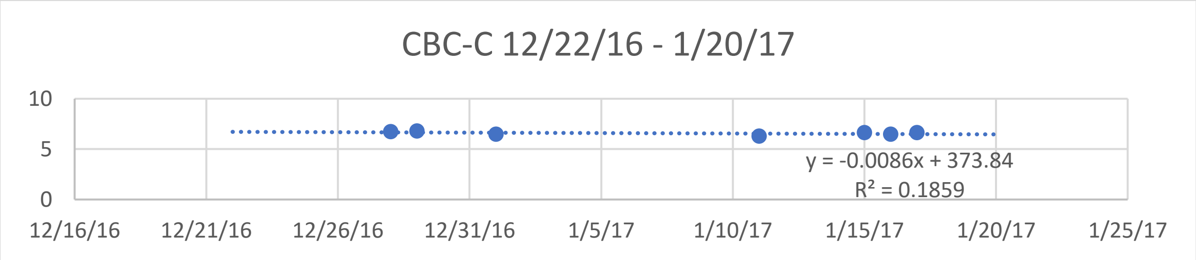


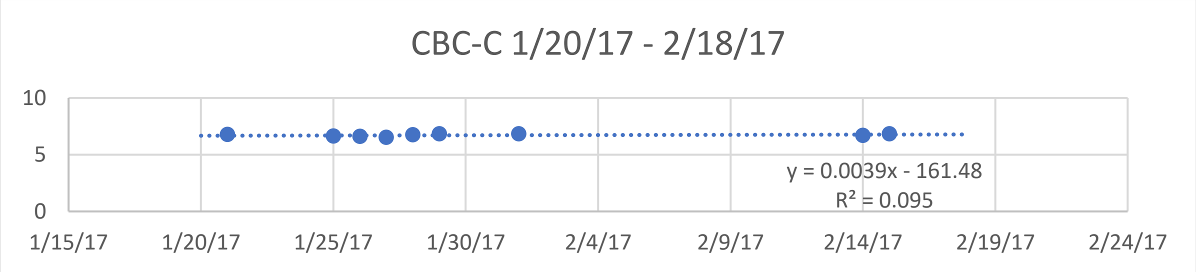


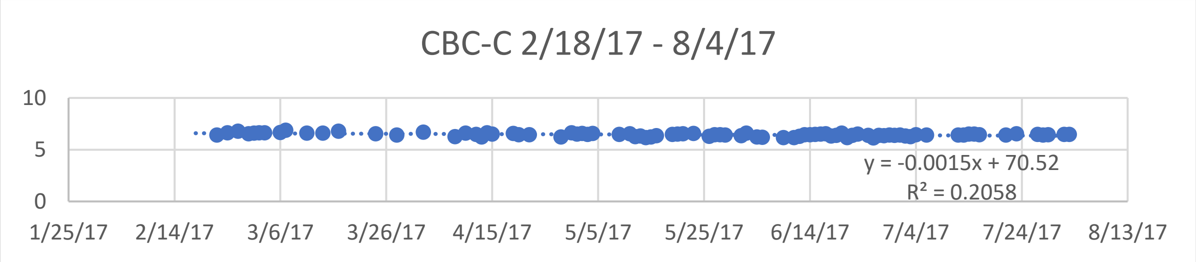


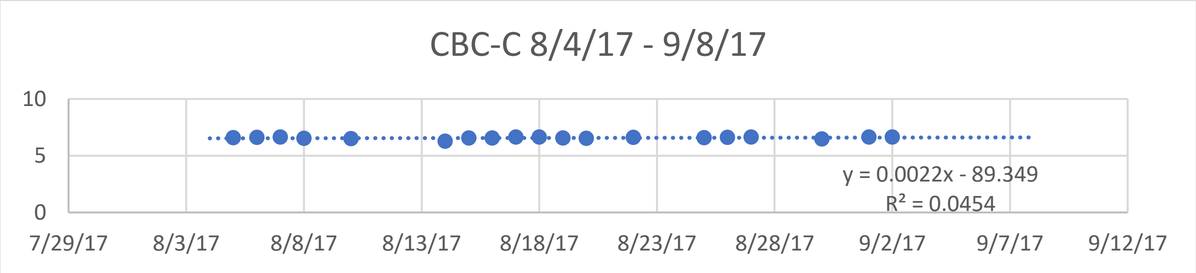

CBC-C 4/28/16 - 7/1/16
10
5
0
4/20/16
4/30/16
5/10/16
5/20/16
5/30/16
6/9/16
6/19/16
6/29/16
7/9/16
y = 0.0006x - 18.07
R² = 0.0037

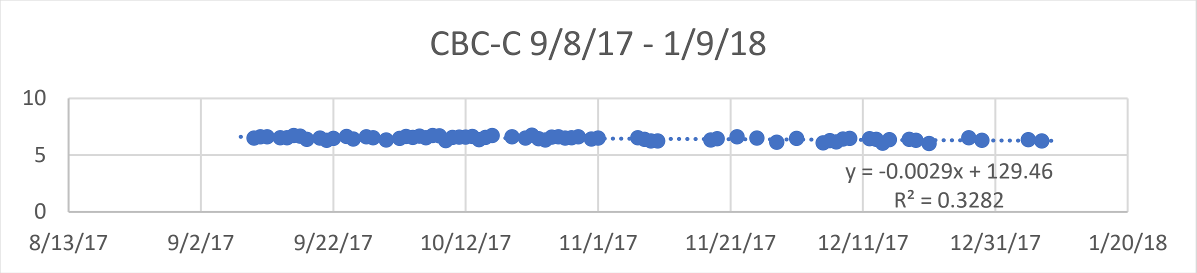

CBC-C 7/1/16 - 12/22/16
10
5
0
6/19/16
7/9/16
7/29/16
8/18/16
9/7/16
9/27/16
10/17/16
11/6/16
11/26/16
12/16/16
1/5/17
y = -0.0005x + 25.894
R² = 0.018

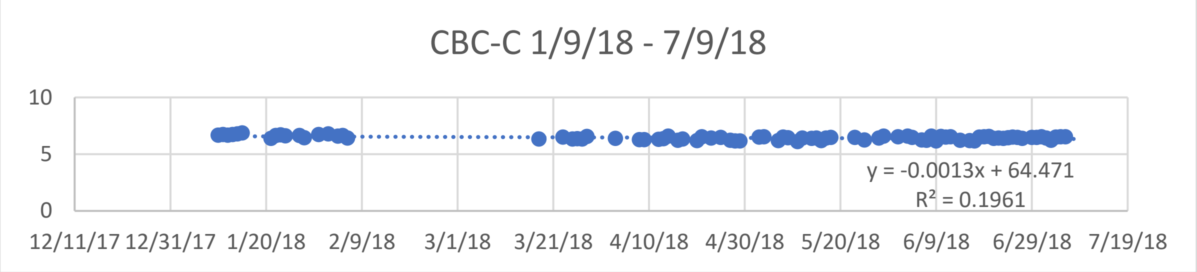

CBC-C 12/22/16 - 1/20/17
10
5
0
12/16/16
12/21/16
12/26/16
12/31/16
1/5/17
1/10/17
1/15/17
1/20/17
1/25/17
y = -0.0086x + 373.84
R² = 0.1859

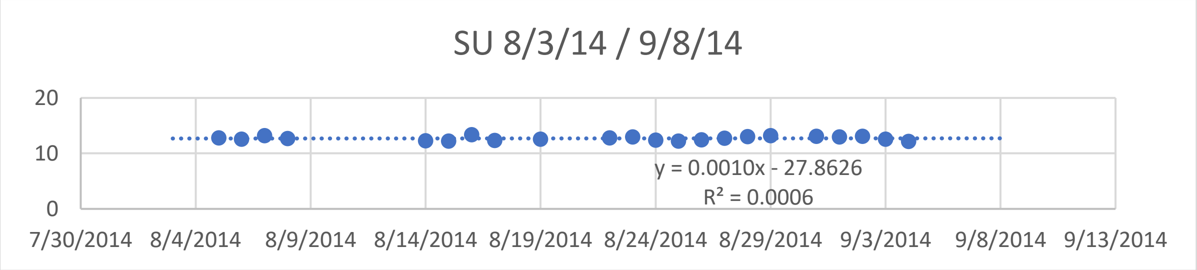

CBC-C 1/20/17 - 2/18/17
10
5
0
1/15/17
1/20/17
1/25/17
1/30/17
2/4/17
2/9/17
2/14/17
2/19/17
2/24/17
y = 0.0039x - 161.48
R² = 0.095

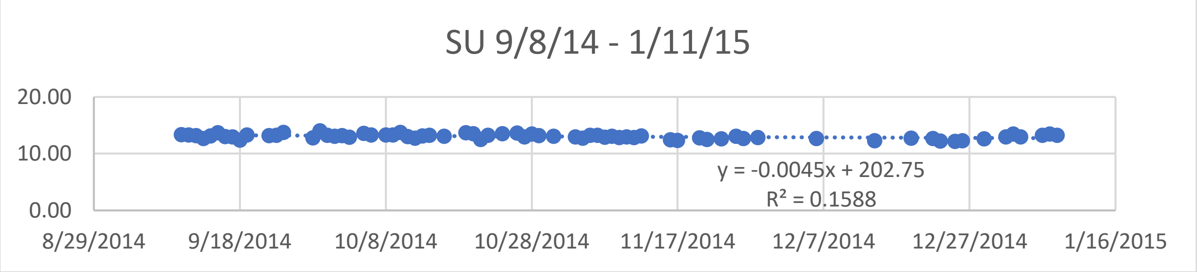

CBC-C 2/18/17 - 8/4/17
10
5
0
1/25/17
2/14/17
3/6/17
3/26/17
4/15/17
5/5/17
5/25/17
6/14/17
7/4/17
7/24/17
8/13/17
y = -0.0015x + 70.52
R² = 0.2058

