University of Southern Queensland
Faculty of Engineering and Surveying

Home based solar power grid system monitoring, service, storm damage protection and recycling.

A dissertation submitted by

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Abstract

This research project is being conducted with the aim of understanding home based solar power grid system monitoring, service, storm damage protection and recycling options that are available and how these can be implemented into current installations and installation processes. This project idea has arisen due to solar PV installations being installed at an increased rate within Australia and worldwide, with no consideration for maintaining the efficiency and integrity of these panels once installed and how to maximise the life expectancy of these installations.

This report aims to investigate maintenance strategies that have been researched, and the identification of the most ideal strategies to implement in Australia, and more specifically the Gladstone region. These maintenance strategies will be modelled in MATLAB using the various environmental conditions that may be experienced by a solar PV installation. This will lead the research further into exploring storm damage protection options available to ensure the solar panel integrity and life-expectancy of the panel is maintained.

Due to the increased popularity of solar PV panel installations across the world, the materials used to manufacture these panels can become less resistant to storms due to the cheaper materials being used to make it affordable and more attractive for the customers installing these panels. Solar panels have an end-of-life expectancy and another revelation that has been made is the lack of recycling options available for these panels. Recycling options will be discussed, as well as research around what options are currently available for recycling, and what the benefits are for this process.

Simulation tools within MATLAB will be utilised throughout this research project, and various literature reviews will be conducted to understand what current practices exist or have been further explored. This project aims to provide a suggested maintenance strategy that will be suitable for the Gladstone region, storm damage protection options for the weather conditions experienced in this region as well as recycling options that could be implemented to ensure the whole life-cycle of the panel is sustainable and reduces our contributions to climate change.

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Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses, and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Ainsley Cooper - [redacted]

10/10/2023

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1. Introduction

Project Title

Home based solar power grid system monitoring, service, storm damage protection and recycling.

Background information

Renewable energy is a topic currently being discussed worldwide, specifically focussing on what communities, the government and businesses are doing to ensure appropriate actions are taken to minimise our effect on climate change as a result of carbon emissions and pollution.

Solar energy is a form of renewable energy, converting the light and heat energy produced from sunlight into energy. This harnessed energy can be converted into electricity or used as a thermal heating source for substances such as air and water.

Solar energy which uses light to generate electricity is called Solar Photovoltaic (PV), and this process occurs with the use of a solar PV cell which converts this light energy into electricity (AREA 2023). Solar PV panels are Australia's most common and widespread form of solar energy, and in Australia as of the 31st of January 2022, 3 million rooftop solar photovoltaic panels have been installed in various locations across Australia. Australia is one of the leading countries in solar photovoltaic installations worldwide, with approximately 30% of residents having these installations at home (DCCEEW 2023).

Solar PV systems are highly encouraged across Australia as these installations will assist the country in achieving the renewable energy target of net zero emissions before 2050, a target set by the government to ensure we actively play our part in ensuring renewable energy is introduced into our everyday lives, as well as ensuring we create a sustainable future for the world (The Hon Angus Taylor MP 2021).

With the significant increase in solar PV installations across Australia, it is important that we understand how to appropriately maintain and recycle these installations to ensure we continue to maintain a renewable future, whilst also achieving the maximum efficiency possible from the solar installations. This has led to the topic of this research paper, focussing on research around home based solar power grid system monitoring, service, storm damage protection and recycling. This research paper will further explore what current maintenance strategies that can be implemented to ensure the solar PV systems are maintained to increase life expectancy as well as electricity generation. It has been identified that currently solar panels are installed with no maintenance strategies put in place to maintain these installations. Further exploration and discussion into storm damage protection options will be conducted, as Australia is exposed to various natural disaster and drastic weather conditions, therefore ensuring the appropriate protection is in place for these solar panels is of upmost importance. With solar panels increasing dramatically in popularity as a form of renewable energy, it is critical to understand what end of life options are available to dispose of the solar panels effectively so that waste generated from these panels is kept to a minimum. We need to ensure that the waste produced as a result of the disposal of these panels, does not outweigh the positive environmental impact this renewable energy is having, and therefore further highlights the importance of adequate maintenance practices to extend the lifespan of these installations not only for Australia, but globally.

What is the problem?

With Solar PV installations becoming increasingly popular not only across Australia, but worldwide, it has become apparent that very little research has been conducted to understand what effective maintenance practices can be implemented to ensure solar panels continue to operate at their maximum efficiency for years after installation. Ensuring these maintenance practices are incorporated throughout the life span will increase the reliability of the panel as well as the overall life expectancy. This leads onto the next problem that needs to be further investigated, involving what recycling practices are currently in place or could be introduced once a solar panel reaches its end of life. Solar panels are being installed to reduce our impact on the environment, as well as positively contributing the reaching the net zero emission targets, significantly reducing our effects on climate change. This highlights the importance of ensuring that these solar panel installations do not generate excessive waste once they reach their end-of-life period, as this will create a further problem which needs to be addressed in future years. Ensuring adequate storm damage protection options are also discussed will also ensure that maximum efficiency of solar panels is maintained as well as promoting an increased life expectancy, and therefore this will also be further investigated as it is a contributing factor to the initial problem of maintenance strategies and recycling of a solar panel once installed.

Project Aim

To investigate a home-based solar panel installation and understand how the efficiency can be improved by implementing effective maintenance practices, monitoring and storm damage protection. The system performance will be analysed, specifically understanding the effect environmental factors contribute to performance efficiency and further, how recycling can be initiated for solar panels at their end of life.

Project Objectives

1. Review and research relevant technical information and background information regarding the solar panel its current installation/maintenance practices.
2. Understand/research potential environmental factors that may be encountered in a home-based installation. Solar panel efficiency and potential influences because of these conditions would need to be further analysed.
3. Gather data for different solar panel installations across Australia based off different environmental conditions that may be experienced.
4. Create a model to represent this system for easy simulation, use the different data gathered to simulate these various solar panel installation conditions experienced across Australia.
5. Review potential maintenance strategies which could be implemented and then replicate these using the modelling software.
6. Research potential storm damage protection options and provide a solution which is practical in an industrial setting, if possible, introduce this into the modelling software to understand the potential benefits of this design.
7. Understand and demonstrate options for recycling solar panels which have reached end of life.

2. Literature Review

Review and research relevant technical information and background information regarding the solar panel its current installation/maintenance practices.

1. A comprehensive review of automatic cleaning systems of solar panels

Solar PV installations harness the energy produced by sunlight to generate an electrical output. This output of electrical energy produced can be affected by various environmental factors that are naturally occurring because of the environment the solar PV systems are installed in. Upon investigating the affect varying environmental conditions have on solar panel installations, it was identified that dust accumulation on these panels is the greatest contributing factors to reduced efficiency of these installations.

Figure 1 represents a study conducted displaying the effect on current and power as voltage increases for a solar PV installation. This is graphed comparing a clean panel with two different dust accumulation densities (Derakhshandeh et al. 2021).

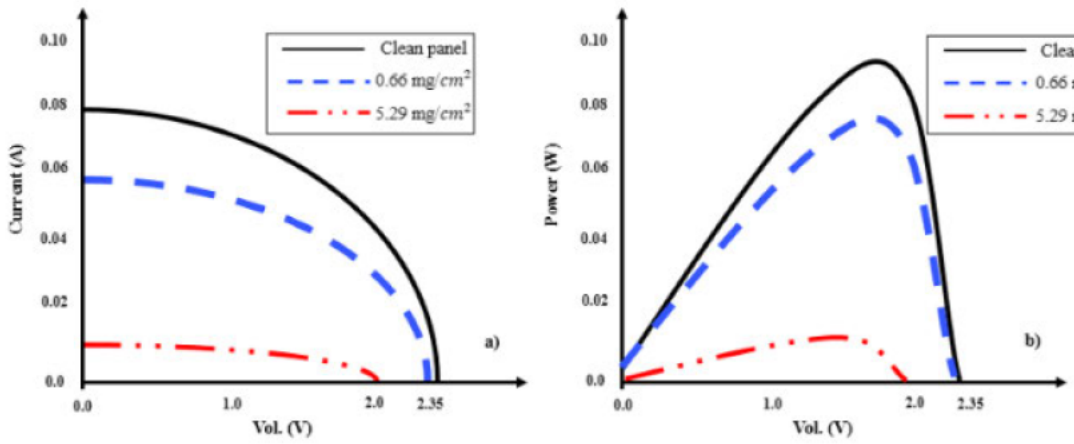

Figure 1 - Dust density accumulation and the effect on current and power as voltage increases (Derakhshandeh et al. 2021).

Through the studies conducted it was identified that the following conditions will have the most significant effect on the solar PV installation and the efficiency of these installations. It was also discussed that both environmental and non-environmental conditions can significantly affect the efficiency of the panels, with non-environmental conditions being introduced through conditions such as atmospheric pollution (Derakhshandeh et al. 2021).

Conditions affecting solar installations include:

- Humidity
- Wind speed
- Precipitation
- Temperature
- Atmospheric pollution
- Dust accumulation
- Bird droppings

The research paper further focusses on the existing and most common cleaning systems implemented for solar PV installations to reduce the effect of dust accumulation on these panels. There are two types of systems available to maintain solar panels which can be further categorised and identified as either being a passive or active cleaning system.