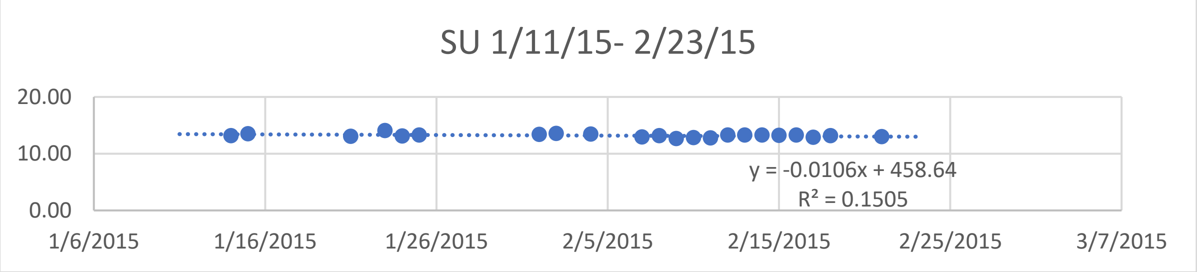

CBC-C 8/4/17 - 9/8/17
10
5
0
7/29/17
8/3/17
8/8/17
8/13/17
8/18/17
8/23/17
8/28/17
9/2/17
9/7/17
9/12/17
y = 0.0022x - 89.349
R² = 0.0454

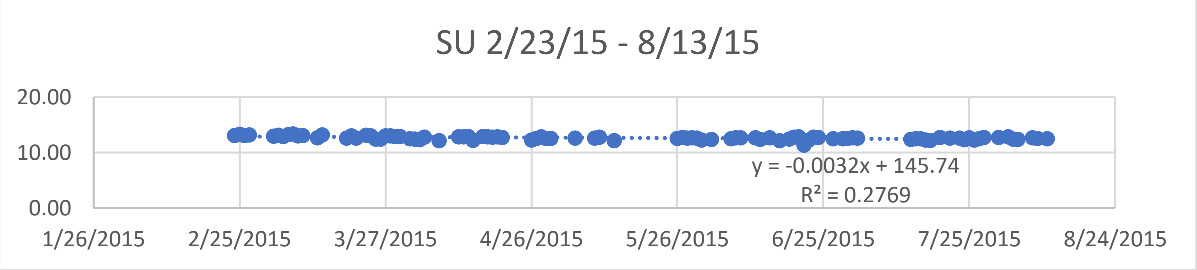

CBC-C 9/8/17 - 1/9/18
10
5
0
8/13/17
9/2/17
9/22/17
10/12/17
11/1/17
11/21/17
12/11/17
12/31/17
1/20/18
y = -0.0029x + 129.46
R² = 0.3282

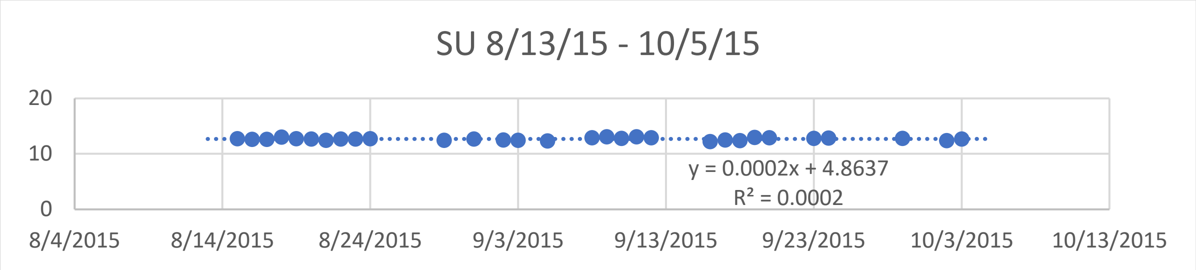

CBC-C 1/9/18 - 7/9/18
10
5
0
12/11/17
12/31/17
1/20/18
2/9/18
3/1/18
3/21/18
4/10/18
4/30/18
5/20/18
6/9/18
6/29/18
7/19/18
y = -0.0013x + 64.471
R² = 0.1961

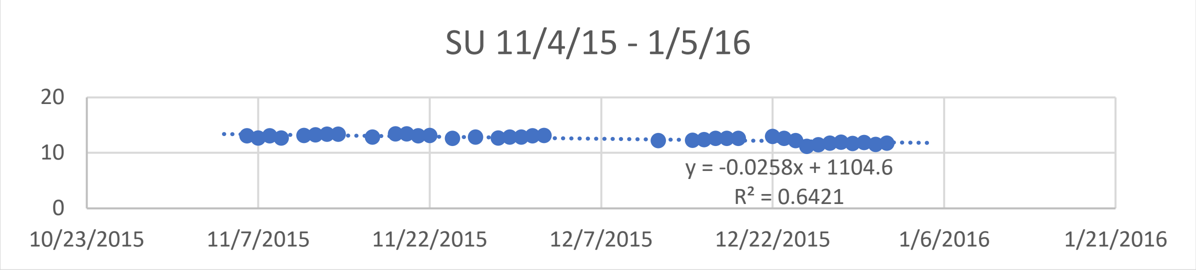

SU 8/3/14 / 9/8/14
20
10
0
7/30/2014
8/4/2014
8/9/2014
8/14/2014
8/19/2014
8/24/2014
8/29/2014
9/3/2014
9/8/2014
9/13/2014
y = 0.0010x - 27.8626
R² = 0.0006

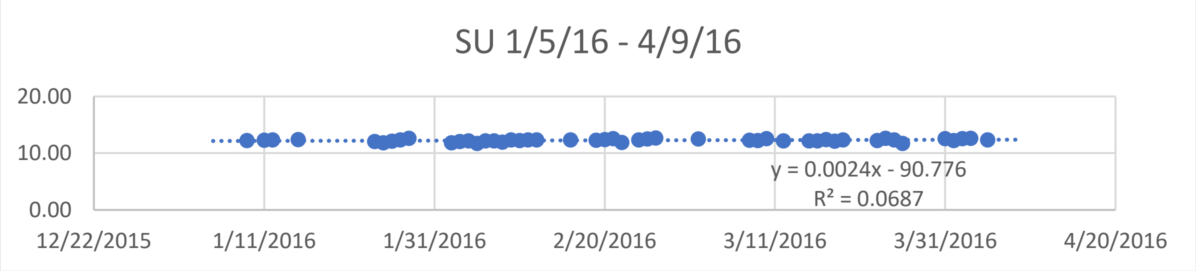

SU 9/8/14 - 1/11/15
20.00
10.00
0.00
8/29/2014
9/18/2014
10/8/2014
10/28/2014
11/17/2014
12/7/2014
12/27/2014
1/16/2015
y = -0.0045x + 202.75
R² = 0.1588

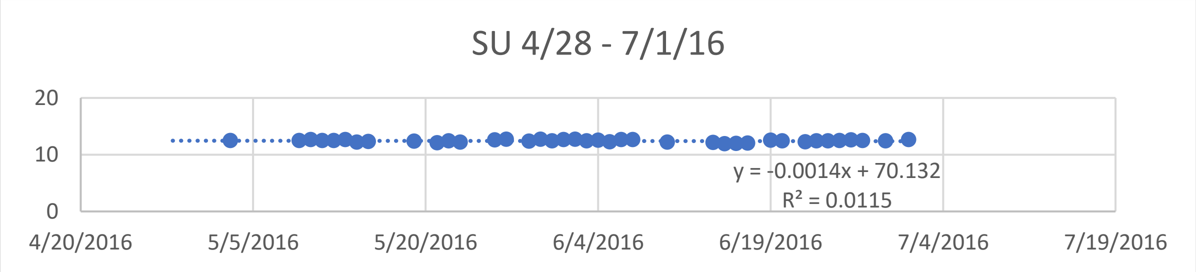

SU 1/11/15- 2/23/15
20.00
10.00
0.00
1/6/2015
1/16/2015
1/26/2015
2/5/2015
2/15/2015
2/25/2015
3/7/2015
y = -0.0106x + 458.64
R² = 0.1505

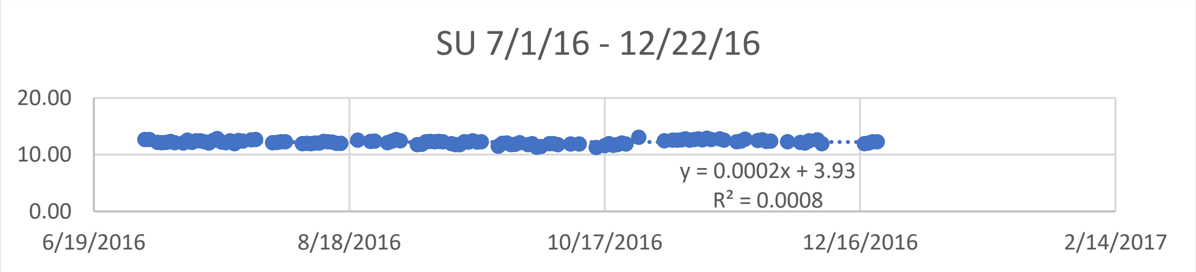

SU 2/23/15 - 8/13/15
20.00
10.00
0.00
1/26/2015
2/25/2015
3/27/2015
4/26/2015
5/26/2015
6/25/2015
7/25/2015
8/24/2015
y = -0.0032x + 145.74
R² = 0.2769

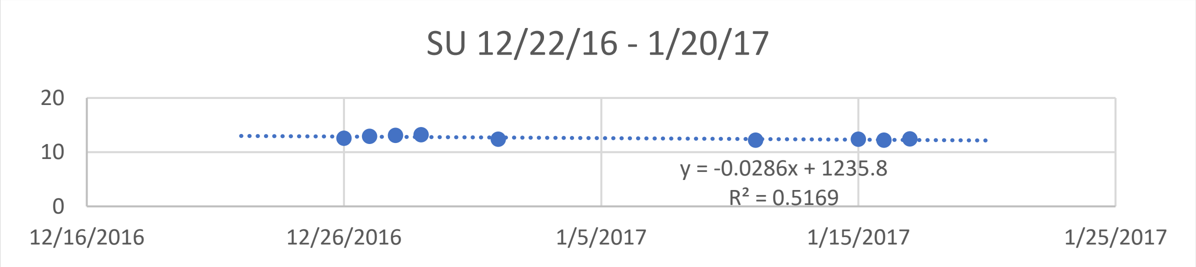

SU 8/13/15 - 10/5/15
20
10
0
8/4/2015
8/14/2015
8/24/2015
9/3/2015
9/13/2015
9/23/2015
10/3/2015
10/13/2015
y = 0.0002x + 4.8637
R² = 0.0002

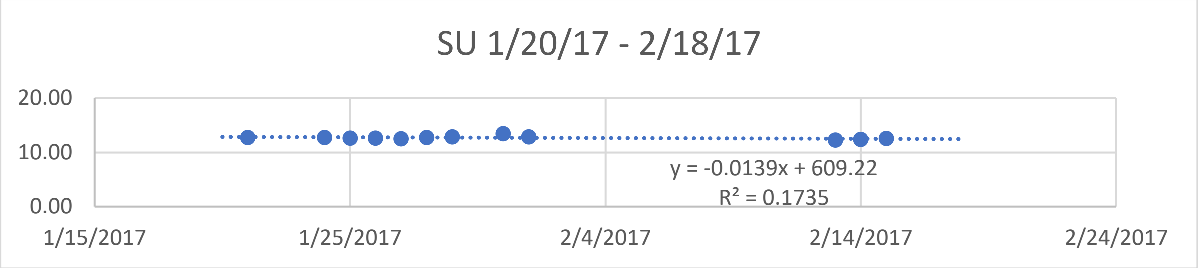

SU 11/4/15 - 1/5/16
20
10
0
10/23/2015
11/7/2015
11/22/2015
12/7/2015
12/22/2015
1/6/2016
1/21/2016
y = -0.0258x + 1104.6
R² = 0.6421

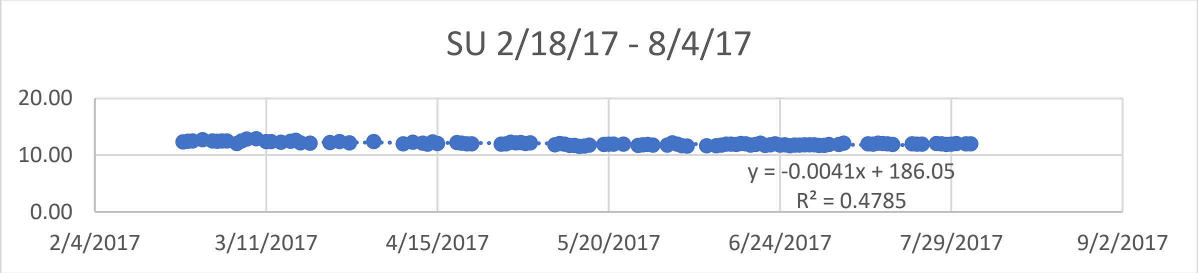

SU 1/5/16 - 4/9/16
20.00
10.00
0.00
12/22/2015
1/11/2016
1/31/2016
2/20/2016
3/11/2016
3/31/2016
4/20/2016
y = 0.0024x - 90.776
R² = 0.0687

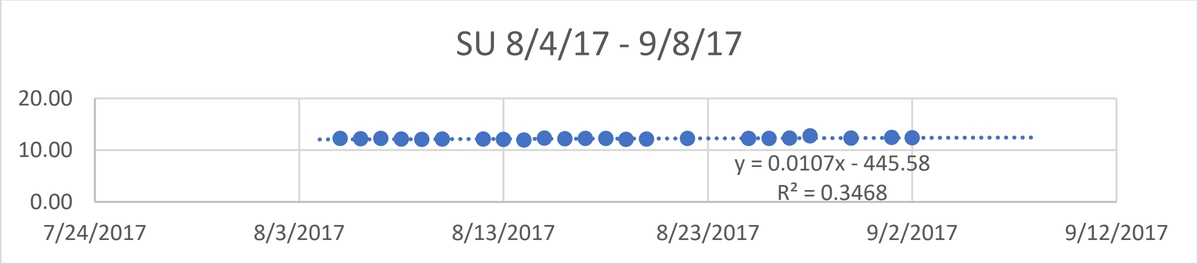

SU 4/28 - 7/1/16
20
10
0
4/20/2016
5/5/2016
5/20/2016
6/4/2016
6/19/2016
7/4/2016
7/19/2016
y = -0.0014x + 70.132
R² = 0.0115

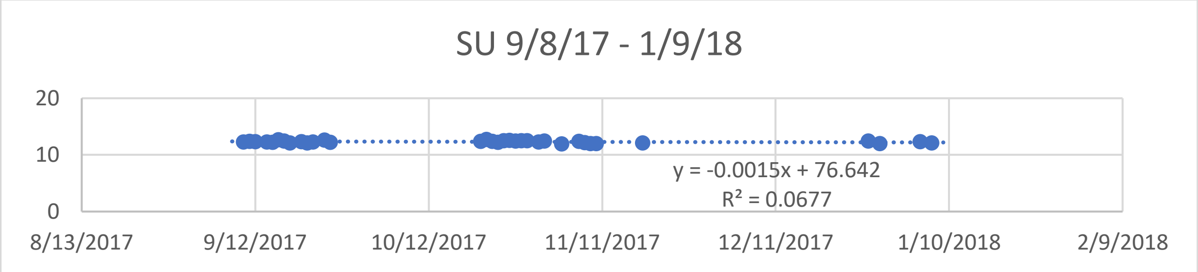

SU 7/1/16 - 12/22/16
20.00
10.00
0.00
6/19/2016
8/18/2016
10/17/2016
12/16/2016
2/14/2017
y = 0.0002x + 3.93
R² = 0.0008

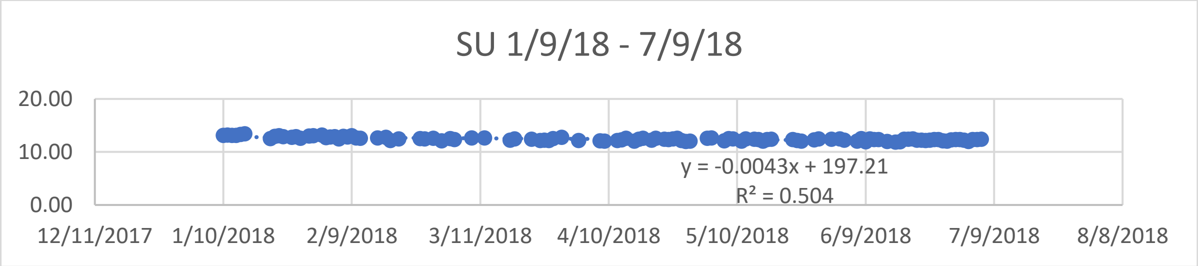

SU 12/22/16 - 1/20/17
20
10
0
12/16/2016
12/26/2016
1/5/2017
1/15/2017
1/25/2017
y = -0.0286x + 1235.8
R² = 0.5169

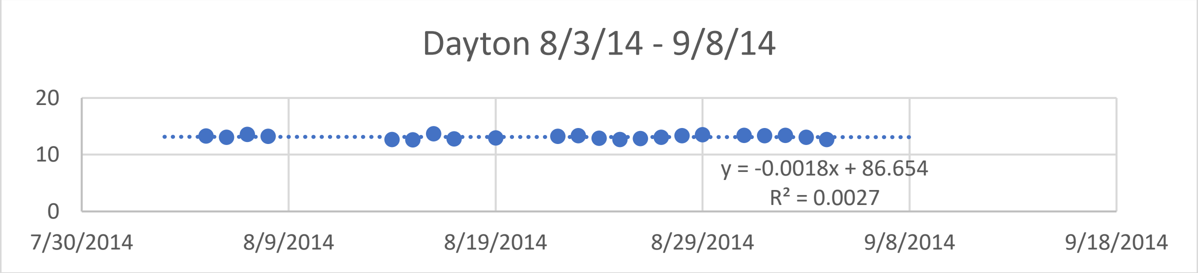

SU 1/20/17 - 2/18/17
20.00
10.00
0.00
1/15/2017
1/25/2017
2/4/2017
2/14/2017
2/24/2017
y = -0.0139x + 609.22
R² = 0.1735