A system which is passive does not require any power input to allow the cleaning system to be functional. Examples of a passive system would be the coating method, or manual cleaning using physical labour (Derakhshandeh et al. 2021).

An active system can be described as an automatic system which requires input power to allow for self-cleaning to occur on the panel. Examples of this type of cleaning method can include, electrostatic and mechanical methods such as robotic cleaning systems, or vacuum systems introduced on the panel (Derakhshandeh et al. 2021).

The research paper has displayed pros and cons of various systems implemented for the cleaning of solar panels that are both passive and active systems. The author uses information gathered from a range of different scholars to present this information in a tabular form as displayed below.

Proposed Method	Mechanism	Pros	Cons	Efficiency improvement
Spraying water over PV (Active system)	Remove dust from PV panels by using a water pumping system.	- Cost-effective - Reduce the temperature of PV - Exhibit long-term life recovery - Can be used in hot weather	- It requires water - It needs work to clean and remove sticky particles - It needs maintenance for the water pumping systems.	- Improving PV cell efficiency up to 3.26%.
Vacuum suction cleaner(Active system)	The air pump creates a partial vacuum to suck up dust and dirt.	- Efficient. - Automated cleaning. - No need for regular maintenance - Reasonable cost	- Power consumption that might reach to loss equals the loss of power caused by dirt.	- Up to 50%.
- Ultrasonic system for cleaning solar panels - Using FEM and Exp. Tests (Active system)	- Ultrasonic cleaning method can be used to infiltrate the small gaps.	- Both numerical results and experimental data are well matched. - Very suitable for thick water layer	- Not very practical for thin water layer	- No available data
robotic arm (Active system)	A mechanism powered by a DC motor consists of sprinkle water, air blower, and wiper.	- Overcome some factors like; air pollution, bird droppings, and dust. - Water and power consumption will be less.	- The weight of the robotic arm is a significant negative impact.	- Up to 9.1%.
drone retrofitting (Active system)	Using drones in cleaning solar panels	- Automatic system. - No need for human interaction - Water free.	- High in cost - Requires fuel stationary.	- No available data
Dry-Cleaning system (Active system)	Cylinder with built-in nozzles to jet spray compressed air.	- No human intervention. - Efficient cleaning. - No need for water	- Loss of the power output - May scratch the panel surface	- Up to 15%
Robotic system (Active system)	The system uses a pneumatic suction pump and dry methods for cleaning.	- Water-free	- Cannot remove sticky dust - May damage the surface of panels.	- Not available
Manual cleaning (Passive system)	It depends on laborers to clean the solar cell panels manually.	- Very efficient. - Cleans the system effectively	- Can put labors in danger. - Costly. - Time-consuming for large scale capacity	- Up to 98%

Table 1 - Comparison of different cleaning methods for Solar PV Installations (Derakhshandeh et al. 2021).

Proposed Method	Mechanism	Pros	Cons	*Efficiency improvement
Autonomous Vehicles (Active system)	A dry-cleaning method that used as the central processing system	- Reduce the operational costs	- Expensive - Does not have the agility	- No available data
Water pumping system (Active system)	Pump the water through the solar cell panels.	- Removes all kinds of dirt. - It is an automated system.	- Waste of water - Requires maintenance - Relatively expensive	-Not available data
Rainfall cleaning (Passive system)	It depends on the water droplets that come from rain	-It is free of charge	- Rains are not accurately - predictable - Is not suggested for dry regions with dusty air	- Varies and depends on adequate rainfall
Acoustic waves (Active system)	Cleaning solar panels using Surface Acoustic Waves	- Low-cost - No surface damage	- Removing large dust particles with a size of 0.2 mm and above. - Depends on the tilt angle.	- Up to 54% improving in terminal voltage of Panel

Table 2 - Continued... Comparison of different cleaning methods for Solar PV Installations (Derakhshandeh et al. 2021).

2. Review of yield increase of solar panels through soiling prevention, and a proposed water-free automated cleaning solution

This research paper explores the efficiency of solar panels, and the effect different factors can have, both environmental and non-environmental, on the overall efficiency of solar panel installations (Deb & Brahmbhatt 2018).
Factors which may influence the efficiency of solar panel installations may include:

- Orientation of the panel
- Shade
- Wind Speed
- Ambient temperature
- Precipitation
- Dust deposition

Current practices used to maintain and clean solar panel installations include water based and manual cleaning practices, which can become expensive due to the physical labour, and also may not be practical when solar panel installations are present in areas with minimal water supply. The purpose of this paper is to explore alternative options to the current maintenance strategies implemented and focus on developing an automated water-free cleaning device that can be utilised in the maintenance of solar PV installations (Deb & Brahmbhatt 2018).

Throughout the research conducted, it was originally believed that rainfall was enough to clean solar panels surfaces in locations where rainfall is present. Through further studies being conducted it was identified that rainfall was not sufficient to clean solar panel surfaces and therefore soiling and accumulation of dust and other particles has a significant effect on the overall efficiency and energy yield of the solar panel installations (Deb & Brahmbhatt 2018).

Cleaning solutions for solar panel surfaces were identified and discussed as shown below (Deb & Brahmbhatt 2018):

1. Forced flow from air conditioning systems.
   - This utilised the air flow present from a fan or air conditioner which may be utilised for solar panel dust removal.
2. Rainfall cleaning.
   - This cleaning method uses the natural water from rainfall and a titled solar panel to keep the solar panels clean from dust or environmental pollution and accumulation. If rainfall is not sufficient to adequately clean the dust off the solar panel, a residue may be left behind that consists of dust stuck to the solar panel as a result of the moisture left behind, that will only be able to get removed from heavy rainfall.

3. Water-based cleaning
    - This process involves high pressure water being used to clean solar panel surfaces using manual intervention. Cleaning agents can also be introduced into this type of cleaning to assist in making the cleaning process easier as well as allowing the solar panel to cool down in the hotter periods throughout the year.
4. Manual cleaning
    - This involves both the use of water and brushes to clean the surface of the solar panel manually.
5. Mechanized cleaning
    - Mechanized cleaning involves automatic (mechanical/robotic) wipers that will clean the panel surfaces with spray jets of water using automated technology, such as sensors and microcontrollers.
6. Electrodynamic screens (EDS)
    - Electric fields can be generated using electricity supplies which activate electrodes that are on the solar panel surface. This will repel/remove any dust particles both charged and uncharged from the surface of the panel, moving them closer to the outside of the panel surface.
7. Super hydrophobic plane (SHOP)
    - A coating can be applied to the solar panel surface whether it is initially installed as a specially made hydrophobic surface or a physical chemical coating applied to the surface of the solar panel. This does not utilise any input power and will be a passive form of solar panel cleaning method.
8. Super hydrophilic plane (SHIP)
    - This method is almost identical to the SHOP cleaning solution. It is more reliable than the SHOP method as it is more durable and long-lasting once applied to the panel surface.

Table 3 was utilised in the research paper to allow for an easy comparison of the different cleaning solution methods for the solar PV panel installations.

Method	Requisites	Benefit(s)	Drawback(s)	Efficiency; Remark(s)
Rainfall cleaning	tilted panels [23–25]; rain	no cleaning cost	weather and location dependent; only large particles removed [26]	least efficient [27,28]; not predicable; surface property can be improvised
Manual cleaning	labor; water; cleansing agents and equipment	considerably efficient in reinstating panels to clean condition	expensive cleaning cost [29]; can be abrasive to panel surface	effective in all conditions; need to find cheap labor; surface abrasion
Water-based cleaning	pressurized water; surface active agent [30]	cool down PV system [31–35]; improvisation of rainfall cleaning	ineffective in dry areas; high water usage; chemical deposition; water clogging; reduced power output; needs water tank refilling [30]; dust magnet when wet; fear of thermal shock	medium efficiency, need to schedule cleaning action to avoid thermal damage; need to use efficient pumps to minimize energy losses during cleaning
Mechanized cleaning	Apparatus like motor to operate brush or wiper; [36–40]; robot (if any) [41–43]	cool panels with water; automated operation by sensors and controller [40,44]; scares birds [40]; less labor cost; system is independent when unmanned control is imperative [45].	direct touch with panel surface is abrasive; dust accumulation on cleaning equipment; more energy consumed; higher capital cost; higher maintenance cost	uncertainty in efficiency; need to minimize abrasiveness, and manage timing of cleaning to avoid thermal damage; use of high effici- -ency motors can minimize energy losses; needs periodic maintenance
Electrodynamic Screens (EDS)	clear screen; high voltage supply [46–48]	distinct fast cleaning [49]; lower energy consumed; automated operation by sensors and controller [48]	degradation of plastic screen due to UV; 15% decrease in power output; not effective for wet dust [49]; less efficient for particles (0–5 mm); expensive	highly efficient in dry condition (low for wet); weather proof polymer or glass can be used to increase its durability
Super hydrophobic plane (SHOP)	tailor-made hydrophobic surface or chemical coating or screen layer; water [18]	passive method; does not require power	degradation of plastic screen due to UV [50]; dust accumulation in long time intervals; cleaning can be done only with water	medium efficiency (in rain) [16]; needs weather-proof glass or coating to improve its cooling; regular surface washing to avoid soiling
Super hydrophillic plane (SHIP)	tailor-made hydrophillic surface or chemical coating or screen layer [20]; water	passive method; doesn't require power; dust decomposes [51–53]; least adhesive to dust; more effective than SHOP [54]	more durability (not polymer-based material) [21,20] accumulates more dust with deteriorating coating	medium efficiency (in rain); regular surface washing; need to avoid soiling in dry conditions; reinstates ~ 3.6 to 5.4% more energy efficien-cy than uncoated panels [22]

Table 3 - Comparison of the different solar PV panel installations cleaning solution methods (Deb & Brahmbhatt 2018).