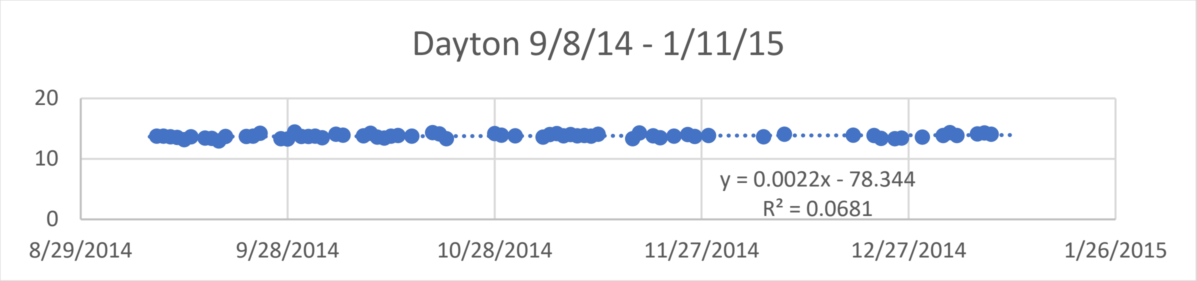

SU 2/18/17 - 8/4/17
20.00
10.00
0.00
2/4/2017
3/11/2017
4/15/2017
5/20/2017
6/24/2017
7/29/2017
9/2/2017
y = -0.0041x + 186.05
R² = 0.4785

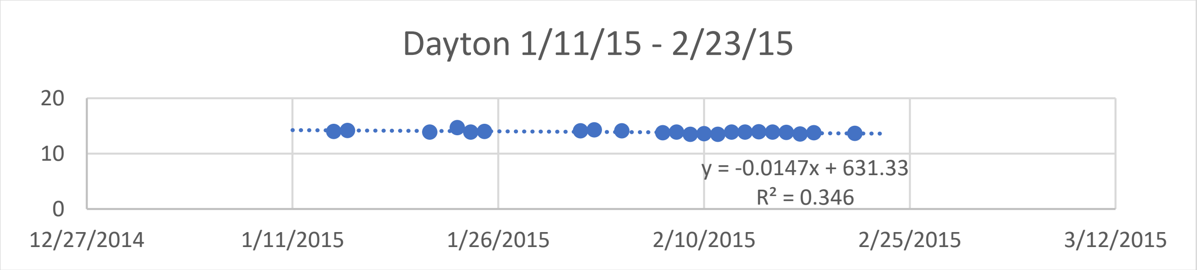

SU 8/4/17 - 9/8/17
20.00
10.00
0.00
7/24/2017
8/3/2017
8/13/2017
8/23/2017
9/2/2017
9/12/2017
y = 0.0107x - 445.58
R² = 0.3468

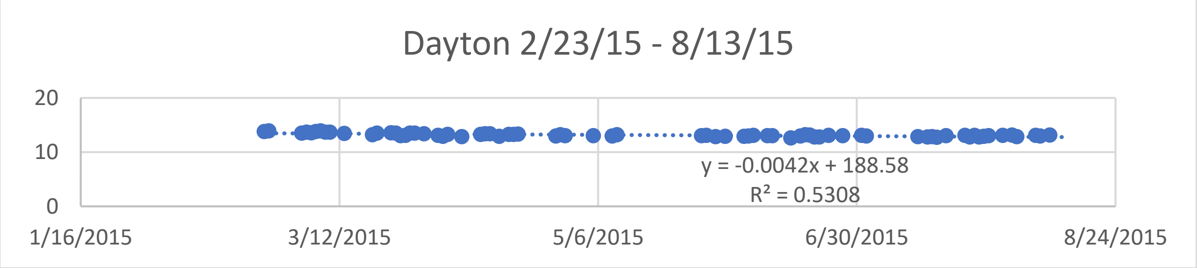

SU 9/8/17 - 1/9/18
20
10
0
8/13/2017
9/12/2017
10/12/2017
11/11/2017
12/11/2017
1/10/2018
2/9/2018
y = -0.0015x + 76.642
R² = 0.0677

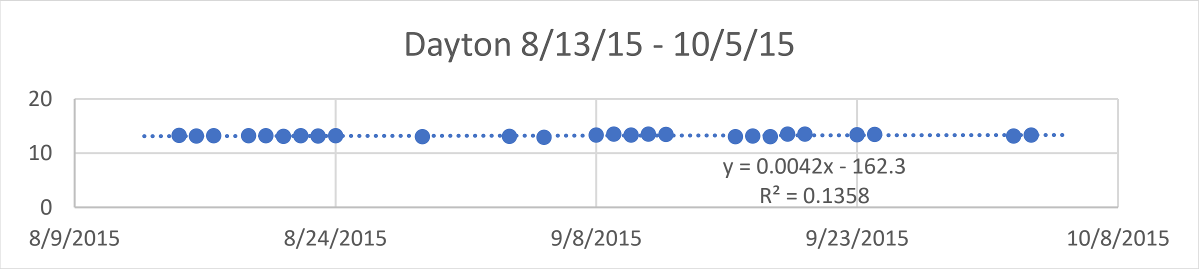

SU 1/9/18 - 7/9/18
20.00
10.00
0.00
12/11/2017
1/10/2018
2/9/2018
3/11/2018
4/10/2018
5/10/2018
6/9/2018
7/9/2018
8/8/2018
y = -0.0043x + 197.21
R² = 0.504

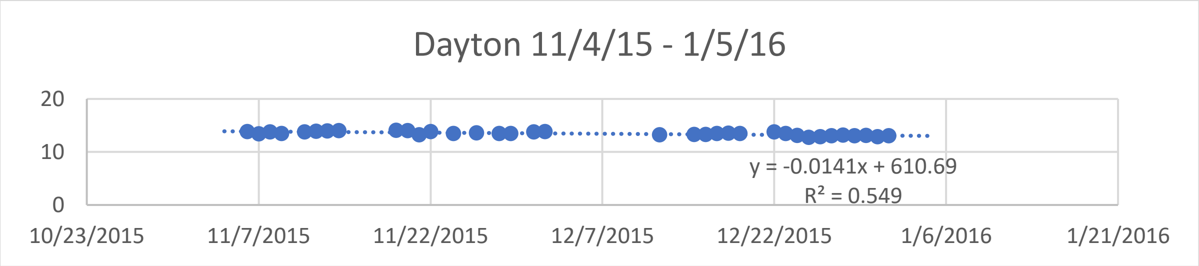

Dayton 8/3/14 - 9/8/14
20
10
0
7/30/2014
8/9/2014
8/19/2014
8/29/2014
9/8/2014
9/18/2014
y = -0.0018x + 86.654
R² = 0.0027

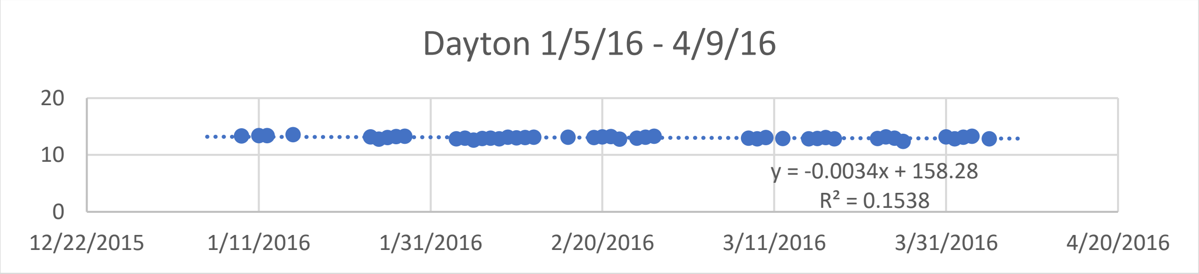

Dayton 9/8/14 - 1/11/15
20
10
0
y = 0.0022x - 78.344
R² = 0.0681
8/29/2014
9/28/2014
10/28/2014
11/27/2014
12/27/2014
1/26/2015

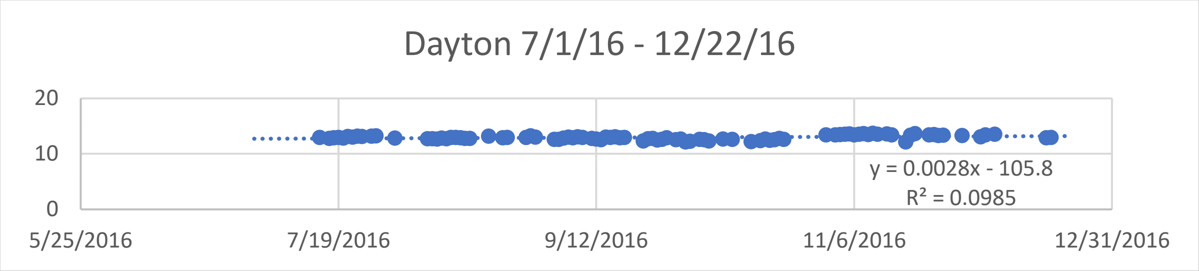

Dayton 1/11/15 - 2/23/15
20
10
0
y = -0.0147x + 631.33
R² = 0.346
12/27/2014
1/11/2015
1/26/2015
2/10/2015
2/25/2015
3/12/2015

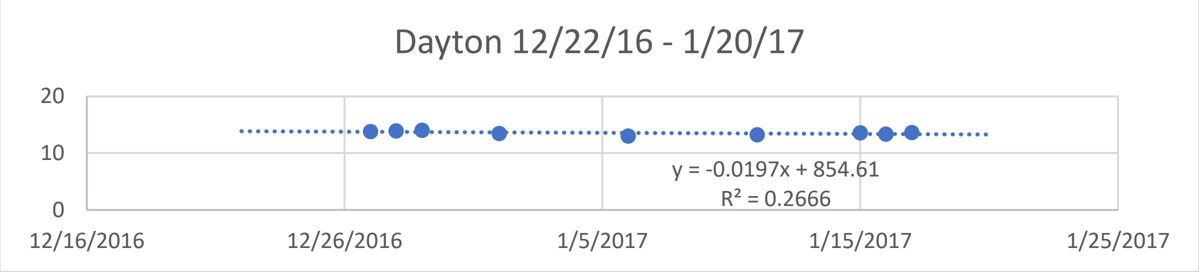

Dayton 2/23/15 - 8/13/15
20
10
0
y = -0.0042x + 188.58
R² = 0.5308
1/16/2015
3/12/2015
5/6/2015
6/30/2015
8/24/2015

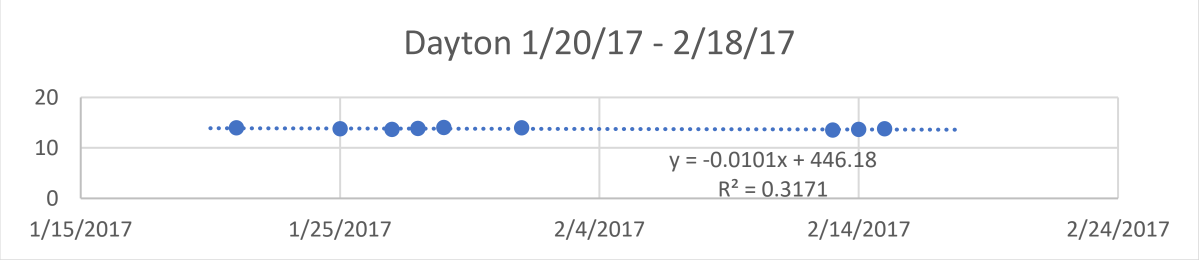

Dayton 8/13/15 - 10/5/15
20
10
0
y = 0.0042x - 162.3
R² = 0.1358
8/9/2015
8/24/2015
9/8/2015
9/23/2015
10/8/2015


Dayton 11/4/15 - 1/5/16
20
10
0
y = -0.0141x + 610.69
R² = 0.549
10/23/2015
11/7/2015
11/22/2015
12/7/2015
12/22/2015
1/6/2016
1/21/2016

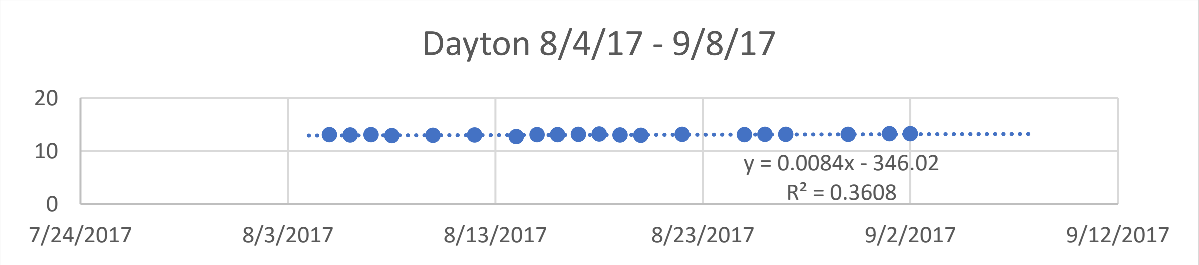

Dayton 1/5/16 - 4/9/16
20
10
0
y = -0.0034x + 158.28
R² = 0.1538
12/22/2015
1/11/2016
1/31/2016
2/20/2016
3/11/2016
3/31/2016
4/20/2016

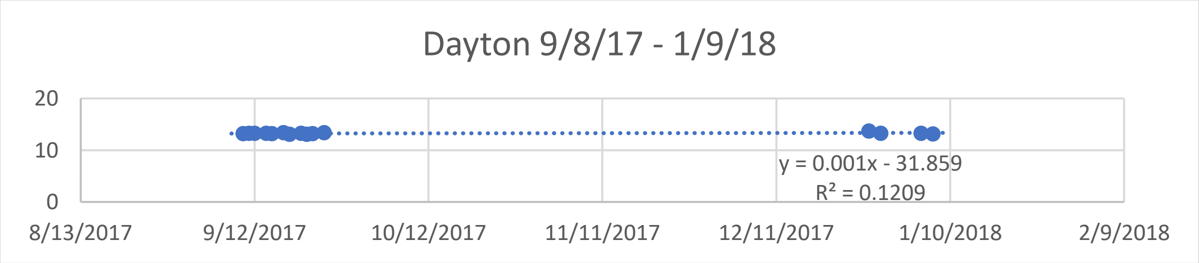

Dayton 7/1/16 - 12/22/16


Dayton 12/22/16 - 1/20/17


Dayton 1/20/17 - 2/18/17


Dayton 2/18/17 - 8/4/17


Dayton 8/4/17 - 9/8/17


Dayton 9/8/17 - 1/9/18

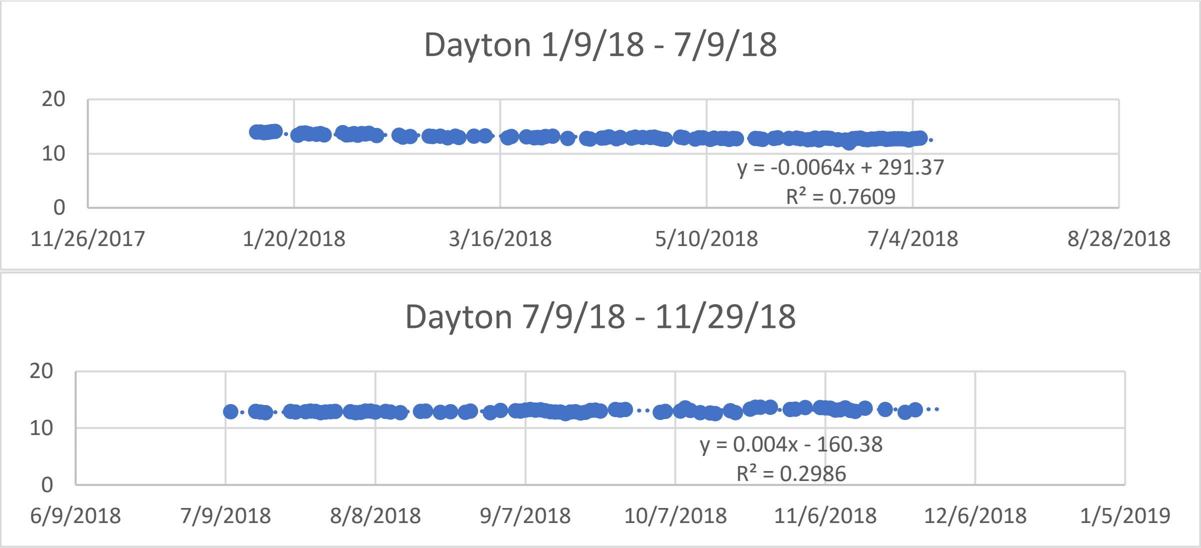
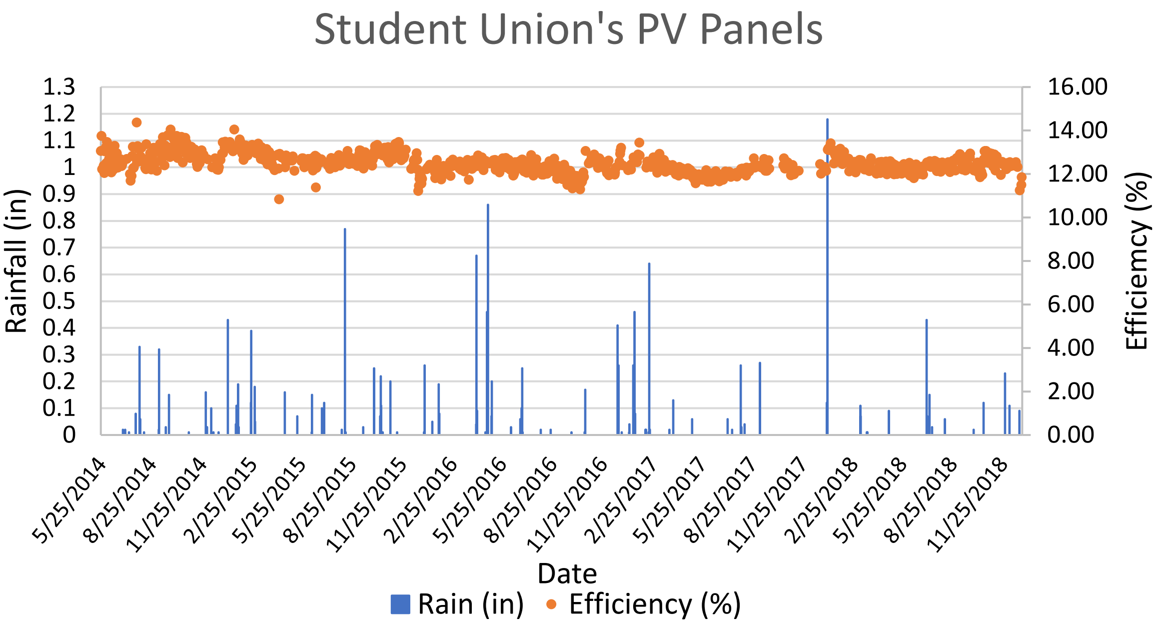
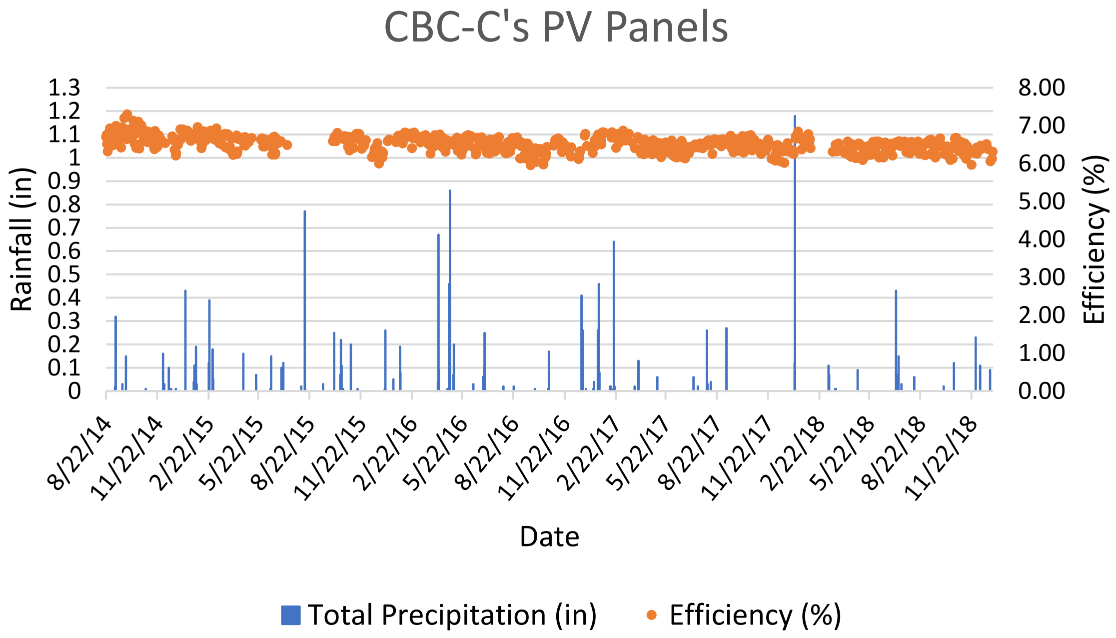