The proposed water-free automated solar cleaning service unit will clean the solar panel installations based off the panel's current status and takers into consideration the required cleaning based off the user defined data. The unit incorporates a brush that will rotate along a solar installation built in a row, with three wheels allowing the unit to crawl along the length of the solar panel installation. The brush will continue to rotate as this unit moves along the panels (Deb & Brahmbhatt 2018).

Understand/research potential environmental factors that may be encountered in a home-base solar PV installation setting. Solar panel efficiency and potential influences because of these conditions would need to be further analysed.

1. <u>Effect Of Dust On The Performance Of Solar PV Panel</u>

Although maintenance strategies are important to ensure solar panels are clean and maintained to allow for full efficiency of the solar PV installations, it is also just as important to understand what environmental conditions can affect the solar installation and what research has been done to understand these conditions and their effect (Rajput & Sudhakar 2013).

This research paper specifically discusses the effect dust has on a solar PV panel installation and it is mentioned that to date, there has not been a significant amount of research conducted on this topic. Through the research, it was able to be concluded that dust has a significant impact on the overall performance of a solar PV installation, reducing the efficiency of these installations. The efficiency of a cell is generally used a criterion when assessing the feasibility of a solar panel installation. This cell efficiency will be used as an input to assist in the calculation of the optimal system configuration considering the lifespan of the panel, the sizing, and the demand that would be associated with the installation (Rajput & Sudhakar 2013).

Due to dust being such a complex environmental factor due to the range of environmental conditions that may be experienced, it tends to not be explored in depth. This is not ideal as dust can have significant impacts on the effect of a solar panel's efficiency and therefore, should be a considered factor when assessing the feasibility of a solar panel installation (Rajput & Sudhakar 2013).

Factors tested throughout the duration of the research:

- Solar Radiation vs Time characteristics.
- Ambient Temperature vs Time characteristics.
- Panel efficiency vs Time analysis with dust.
- Panel efficiency vs Time analysis without dust.

Calculations used in the experimental stage of the research for solar panel efficiency also incorporating the effect of dust on the panel, include (Rajput & Sudhakar 2013):

Power output (watt) $P_o = V_{sc} * I_{sc} * FF$

We calculate the solar panel efficiency (%) by the following formula:[9]

$$\eta = \frac{V_{oc} * I_{sc} * FF}{A * I} \times 100$$

Where,

V_{oc} -Voltage of electricity produced (volts)
I_{sc} – Electrical current produced by the solar PV panel (Ampere)
FF- fill factor
A- Area of solar panel (cross-section of panel)
I- Intensity of Solar Radiation (W/m^2)

$$\% \text{ reduction in power} = \frac{P_{without\ dust} - P_{with\ dust}}{P_{without\ dust}} \times 100$$

$$\% \text{ reduction in efficiency} = \frac{\eta_{without\ dust} - \eta_{with\ dust}}{\eta_{without\ dust}} \times 100$$

Figure 2 - Solar Panel Efficiency Calculations (Rajput & Sudhakar 2013).

Below it can be identified the effect dust has on the overall efficiency of a solar panel. Significant differences in efficiency can be seen when comparing the two graphs, and therefore highlights the importance of implementing effective maintenance strategies to ensure solar PV panel installations are maintained.

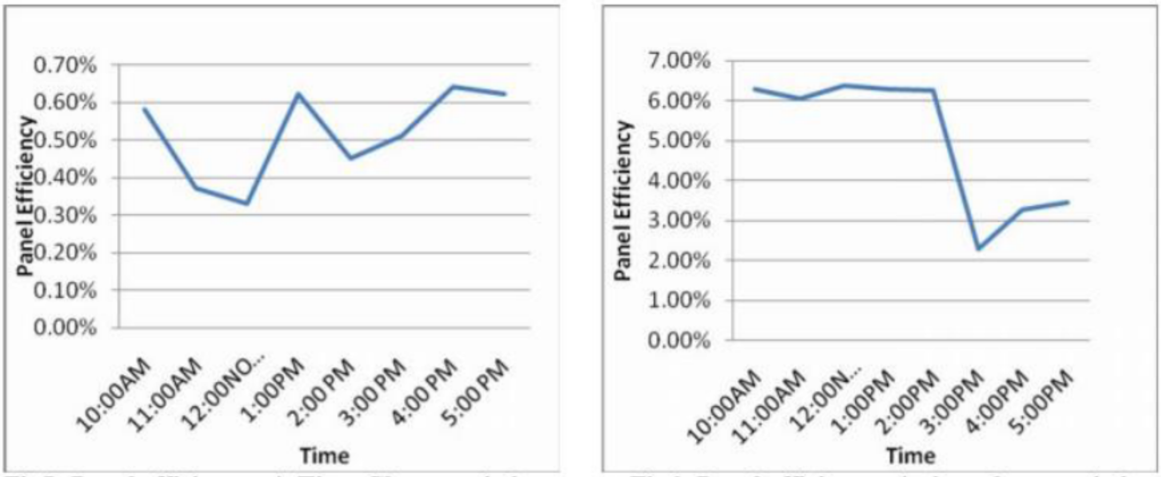

Fig5- Panel efficiency v/s Time Characteristics With dust

Fig6- Panel efficiency v/s time characteristics without dust

Figure 3 - Solar Panel Efficiency Dust vs No Dust (Rajput & Sudhakar 2013).

2. Impact of dust on solar photovoltaic (PV) performance: Research status, challenges, and recommendations

This research paper has identified that with climate change actively occurring the popularity of solar PV installations has significantly increased due to its sustainable and eco-friendly form of power generation. Although the installation of solar panels contributes positively towards creating a future powered by renewable energy and various factors are taken into consideration when these installations occur such as location of the panel, tilt, orientation and much more to allow for the highest yield of power, factors that may become present after the installation of the panels are often not incorporated or considered in this design and installation process. This specifically refers to the environmental factors that may become present such as dust, a less acknowledged issue that can significantly affect the overall efficiency and performance of the solar PV installations (Mani & Pillai 2010).

This research paper specifically focusses on this less discussed issue and identifies what current study has been conducted around dust accumulation. Challenges are identified if further research was to be conducted around dust accumulation and the overall effect it can introduce to the system over its lifespan (Mani & Pillai 2010).

Below a flow diagram can be identified, revealing various factors both controlled and uncontrolled that can affect the overall yield of the solar PV installations. It is important that all these factors are considered when designing a solar installation.

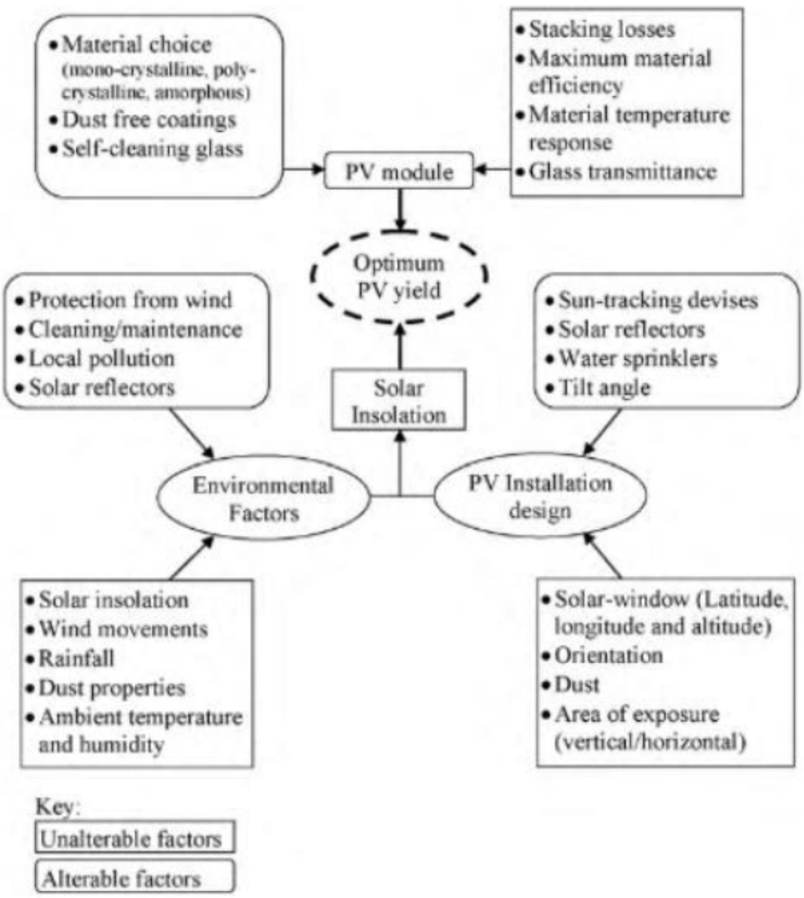

Figure 4 - Alterable and unalterable factors determining maximum PV system yield. (Mani & Pillai 2010).