Figure G.26 – Regression Lines of Efficiency Decrease for Different Dry Periods from 2014-2018 for the PV Plants on Different Buildings at UNLV

Appendix H

Graphs of calculated efficiency for the different buildings as well as the rainfall events.





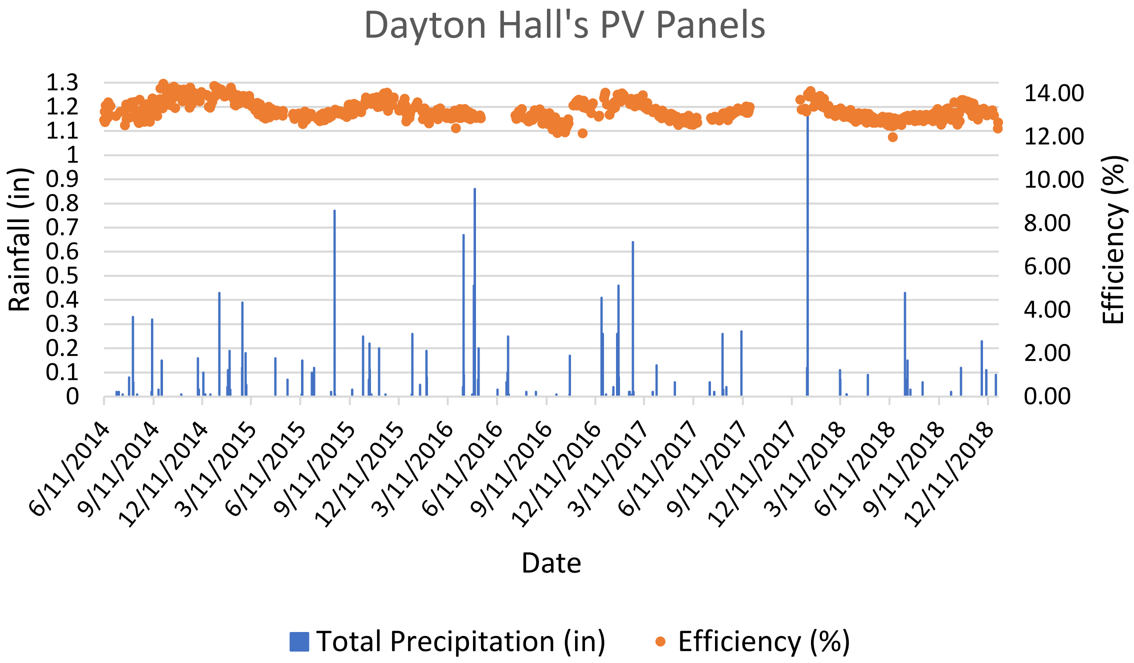


Figure H.27 – Graphs showing the Efficiency and Rainfall Events Throughout the Years for Different Buildings at UNLV

References

Ackermann, T., Andersson, G., & Soder, L. (2001). Distributed Generation : A Definition Distributed generation : a definition, *7796*(August 2016), 195–204. https://doi.org/10.1016/S0378-7796(01)00101-8

Adinoyi, M. J., & Said, S. A. M. (2013). Photovoltaic Failure Analysis : Techniques for Microelectronics and Solar. *Renewable Energy*, *60*, 633–636. https://doi.org/10.1016/j.renene.2013.06.014

Afridi, M. A., Arbab, M., Bilal, M., Ullah, H., & Ullah, N. (2017). Determining the Effect of Soiling and Dirt Particles at Various Tilt Angles of Photovoltaic Modules. *International Journal of Engineering Works*, *4*, 143–146. https://doi.org/10.5281/zenodo.838258

Al-Ammri, A. S., Ghazi, A., & Mustafa, F. (2013). Dust effects on the performance of PV street light in Baghdad city. *Proceedings of 2013 International Renewable and Sustainable Energy Conference, IRSEC 2013*, 18–22. https://doi.org/10.1109/IRSEC.2013.6529687

Al-Sabounchi, A. M., Yalyali, S. A., & Al-Thani, H. A. (2013). Design and performance evaluation of a photovoltaic grid-connected system in hot weather conditions. *Renewable Energy*, *53*, 71–78. https://doi.org/10.1016/j.renene.2012.10.039

Ali, H. M., Zafar, M. A., Bashir, M. A., Nasir, M. A., Ali, M., & Siddiqui, A. M. (2015). Effect of dust deposition on the performance of photovoltaic modules in Taxila, Pakistan. *Thermal Science*, *2015*(2), 1–11. https://doi.org/10.2298/TSCI140515046A

Arizona Corporation Commission. (n.d.-a). About Arizona Goes Solar. Retrieved September 4, 2018, from http://arizonagoessolar.org/About.aspx

Arizona Corporation Commission. (n.d.-b). Ajo Improvement Company. Retrieved September 5, 2018, from http://arizonagoessolar.org/UtilityPrograms/AjoImprovementCompany.aspx

Arizona Corporation Commission. (n.d.-c). Renewable Energy Standard & Tariff. Retrieved September 3, 2018, from https://www.azcc.gov/divisions/utilities/electric/environmental.asp

Asl-Soleimani, E., Farhangi, S., & Zabihi, M. S. (2001). The effect of tilt angle, air pollution on performance of photovoltaic systems in Tehran. *Renewable Energy*, *24*(3–4), 459–468. https://doi.org/10.1016/S0960-1481(01)00029-5

Bird, R. E., & Riordan, C. (1985). Simple Solar Spectral Model for Direct and Diffuse Irradiance on Horizontal and Tilted Planes at the Earth’s Surface for Cloudless Atmospheres. *Journal of Climate and Applied Meteorology*, *25*, 87–97.

Boeing, A. (2018). *The Impact of Waters of Low Quality on Soiling Removal from Photovoltaic Panels*. University of Nevada, Las Vegas.

Bonn, D., Eggers, J., Indekeu, J., & Meunier, J. (2009). Wetting and spreading. *Reviews of Modern Physics*, *81*(2), 739–805. https://doi.org/10.1103/RevModPhys.81.739

Bukhary, S., Ahmad, S., & Batista, J. (2017). Analyzing land and water requirements for solar deployment in the Southwestern United States. *Renewable and Sustainable Energy Reviews*, (April), 1–18. https://doi.org/10.1016/j.rser.2017.10.016

California Public Utilities Commission. (2018a). Investor-Owned Utility Solar Photovoltaic (PV) Programs. Retrieved September 10, 2018, from http://cpuc.ca.gov/RPS_SPVP/

California Public Utilities Commission. (2018b). RPS Procurement Programs. Retrieved

September 5, 2018, from http://www.cpuc.ca.gov/RPS_Procurement_Programs/

Cano, J. (2011). *Photovoltaic Modules: Effect of Tilt Angle on Soiling*. *A Thesis Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in Technology*.

Cardell, J., & Tabors, R. (1997). Operation and Control in a Competitive Market : Distributed Generation in a Restructured Industry. *The Energy Journal*, *18*, 111–136.

Caron, J. R., & Littmann, B. (2013). Direct monitoring of energy lost due to soiling on first solar modules in California. In *IEEE Journal of Photovoltaics* (Vol. 3, pp. 336–340). IEEE. https://doi.org/10.1109/JPHOTOV.2012.2216859

CEMP. (n.d.). Station Monthly Summary Las Vegas Nevada. Retrieved June 4, 2019, from https://cemp.dri.edu/cgi-bin/cemp_stations.pl?prod=5&stn=lasv

Clark County Regional Flood Control District (CCRFCD). (n.d.). Gage Data. Retrieved from http://gustfront.ccrfcd.org/gagedatalist/default.aspx

Dincer, I. (2000). Renewable energy and sustainable development: a crucial review. *Renewable and Sustainable Energy Reviews*, *4*(2), 157–175. https://doi.org/10.1016/S1364-0321(99)00011-8

Durkay, J. (2017). National Conference of State Legislatures. Retrieved April 27, 2018, from http://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

Elminir, H. K., Ghitas, A. E., Hamid, R. H., El-Hussainy, F., Beheary, M. M., & Abdel-Moneim, K. M. (2006). Effect of dust on the transparent cover of solar collectors. *Energy Conversion and Management*, *47*(18–19), 3192–3203. https://doi.org/10.1016/j.enconman.2006.02.014

Evans, D. L. (1981). Simplified method for predicting photovoltaic array output. *Solar Energy*, *27*(6), 555–560. https://doi.org/10.1016/0038-092X(81)90051-7

Frisvold, G. B., & Marquez, T. (2013). Water requirements for large-scale solar energy projects in the West. *Journal of Contemporary Water Research & Education*, *151*(1), 106–116. https://doi.org/10.1111/j.1936-704X.2013.03156.x

Governor's Office of Energy Development. (2018). Renewable Energy Systems Tax Credit. Retrieved September 10, 2018, from https://energy.utah.gov/renewabletaxcredit/

Green, M. A. (2016). Commercial progress and challenges for photovoltaics. *Nature Energy*, *1*(1), 1–4. https://doi.org/10.1038/nenergy.2015.15

Groll, M., Opp, C., & Aslanov, I. (2013). Spatial and temporal distribution of the dust deposition in central asia - results from a long term monitoring program. *Aeolian Research*, *9*, 49–62. https://doi.org/10.1016/j.aeolia.2012.08.002

Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., … Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, *29*, 766–779. https://doi.org/10.1016/j.rser.2013.08.041

Hudedmani, M. G., Joshi, G., Umayal, R. M., & Revankar, A. (2017). A Comparative Study of Dust Cleaning Methods for the Solar PV Panels. *Advanced Journal of Graduate Research*, *1*(1), 24–29. https://doi.org/10.21467/ajgr.1.1.24-29

International Finance Corporation [IFC]. (2015). *Utility-Scale Solar Photovoltaic Power Plants*. *World Bank Group*. Retrieved from https://www.ifc.org/wps/wcm/connect/f05d3e00498e0841bb6fbbe54d141794/IFC+Sola r+Report_Web+_08+05.pdf?MOD=AJPERES

Jiang, Y., Lu, L., Ferro, A. R., & Ahmadi, G. (2018). Analyzing wind cleaning process on the accumulated dust on solar photovoltaic (PV) modules on flat surfaces. *Solar Energy, 159*(April 2017), 1031–1036. https://doi.org/10.1016/j.solener.2017.08.083

Jordan, D. C., Silverman, T. J., Wohlgemuth, J. H., Kurtz, S. R., & VanSant, K. T. (2017). Photovoltaic failure and degradation modes. *PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS*, (25), 318–326. https://doi.org/10.1002/pip

Kaldellis, J. K., Kapsali, M., & Kavadias, K. A. (2014). Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece. *Renewable Energy, 66*, 612–624. https://doi.org/10.1016/j.renene.2013.12.041

Kalogirou, S. A., Agathokleous, R., & Panayiotou, G. (2013). On-site PV characterization and the effect of soiling on their performance. *Energy, 51*, 439–446. https://doi.org/10.1016/j.energy.2012.12.018

Kazem, H. A., & Chaichan, M. T. (2015). Effect of Humidity on Photovoltaic Performance Based on Experimental Study. *International Journal of Applied Engineering Research, 10*(23), 4357–43577.

Khonkar, H., Alyahya, A., Aljuwaied, M., Halawani, M., Al Saferan, A., Al-khaldi, F., … Wacaser, B. A. (2014). Importance of cleaning concentrated photovoltaic arrays in a desert environment. *Solar Energy*, *110*, 268–275. https://doi.org/10.1016/j.solener.2014.08.001

Kimball, J. S., Running, S. W., & Nemani, R. (1997). An improved method for estimating surface humidity from daily minimum temperature. *Agricultural and Forest Meteorology, 85*(1–2), 87–98. https://doi.org/10.1016/S0168-1923(96)02366-0

Kimber, A., Mitchell, L., Nogradi, S., & Wenger, H. (2006). The effect of soiling on large grid-connected photovoltaic systems in California and the Southwest Region of the United States. In *Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion, WCPEC-4* (Vol. 2, pp. 2391–2395). https://doi.org/10.1109/WCPEC.2006.279690

Kimber, Adrianne. (2007). The Effect Of Soiling On Photovoltaic Systmes Located In Arid Climates.

Köntges, M., Kurtz, S., Packard, C., Jahn, U., Berger, K. A., Kato, K., … Iseghem, M. Van. (2014). *Performance and reliability of photovoltaic systems subtask 3.2: Review of failures of photovoltaic modules : IEA PVPS task 13 : external final report IEA-PVPS*.

Legislative Counsel. Assembly Bill No. 405 (2017). Brooks, Watkins, Frierson, Yeager, McCurdy II; Araujo, Bilbray-Axelrod, Carrillo, Cohen, Diaz, Fumo, Jauregui, Joiner, Miller, Monroe- Moreno, Neal, Swank and Thompson.

Leon, W. (2012). *Designing the Right RPS: A Guide to selecting goals and program options for a Renewable Portfolio Standard*.

Lewis, N. S. (2007). Toward Cost-Effective Solar Energy Use. *Science, 315*(February), 798–802.

Lovich, J. E., & Ennen, J. R. (2011). Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States. *BioScience, 61*(12), 982–992. https://doi.org/10.1525/bio.2011.61.12.8

Lu, H., & Zhao, W. (2018). Effects of particle sizes and tilt angles on dust deposition characteristics of a ground-mounted solar photovoltaic system. *Applied Energy*, *220*(February), 514–526. https://doi.org/10.1016/j.apenergy.2018.03.095

Macknick, J., Newmark, R., Heath, G., & Hallett, K. (2011). A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies. NREL Technical Report NREL/TP-6A20-50900, (March), 23.

Maghami, M. R., Hizam, H., Gomes, C., Radzi, M. A., Rezadad, M. I., & Hajighorbani, S. (2016). Power loss due to soiling on solar panel: A review. *Renewable and Sustainable Energy Reviews*, *59*, 1307–1316. https://doi.org/10.1016/j.rser.2016.01.044

Mani, M., & Pillai, R. (2010). Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. *Renewable and Sustainable Energy Reviews*, *14*(9), 3124–3131. https://doi.org/10.1016/j.rser.2010.07.065

Martinez-Plaza, D., Abdallah, A., Figgis, B. W., & Mirza, T. (2015). Performance Improvement Techniques for Photovoltaic Systems in Qatar: Results of First year of Outdoor Exposure. *Energy Procedia*, *77*(August), 386–396. https://doi.org/10.1016/j.egypro.2015.07.054

Massi Pavan, A., Tessarolo, A., Barbini, N., Mellit, A., & Lughi, V. (2011). The effect of soiling on energy production for large-scale photovoltaic plants. *Solar Energy*, *117*(5), 282–289. https://doi.org/10.1016/j.solener.2015.05.003

Masters, G. M. (2013). Photovoltaic Materials And Electrical Characteristics. In *Renewable And Efficient Electric Power Systems* (Second Edi, pp. 253–315). Hoboken: John Wiley & Sons, Inc. https://doi.org/10.1136/bmj.39395.370278.80

Mejia, F. A., & Kleissl, J. (2013a). Soiling losses for solar photovoltaic systems in California. *Solar Energy*, *95*, 357–363. https://doi.org/10.1016/j.solener.2013.06.028

Mejia, F. A., & Kleissl, J. (2013b). Soiling losses for solar photovoltaic systems in California. *Solar Energy*, *95*, 357–363. https://doi.org/10.1016/j.solener.2013.06.028

Mejia, F., Kleissl, J., & Bosch, J. L. (2013). The effect of dust on solar photovoltaic systems. *Energy Procedia*, *49*, 2370–2376. https://doi.org/10.1016/j.egypro.2014.03.251

Mekhilef, S., Saidur, R., & Kamalisarvestani, M. (2012). Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. *Renewable and Sustainable Energy Reviews*, *16*(5), 2920–2925. https://doi.org/10.1016/j.rser.2012.02.012

Mohave Electric Company. (2017). Sunwatts Renewable Energy Incentive Program. Retrieved September 5, 2018, from http://www.mohaveelectric.com/content/sunwatts-renewable-energy-incentive-program

NASA. (n.d.). Dust Deposition in Southern Nevada and California. Retrieved from https://cmr.earthdata.nasa.gov/search/concepts/C1214613246-SCIOPS

National Renewable Energy Laboratory. (n.d.). Solar Research - Utah. Retrieved September 10, 2018, from https://www.nrel.gov/solar/rps/ut.html

National Technology and Engineering Solutions of Sandia. (2018). Plane of Array (POA) Irradiance. Retrieved from https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/plane-of-array-poa-irradiance/

Navidi, W. (2015). *Statistics for Engineers & Scientists* (4th Editio). New York: McGraw-Hill Education.