After reviewing various research that has already been conducted regarding the affect dust settlement can have on a solar PV system, the below flow diagram was created to visually identify the factors that will influence the dust settlement on a solar PV system.

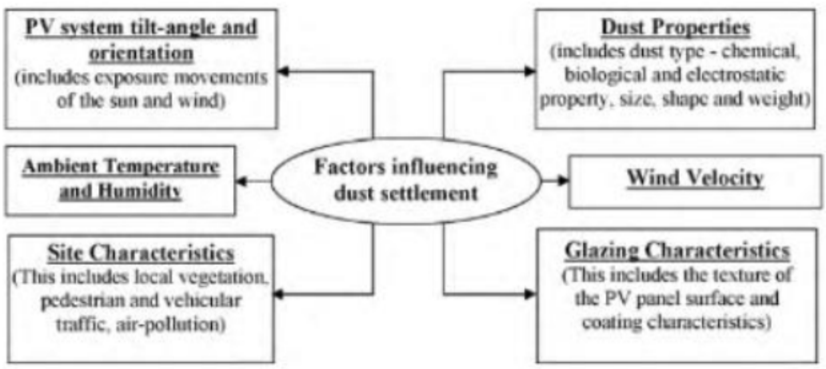

Figure 5 - Factors influencing dust settlement (Mani & Pillai 2010).

The research conducted split the different research into two phases, research conducted between 1940-1990 and research conducted after 1990. It is suggested that as studies advanced, research conducted after 1990 was more reliable, rigorous, and accurate, focussing more on the physical properties of dust and how the density of this material could affect the overall efficiency of a solar panel system. Experiments were conducted using various forms of dust and a halogen light to simulate a constant source of light, replicating that of the sun present throughout the day. The varying factors in these simulations were the types of dust, focussing on what effect this variance in dust accumulation had on the overall solar intensity. These results obtained are displayed in the below graph, which gives a good insight into what effects the dust deposition density has on the overall percentage reduction in solar intensity (Mani & Pillai 2010).

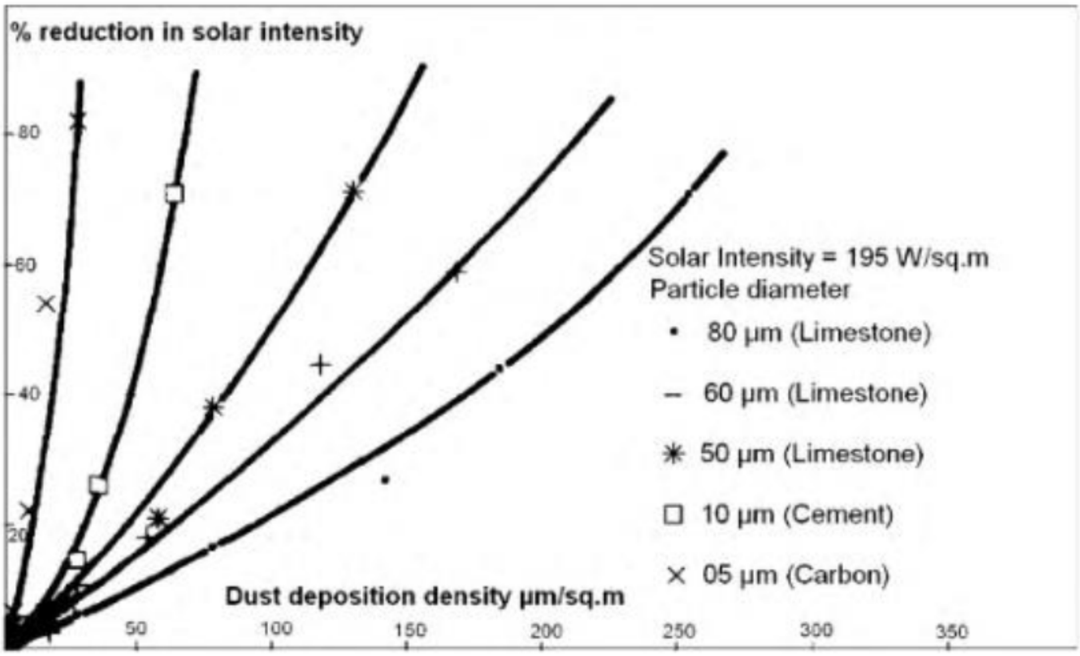

Figure 6 - Solar-intensity reduction in response to dust deposition (Mani & Pillai 2010).

3. <u>Numerical simulation of the dust particles deposition on solar photovoltaic panels and its effect on power generation efficiency.</u>

This research article has identified that the accumulation of dust particles on the surface layer of a solar PV panel will essentially lead to a decreased efficiency of power output. This research conducted explores the effect wind loadings, wind speed, wind angles and sizes of dust particles and the effect these varying factors will have on the overall efficiency and dust accumulation of the solar PV installation. Various simulation tools were used to simulate a solar PV installation, allowing the various factors influencing the dust accumulation to be modelled using this software simulation tools (Yang & Wang 2022).

An example of a condition simulated is the different wind speeds and how this can affect the accumulation and distribution of particles throughout the solar PV installation can be seen modelled below (Yang & Wang 2022).

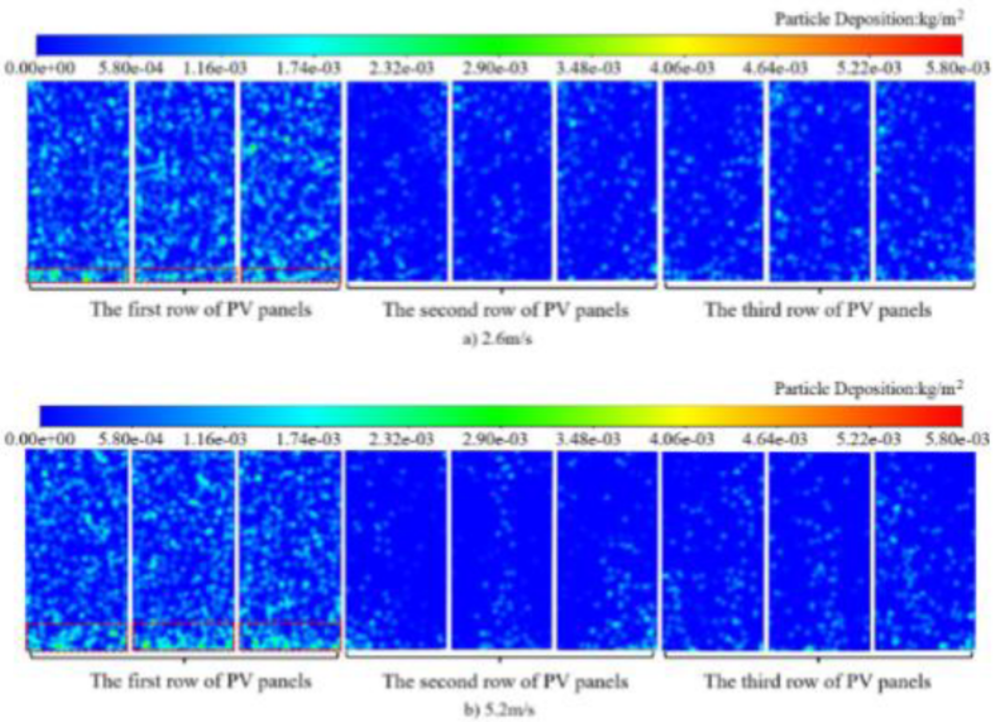

Figure 7 - Distribution of particle deposition at different wind speeds (Yang & Wang 2022).

It can be identified that the first row of the solar PV panel installation will have the greatest dust deposition present at different wind speeds, gradually decreasing as the rows go further back (Yang & Wang 2022).

The overall findings from this research conducted indicate that as the wind speed of the simulation was increased, the dust accumulation amount gradually decreased as the rows went further back. Another finding revealed that as the particle sizes were increased the amount of accumulation from the particles also increased at a gradual rate. The wind angle at zero degrees identified that the first row of panels experiences the greatest particle accumulation and as the wind angle increased to 45 degrees the second and third row experiences an increase in particle accumulations when compared to the first row which had significantly less (Yang & Wang 2022).

4. Prediction of dust particle size effect on efficiency of photovoltaic modules with ANFIS: An experimental study in Aegean region, Turkey

This research paper explores the effect of coal dust on photovoltaic panels in the Aegean region in Turkey. The experiment utilises coal dust of various particle sizes and weights to understand what effect this has on the overall solar PV panel efficiency, with a specific model created to predict the overall performance of these panels (Adıgüzel et al. 2019).

Background study indicates that dust can occur in various sizes and shapes and the overall decrease in efficiency that solar panels experience due to this accumulation is dependent upon the mass and overall size of the particles that are present on the surface of the solar PV panel installations. It has been identified that as the dust particle sizes become smaller, the irradiance passing through these particles is significantly decreased, resulting in the decreased efficiency of the panel due the light being blocked by these small particles (Adıgüzel et al. 2019).

A physical indoor solar panel setup was implemented, with physical coal dust used on the surface of the solar panel. This coal dust was separated into various sizes to ensure testing was carried out in a controlled manner. The below tables were able to be generated following the testing of the dust accumulation on the solar panels, and this allowed for the overall efficiency during each stage of testing to be calculated based off the particle size (Adıgüzel et al. 2019).

Particle size (μm)	Weight (g)	V_{mpp} (V)	I_{mpp} (A)	P_{mpp} (W)	P_{loss} (W)	P_{loss} (%)
Clean	0	17.50	2.86	50	0	0
−38	5	16.50	1.83	30.20	19.81	39.61
	10	16.50	1.45	23.93	26.08	52.15
	15	16.50	1.15	18.98	31.03	62.05
+38/−53	5	16.50	1.92	31.68	18.32	36.64
	10	16.50	1.58	26.07	23.93	47.86
	15	16.50	1.34	22.11	27.89	55.78
+53/−75	5	17.60	1.92	33.79	16.21	32.42
	10	16.50	1.73	28.55	21.46	42.91
	15	16.50	1.49	24.59	25.42	50.83
+75/−106	5	17.60	2.09	36.78	13.22	26.43
	10	16.50	1.88	31.02	18.98	37.96
	15	16.50	1.69	27.89	22.12	44.23
+106/−250	5	17.60	2.25	39.60	10.40	20.80
	10	17.60	2.01	35.38	14.62	29.25
	15	16.50	1.91	31.52	18.49	36.97
+250/−500	5	17.60	2.41	42.42	7.58	15.17
	10	17.60	2.27	39.95	10.05	20.10
	15	17.60	2.02	35.55	14.45	28.90

Table 4 - Measured voltage, current, power, and calculated power loss at MPP of a m-Si PV module (Adıgüzel et al. 2019).

Particle size (μm)	Weight (g)	V_{mpp} (V)	I_{mpp} (A)	P_{mpp} (W)	P_{loss} (W)	P_{loss} (%)
Clean	0	17.50	2.86	50	0	0
−38	5	16.50	1.86	30.74	19.26	38.52
	10	16.50	1.58	26.10	23.90	47.79
	15	16.50	1.21	19.97	30.04	60.07
+38/−53	5	17.60	1.96	34.46	15.54	31.08
	10	16.50	1.71	28.17	21.83	43.67
	15	16.50	1.30	21.48	28.52	57.03
+53/−75	5	17.60	2.08	36.61	13.39	26.78
	10	16.50	1.82	29.96	20.04	40.07
	15	16.50	1.45	23.93	26.08	52.15
+75/−106	5	17.60	2.21	38.90	11.10	22.21
	10	17.60	1.98	34.85	15.15	30.30
	15	16.50	1.71	28.17	21.83	43.67
+106/−250	5	17.60	2.35	41.36	8.64	17.28
	10	17.60	2.26	39.83	10.17	20.34
	15	17.60	2.02	35.53	14.47	28.93
+250/−500	5	17.60	2.53	44.53	5.47	10.94
	10	17.60	2.51	44.14	5.86	11.72
	15	17.60	2.42	42.52	7.48	14.96

Table 5 - Measured voltage, current, power, and calculated power loss at MPP of a p-Si PV module (Adıgüzel et al. 2019).

The data collected was then also able to be graphed to visually display the effect different particle sizes have on the current as the solar PV panel overall voltage output is increased. This can be seen in the below extract from the research report (Adıgüzel et al. 2019).

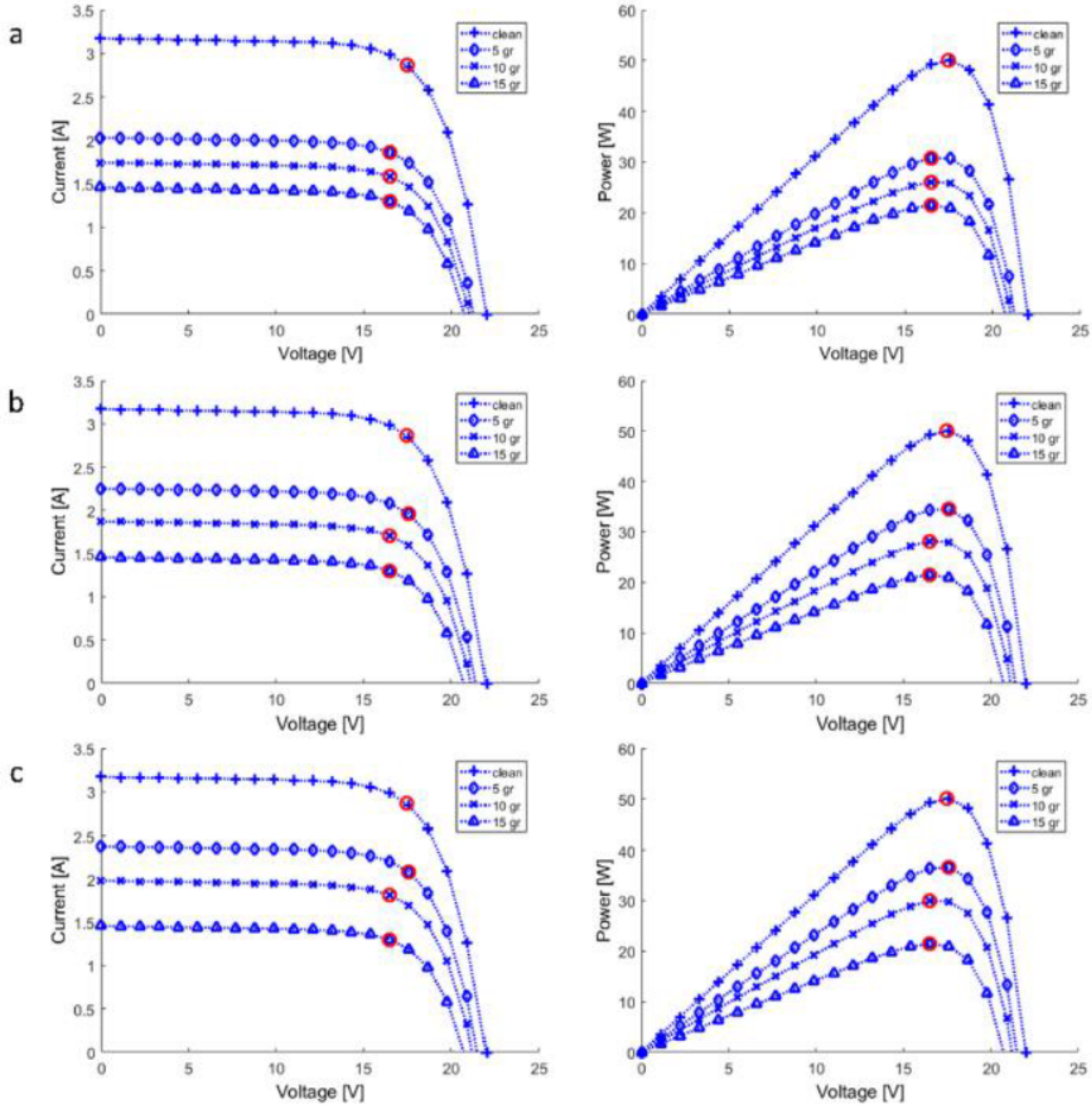

Figure 8 - Measured electrical characteristic of p-Si module. (a) Particle size (μm): (−38), (b) (+38/−53), (c) (+53/−75), (d) (+75/−106), (e) (+106/−250), (f) (Adıgüzel et al. 2019).