Nelson, V., & Starcher, K. (2016a). Photovoltaics. In A. Ghassemi (Ed.), *Introduction to Renewable Energy* (Second Edi, pp. 105–135). Boca Raton: CRC Press.

Nelson, V., & Starcher, K. (2016b). Sun. In *Introduction to Renewable Energy* (pp. 39–57).

NREL. (2019). Measurement and Instrumentation Data Center (MIDC). Retrieved from https://midcdmz.nrel.gov/apps/go2url.pl?site=UNLV

NV Energy. (2019). Energy Pricing Plans. Retrieved from https://www.nvenergy.com/account-services/energy-pricing-plans

Ogren, J. A., Groblicki, P. J., & Charlson, R. J. (1984). Measurement of the removal rate of elemental carbon from the atmosphere. In *Science of the Total Environment, The* (Vol. 36, pp. 329–338). https://doi.org/10.1016/0048-9697(84)90284-5

PUCN. (2017a). Net Metering in Nevada. Retrieved from http://puc.nv.gov/Renewable_Energy/Net_Metering/

PUCN. (2017b). Renewable Energy Rebate Programs. Retrieved July 20, 2018, from http://puc.nv.gov/Renewable_Energy/Renewable_Energy_Programs/

PUCN. (2017c). Renewable Energy Statutes & Regulations. Retrieved July 20, 2018, from http://puc.nv.gov/Renewable_Energy/RPS/Statutes_Regulations/

PUCN. (2017d). Renewable Portfolio Standard. Retrieved July 20, 2018, from http://puc.nv.gov/Renewable_Energy/Portfolio_Standard/

PUCN. (2017e). Solar Enenergy Systems Incentive Program. Retrieved July 20, 2018, from http://puc.nv.gov/Renewable_Energy/Renewable_Programs/Solar_Energy/

PUCN. (2019). Renewable Energy Projects Approved and/or Permitted by the PUCN.

Retrieved from http://puc.nv.gov/Renewable_Energy/ApprovedREFacilities/

Qasem, H., Betts, T. R., Müllejans, H., AlBusairi, H., & Gottschalg, R. (2014). Dust-induced shading on photovoltaic modules. *PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS*, (22), 218–226. https://doi.org/10.1002/pip.2230

Rajput, D. S., & Sudhakar, K. (2013). Effect of dust on the performance of solar PV panel. *International Journal of ChemTech Research*, *5*(2), 1083–1086.

Rao, A., Pillai, R., Mani, M., & Ramamurthy, P. (2014). Influence of dust deposition on photovoltaic panel performance. *Energy Procedia*, *54*, 690–700. https://doi.org/10.1016/j.egypro.2014.07.310

Reheis, M. C. (2013). Dust Deposition in Nevada, California, and Utah, 1984-2002. Retrieved from https://pubs.usgs.gov/of/2003/ofr-03-138/

Rehman, S., & El-Amin, I. (2012). Performance evaluation of an off-grid photovoltaic system in Saudi Arabia. *Energy*, *46*(1), 451–458. https://doi.org/10.1016/j.energy.2012.08.004

Reitan, C. H. (1963). Surface Dew Point and Water Vapor Aloft. *Journal of Applied Meteorology*, *2*(6), 776–779. https://doi.org/10.1175/1520-0450(1963)002<0776:SDPAWV>2.0.CO;2

Sayyah, A., Horenstein, M. N., & Mazumder, M. K. (2014). Energy yield loss caused by dust deposition on photovoltaic panels. *Solar Energy*, *107*, 576–604. https://doi.org/10.1016/j.solener.2014.05.030

Schill, C., Brachmann, S., Heck, M., Weiss, K.-A., & Koehl, M. (2011). Impact of heavy soiling on the power output of PV modules. *Reliability of Photovoltaic Cells, Modules,* *Components, and Systems IV*, *8112*(September 2011), 811207. https://doi.org/10.1117/12.893721

Sharma, D., & Bartels, R. (1997). Distributed Electricity Generation in Competitive Energy Markets : A Case Study in Australia. *The Energy Journal*, *18*, 17–39.

Skoplaki, E., & Palyvos, J. A. (2008). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy*, *83*(5), 614–624. https://doi.org/10.1016/j.solener.2008.10.008

SMA Solar Technology. (2019). Sunny Portal. Retrieved from https://www.sunnyportal.com/Templates/Start.aspx?ReturnUrl=%2F

Tan, W. S., Hassan, M. Y., Majid, M. S., & Abdul Rahman, H. (2013). Optimal distributed renewable generation planning: A review of different approaches. *Renewable and Sustainable Energy Reviews*, *18*, 626–645. https://doi.org/10.1016/j.rser.2012.10.039

Thornton, P. E., Hasenauer, H., & White, M. A. (2000). Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: An application over complex terrain in Austria. *Agricultural and Forest Meteorology*, *104*(4), 255–271. https://doi.org/10.1016/S0168-1923(00)00170-2

Time and Date AS. (2019). Las Vegas, Nevada, USA — Sunrise, Sunset, and Daylength. Retrieved from https://www.timeanddate.com/sun/usa/las-vegas

Turner, J. A. (1999). A Realizable Renewable Energy Future. *Science*, *285*(5428), 687–689. https://doi.org/10.1126/science.285.5428.687

U.S. Department Of The Interior Bureau Of Land Management. (n.d.). Retrieved April 26, 2018, from https://www.blm.gov/programs/energy-and-minerals/renewable-energy/solar-energy

Unger. (n.d.). Pure Water Cleaning. Retrieved from https://usa.ungerglobal.com/product-category/pure-water-cleaning/

United States Environmental Protection Agency. (2018a). About the U.S. Electricity System and its Impact on the Environment. Retrieved September 18, 2018, from https://www.epa.gov/energy/about-us-electricity-system-and-its-impact-environment

United States Environmental Protection Agency. (2018b). Centralized Generation of Electricity and its Impacts on the Environment. Retrieved September 18, 2018, from https://www.epa.gov/energy/centralized-generation-electricity-and-its-impacts-environment

United States Environmental Protection Agency. (2018c). Distributed Generation of Electricity and its Environmental Impacts. Retrieved September 18, 2018, from https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts

Vasel, A., & Iakovidis, F. (2017). The effect of wind direction on the performance of solar PV plants. *Energy Conversion and Management*, *153*(August), 455–461. https://doi.org/10.1016/j.enconman.2017.09.077

Walpole, R. E., & Myers, R. H. (1989). *Probability and Statistics for Engineers and Scientists* (4th Editio). New York: Macmillan Publishing Company.

Xu, R., Ni, K., Hu, Y., Si, J., Wen, H., & Yu, D. (2017). Analysis of the optimum tilt angle for a soiled PV panel. *Energy Conversion and Management*, *148*, 100–109. https://doi.org/10.1016/j.enconman.2017.05.058

Zhang, X. X., Sharratt, B., Chen, X., Wang, Z. F., Liu, L. Y., Guo, Y. H., … Yang, W. Y. (2017). Dust deposition and ambient PM10 concentration in northwest China: Spatial and temporal variability. *Atmospheric Chemistry and Physics*, *17*(3), 1699–1711. https://doi.org/10.5194/acp-17-1699-2017

Zorrilla-Casanova, J., Piliougine, M., Carretero, J., Bernaola, P., Carpena, P., Mora-Lopez, L., & Sidrach-de-Cardona, M. (2011). Analysis of dust losses in photovoltaic modules. *World Renewable Energy Congress 2011 -- Sweden*, 2985–2992. https://doi.org/10.3384/ecp110572985

CURRICULUM VITAE

Graduate College

University of Nevada, Las Vegas

Amanda Mayumi Tanaka

amandatanaka02@gmail.com

Education:

B.S., Environmental Chemistry, December 2015; Universidade de Sao Paulo, Brazil

Dissertation Title:

Investigation of Efficiency Loss of Distributed Solar Power Due to Soiling and Efficiency Recovery by Rainfall

Dissertation Examination Committee:

Chairperson, Dr. Jacimaria Batista, Ph.D.

Committee Member, Dr. Sajjad Ahmad, Ph.D.

Committee Member, Dr. Dave James, Ph.D.

Committee Member, Dr. Monika Neda, Ph.D.

Graduate College Representative, Dr. Shubhra Bansal, Ph.D.