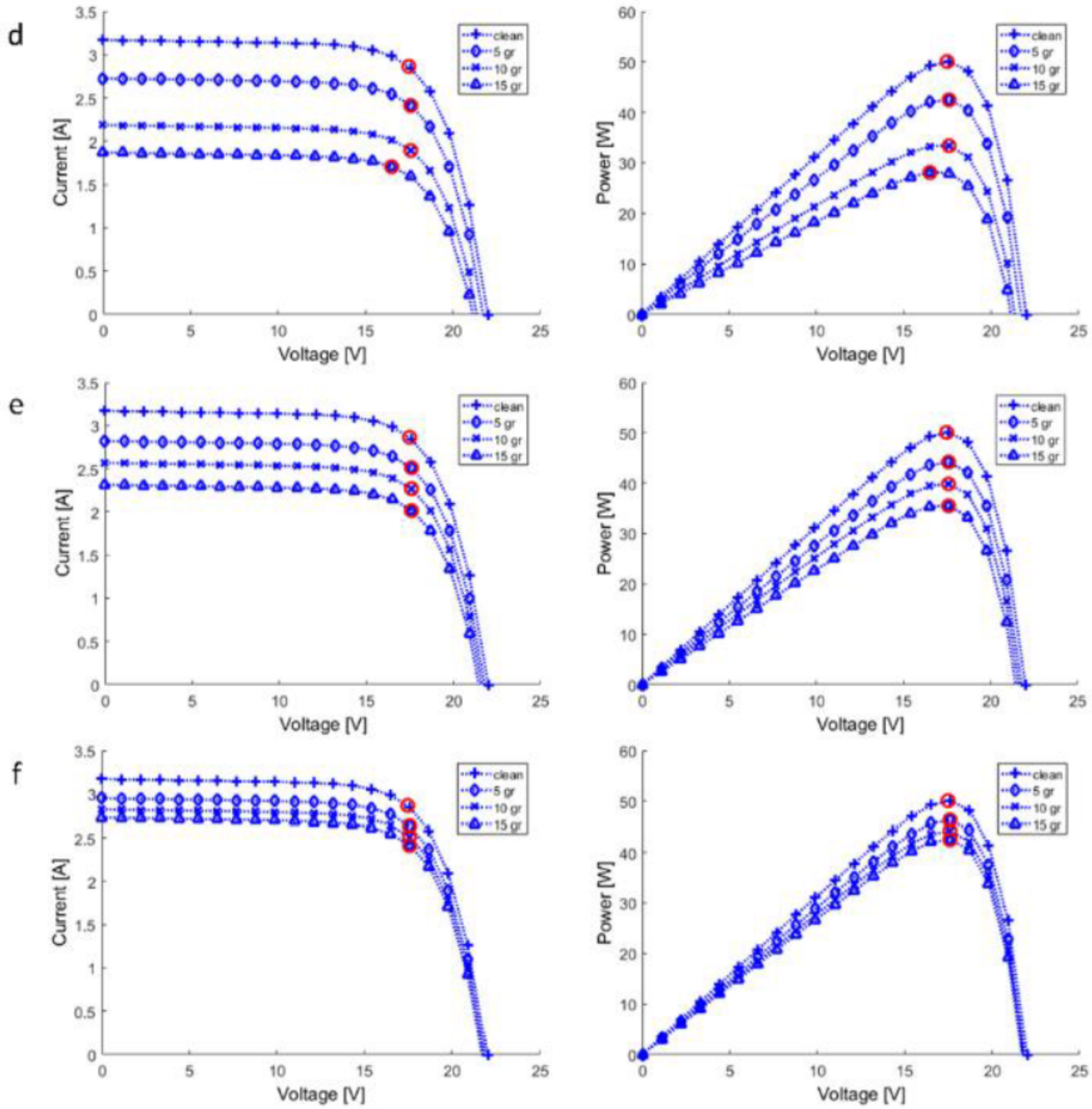

Figure 9 - (continued) (Adıgüzel et al. 2019).

The outcomes of this experiment carried out revealed that the highest power loss on a solar PV panel installation occurred for the smaller particle sizes, but heavier sample weight. The larger the particle size and the lighter the weight of the sample, the less power loss was experienced for the solar panel system. These conclusions proved that the heavier the weight of the sample, the higher efficiency loss, and therefore proves that the more particles present on a solar panel, the greater the effect to the overall efficiency. If the particle weight was able to remain consistent and the particle size is increased, the overall effect on the power loss is decreased, whereas, if the particle size is decreased, the overall power loss is significantly increased.

5. On-site PV characterization and the effect of soiling on their performance

Throughout this research report, three different solar panels are analysed based off their specific characteristics. The three panel types physically tested and analysed include monocrystalline, polycrystalline, and amorphous silicon panels, specifically testing the effect of naturally occurring dust soiling on the panel focussing on the effect of this soiling on output efficiency and power for each panel physically installed on site. Artificial soiling dust conditions were also implemented within the testing, where extreme dust soiling conditions were represented by dust physically placed on the panels, rather than allowing the natural accumulation of the dust to occur (Kalogirou et al. 2013).

During the artificial soiling for extreme dust condition simulation, this was conducted on both a wet and dry panel surface, recording the different output values for all three panel types. The wet surface was implemented to represent conditions where rainfall is present, followed by a dust storm or significant dust soiling event. This was then compared to a dry panel surface which also artificially experienced extreme dust conditions. (Kalogirou et al. 2013).

PV type	Wet surface			Dry surface		
	Clean (W)	Dirty (W)	Difference (%)	Clean (W)	Dirty (W)	Difference (%)
Monocrystalline	172	96	44	143	122	14
Polycrystalline	150	77	49	133	113	15
Amorphous	17	14	20	13.1	13.8	1

Table 6 - Power Output reduction under extreme cases (Kalogirou et al. 2013)

In the above table it can be analysed that a wet surface has a significantly worse efficiency response when compared to a dry surface. This is assumed to be as a result of the dust easily binding to the surface of a wet panel, whereas a dry surface soiled with dust will allow wind to easily remove this product as it is less likely to form a crust layer on the panel surface.

These solar panel installations were left to naturally accumulate dust over specified periods of time. Winter was excluded from this testing as it was believed that the rainfall received within the winter months was enough to adequately clean the surface of the solar panels keeping their surface clean. During spring, weekly measurements were recorded over a period of 4 weeks, and the exponential increase in the percentage of power output losses significantly increases over this period of time. These percentages stabilise around the 3-week point, therefore identifying the point at which the reduction in power for the solar panels is at a peak for dust accumulation present on the panel surface.

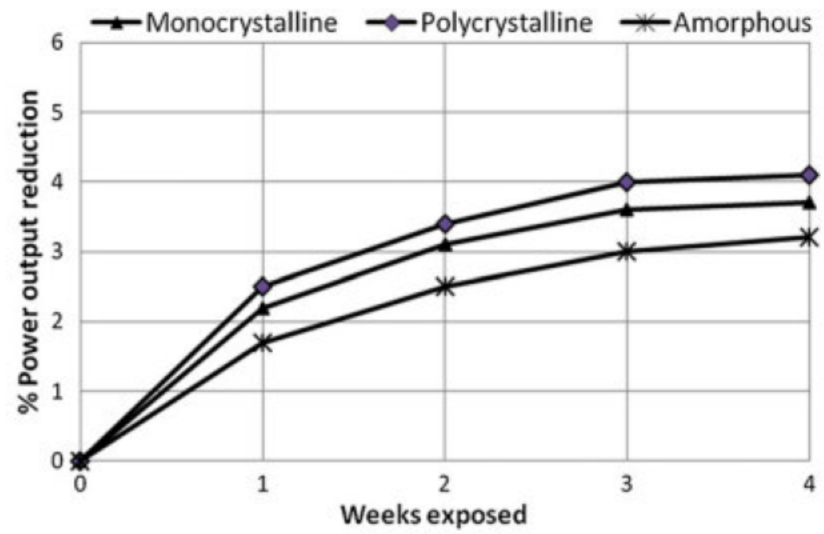

Table 7 - Weekly power output reduction during spring period (Kalogirou et al. 2013)

During the summer period, a significantly higher loss in power output can be identified, potentially as a result of various dust episodes occurring. There is a relatively large increase in the power output reduction in the first 7 weeks of the time period, with the data slowly stabilising after this period. for both summer and spring, the amorphous panel experiences significantly less power efficiency effects as a result of the naturally occurring dust accumulation, followed by monocrystalline and polycrystalline panels which experience almost identical data over the time periods.

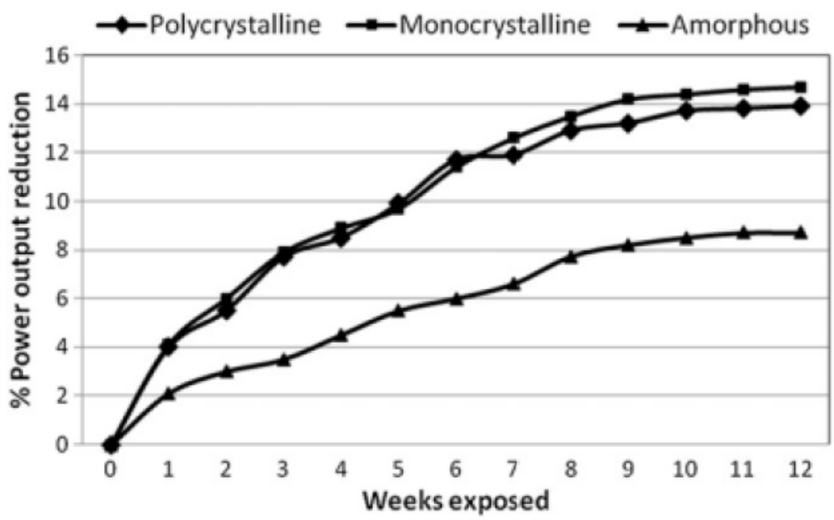

Table 8 - Weekly power output reduction during summer period (Kalogirou et al. 2013)

Overall, this research paper clearly identifies the effect artificial and naturally accumulating dust can have on all three panel types, even when experiencing different surface conditions. It is suggested that cleaning in spring and autumn occurs every 2-3 weeks, with summer intervals being dependent on the comparison of maintenance costs versus efficiency loss costs. This is suggested to improve the overall efficiency of the panel, generating significantly better power output over the lifespan of the solar panel (Kalogirou et al. 2013).

Research potential storm damage protection options and provide a solution which is practical in an industrial setting.

1. Fundamental study related to the development of modular solar panel for improved durability and repairability.

Solar PV panel installations are generally installed, and it is assumed that they will continue to operate with no issues. What isn't understood properly is environmental conditions such as snow, hail, wind, sand, and other similar conditions can result in permanent damage to solar PV installations, therefore resulting in the solar panel requiring replacement. This not only lead to extra costs, but also generates unnecessary waste. Electronic waste is one of the leading forms of waste present across the world, and if people do not consider options of replacing parts on solar panels, electronic waste will continue to rise at a rapid rate due to the popularity of solar installations across the world. This research paper has conducted experimental research to design a modular solar panel design which will ensure that the solar panel is repairable in the event parts are damaged due to environmental conditions. This modular design will also allow for increased durability to survive the harshest environments, ensuring an increased lifespan of the panel (Majdi et al. 2020).

The research paper discusses how one of the main challenges the solar panel industry is faced with includes the difficulty to repair parts of a solar panel and the reduced durability of the panels. The poor durability of solar panels can be explained by the pressure to produce solar panels for an attractive price so that it is affordable for the end user. Unfortunately, this can result in cheaper and less durable parts to manufacture the solar panels with the thickness of these panels being comprised to meet these reduced costs (Majdi et al. 2020).

It has become obvious that for solar panel manufacturers to reduce costs, the carbon footprint introduced as a result of producing less durable and reliable solar panels is significantly increased. This is because solar panels cannot withstand harsh environmental and storm conditions, as well as having limited reparability options to allow to an increased life expectancy. Not only does this eventually result in higher costs for the user but again, the electronic waste generated is significantly increased as these solar panels will need to be replaced rather than simply repaired (Majdi et al. 2020).

The research paper conducted experiments based off the following environmental conditions that have the potential to cause damage to solar PV installations:

- Snow/hail

- Thermal degradation
- Mechanical stress

The experiment conducted revealed that the modular design solution presented was effective in maintain the integrity of the solar panel and was able to reduce/withstand the harsh environmental conditions tested, as well as proving easier to replace components when compared to a current solar PV installation. This also saved on costs due to the new innovative design allowing individual parts to be replaced (Majdi et al. 2020).

2. Lightning protection on photovoltaic systems: A review on current and recommended practices

This research paper explores the potential influence lightning strikes can have on the operation of a solar panel. It has been identified that lightning strikes have the potential to cause heat stress, damage to components and a reduction in the peak voltage output of a panel.

Solar panels are generally installed on the roof of residential buildings, increasing the likelihood of these installations being struck by lightning. Previous research has identified that as lightning voltage impulses increase, the peak output power will decrease gradually, along with these impulses causing severe degradation to the electrical equipment present in these installations, resulting in the degradation of the overall panel (Ahmed et al. 2018).

It has been identified that the installation of lightning protection is necessary for the protection of the installation, however the location of this protection will be dependent upon the location of the installation, purpose, and type of building/construction. It has been identified in Germany, 26% of damage to solar PV panels is as a result of lightning damage, and therefore this value could be significantly higher for locations experiencing more frequent lightning. This study further details the specific components damaged due to these lightning strikes, as shown in the table below (Ahmed et al. 2018).

Components	Damage examples
PV modules	Defects on bypass diodes, broken glasses, and arcing at string ribbon.
Inverter and monitoring combiner boxes (Weather sensors)	All inputs and outputs include data communication/displays.
Cables	Holes in the insulation whereby the spark over from the mounting system and spark over into the soil.
Solar tracker	Communication, sensors, power supply, and drive train.
Security systems	Cameras, sensors, data communication, and theft protection.

Table 9 - Typical damages caused by lightning strike (Ahmed et al. 2018).

This paper further explores the reasoning behind lightning protection being a necessity for solar PV systems, with residential buildings requiring protection for the buildings as well as to prevent any potential damage to these buildings including any health and safety risks that could arise from this lightning protection not being present to reduce the effect of a strike.

Options for lightning protection systems can include:

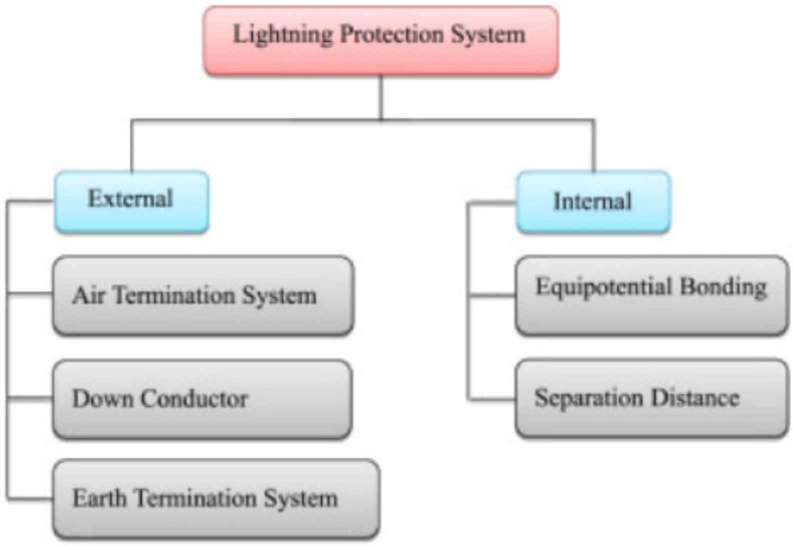

Table 10 - Classification of lightning protection system (Ahmed et al. 2018).

Overall, this research paper highlights the importance of implementing adequate lightning protection systems to prevent system failures which will result in customer loss of return on investment, making the initial changeover to solar powered energy not economical.

Understand and demonstrate options for recycling solar panels which have reached end of life.

1. An overview of solar photovoltaic panels' end-of-life material recycling

It is estimated that the average life cycle of a solar panel will be on average 25 years. Solar PV panel waste generated 'is anticipated to reach between 4%-14% of total generation capacity by 2030 and rise to over 80% (around 78 million tonnes) by 2050.' (Chowdhury 2020).

This research paper discusses how the EU Waste of Electrical and Electronic Equipment (WEEE) has decided that all solar PV panel producers who are providing products to the EU market are required to ensure that initiatives are in place to collect and recycle solar panels which have reached their end-of-life expectancy within Europe. This approach is important as introducing this requirement across all countries will ensure that electronic waste generated by solar panels reaching their end of life are disposed of correctly, reducing the carbon footprint from solar panel disposal (Chowdhury 2020).

Solar power is a highly valuable source of renewable energy, and with its rapid increase in popularity, will continue to be the preferred renewable energy source for people across the world. This highlights the importance of ensuring that as this renewable energy source increases in popularity, so will the installations, and therefore ensuring adequate recycling opportunities and initiatives are implemented is of upmost importance. Solar panels contain hazardous materials which can cause significant damage to the environment and therefore it is important that solar panels are disposed of in a safe and environmentally friendly way.

In 2016, it was estimated that solar panel waste disposed of was equal to 250,000 metric tonnes globally, according to the International Renewable Energy Agency. This electronic waste generated by solar panels contains chemicals such as lead and calcium, as well as various other chemicals which can cause great harm to the environment as it is difficult to remove these chemicals from the solar panels (Chowdhury 2020).

The potential causes for the failure of solar panels can be identified below (Chowdhury 2020):

- Inadequate design or manufacturing defects
- Erosion
- Electrical equipment
- Changes in the environmental conditions
- Crack and failures at a microscopic level

Once a solar panel has failed the research paper describes the below methods as the most effective way of recycling solar panels (Chowdhury 2020):

1) Physical separation

2) Thermal treatment
3) Chemical treatment

As discussed earlier solar panel disposal can cause significant damage to the environment and increase our carbon footprint if not done effectively. The research paper suggests that recycling 186 tonnes of solar PV panel waste would be the equivalent of saving a 2.6MW power stations annual amount of carbon dioxide emissions. This would have a dramatic impact on the carbon footprint created as a result of solar panel disposal, and therefore highlights the significance on ensuring appropriate recycling methods are implemented globally to ensure the whole life cycle of a solar panel is considerate of the environment and generates the least amount of pollution possible (Chowdhury 2020).

2. <u>End-of-life of silicon PV panels: A sustainable materials recovery process</u>

This research paper explores how thermal treatment can be utilised in solar panel end of life disposal practices to remove the polymeric compounds that are present in silicon PV panels. This thermal treatment process will remove chemicals such as glass, Si, Ag, Cu and Al (Fiandra et al. 2019).

It has been identified that during the solar panel disposal process, various precious metals are being lost as well as regular materials, resulting in environmental issues becoming apparent due to some hazardous chemicals and materials being released into the environment (Fiandra et al. 2019).

It has been suggested that the current systems in place to dispose of solar panels is not sufficient in ensuring minimal impact to the environment occurs. This has influenced the need for proper disposal methods to be established to ensure no toxins are being sent downstream from the existing material recovering facilities for solar panels (Fiandra et al. 2019).

This research paper has further developed and proposed processes which can effectively separate various materials within a solar panel ensuring solar panels are managed effectively when being disposed. This proposal further explores the importance of ensuring not only technical and energy targets are met, but also environmental influences and issues are adequately addressed and considered during throughout the lifecycle of a solar panel. The specific treatment proposed is a thermal treatment process, which will specifically target the polymeric compounds in the solar panel ensuring they are eliminated and removed from the panel prior to disposal (Fiandra et al. 2019).

3. Background and Tools

Project Goals

This research project will explore maintenance strategies which can be implemented to ensure efficiency of a solar panel is adequately maintained over the lifespan of a panel. Data will be collected to understand the effects of environmental conditions on the overall efficiency of the panels, and further what options are available to allow cleaning and maintenance to be performed on these panels. To further support maintaining the efficiency of a solar panel, suggestions around storm damage protection will be discussed as well as recycling options when solar panels reach the end of their life. Ensuring storm damage protection is considered, will ensure the life span of the solar panel is maintained, reducing the risk of having to replace the solar panel before its end-of-life expectancy.

Data will be gathered that will compare the efficiency of clean solar panels, with environmentally affected solar panels, focussing on the effect particle accumulation on a solar panel surface can have on the efficiency and output of a solar panel. Weather data will be gathered for the Gladstone region to further discuss whether naturally occurring rainfall is an adequate form of cleaning, or if active and passive systems should be implemented to ensure solar panel surfaces are maintained appropriately. These systems will be compared and the most suitable option for the Gladstone region will be further explored and discussed based of the specific environmental conditions that will be experienced.

Literature Review

The first step of the research project was to conduct an in-depth literature review that explores the various research projects already conducted for this topic of solar PV installation maintenance practices, storm damage protection and recycling initiatives. Each of these components have been individually reviewed, with information from each piece of literature summarised and presented in this report for background knowledge and idea generation for research going forwards. Only reliable sources were utilised for these literature reviews to ensure any information used throughout this report is factual and valid.

Resource Requirements

To complete this research around maintenance strategies, storm protection and recycling options for solar PV panels and their installations, various resources will be required to ensure adequate data can be acquired and appropriate information is gathered that is relevant to the overall research concepts.

Access to a computer and online resources will be required. This will allow for research and literature reviews to be conducted that will allow appropriate information relevant to the research topic to be gathered and reviewed. A computer will also be required during this research project as the modelling conducted as a part of the research will require software that can only be accessed using a computer. The final dissertation as well as progress report will also require access to a computer so these documents can be produced. Microsoft Excel, Word and Project will be required to create these reports.

To allow data to be simulated, compared, graphed, and analysed software will be required that can perform these functions. MATLAB will be required to utilise the add in Simulink, a block diagram environment which will allow for the solar PV system to be modelled. MATLAB will also be used to generate graphs showing the efficiency effect on the overall power output from the solar PV panel.

There will be no extra cash costs associated with this research project as all software required is provided by USQ and is free for student use. This software has previously been downloaded, and therefore no availability constraints will be experienced when starting this project research and modelling.

Simulation Software

The simulation software that will be utilised throughout this research project will be MATLAB, with the Simulink add in. MATLAB will be utilised for its graphing capabilities which will allow for an in-depth analysis and comparison to be made for the various environmental conditions being analysed. Simulink will be utilised to model the solar PV system and will give a visual understanding of the system power, current and voltage requirements, as well as allowing the different installation conditions to be modelled for easy comparison and analysis.

Schedule

To ensure adequate time is allocated to the research project, and that all required data and modelling is achieved in an appropriate timeframe a Gantt chart has been constructed to display how time will be allocated towards this research. The below Gantt chart displays all the necessary steps involved in ensuring the aim of this research topic is achieved.

Task Name	Duration	Start	Finish
1. Scope/Prework Stage	56 days	Wed 8/03/23	Wed 24/05/23
1A. Research relevent technical information	7 days	Wed 8/03/23	Thu 16/03/23
1B. Identify equipment required	2 days	Fri 17/03/23	Mon 20/03/23
1C. Identify potential environmental conditions for testing phase.	3 days	Tue 21/03/23	Thu 23/03/23
1D. Identify suitable maintenance strategies.	3 days	Mon 22/05/2:	Wed 24/05/23
2. Design Stage	40 days	Thu 25/05/23	Wed 19/07/23
2A. Design a small scale solar panel model in MATLAB	40 days	Thu 25/05/23	Wed 19/07/23
3. Testing Stage	21 days	Wed 19/07/2:	Tue 15/08/23
3A. Test solar model with varying environmental conditions	14 days	Wed 19/07/2:	Sat 5/08/23
3B. Simulate proposed maintenance strategies	7 days	Mon 7/08/23	Tue 15/08/23
4. Data Analysis Stage	18 days	Tue 15/08/23	Thu 7/09/23
4A. Compile output data from solar panels	3 days	Tue 15/08/23	Thu 17/08/23
4B. Compare data from different environmental conditions	3 days	Fri 18/08/23	Tue 22/08/23
4C. Compare data from different maintenance strategies	3 days	Wed 23/08/2:	Fri 25/08/23
4D. Revisit testing stage if further data is required.	3 days	Mon 28/08/2:	Wed 30/08/23
4E. Analyse efficiency of solar panel and visually display results from test stage	3 days	Thu 31/08/23	Mon 4/09/23
4F. Analyse condition of solar panel after testing stage.	3 days	Tue 5/09/23	Thu 7/09/23
5. Report Write-Up Stage	31 days	Thu 7/09/23	Thu 19/10/23
5A. Prepare draft dissertation	28 days	Thu 7/09/23	Mon 16/10/23
5B. Suggest further testing/research which would support this study	3 days	Tue 17/10/23	Thu 19/10/23

Figure 10 - Gantt Chart for Project Schedule

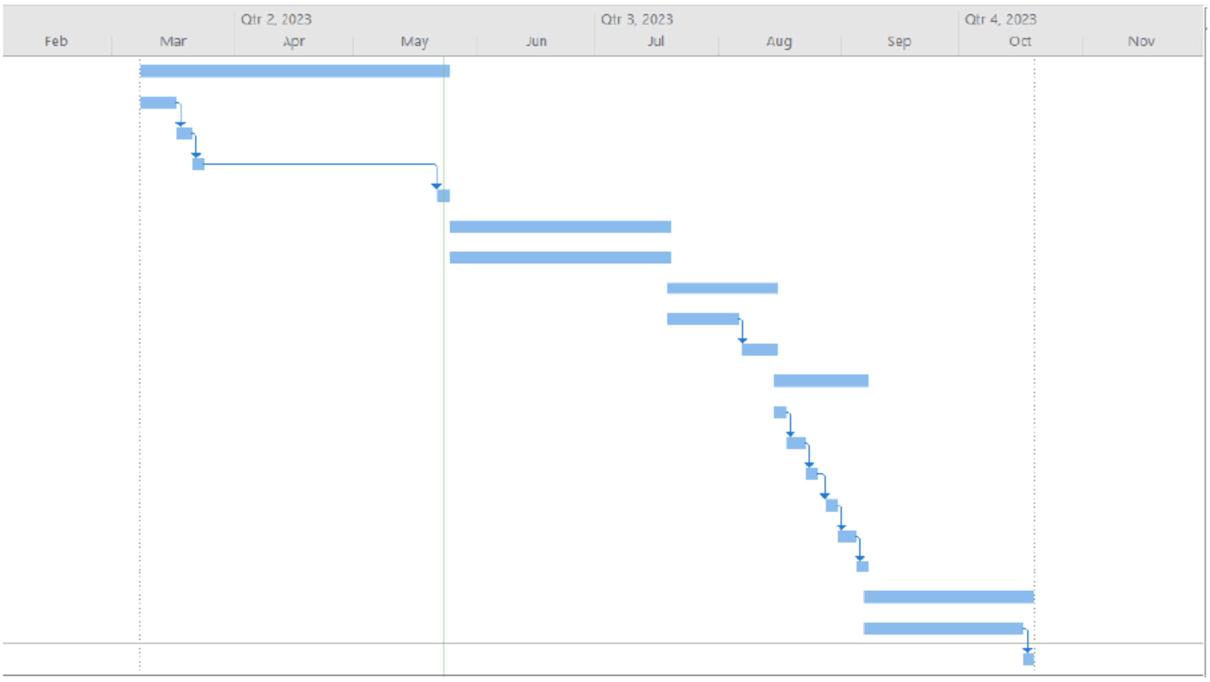

Figure 11 - Gantt continued.

4. Methodology

This section of the report will discuss the methodology that will be followed for this research report, specifically focussing on the modelling of the data and what data will be utilised.

Modelling of Data

Environmental Data

The initial discussion for this research report is very broad, focussing on the maintenance strategies for the cleaning of solar panels, storm damage protection and recycling of end-of-life solar PV panels. To further refine this topic and make it more relevant to Australia, this report will use environmental data that satisfies the Gladstone region. Gladstone is a town full of resource industries, and therefore this will allow for a range of different environmental conditions present within the community. Considering a wide range of environmental conditions, as well as introduced conditions from the existing industries within the town, will ensure any research conducted throughout this report, will not only be relevant to Gladstone, but can also be utilised in other communities within Australia who may experience similar conditions.

The various environmental conditions both introduced and naturally occurring that will be present in the Gladstone region can be identified below:

- Alumina from the refineries and smelting industries.
- Coal from the port export terminal.
- Dust from naturally occurring processes.
- Air Pollution from the existing industries existing within the community.

This data can be tabulated according to particulate size, for the different environmental conditions a solar panel in a community such as Gladstone will experience, as displayed below:

Type of environmental condition	Particle Size (µm)
Alumina	<48
Coal	<74
Dust	<5
Air Pollution	<10

Table 11 - Environmental Conditions in Gladstone and Particle Size

For the purpose of this research project, only the effect on dust and any naturally occurring environmental conditions for the residential solar panel installations in the Gladstone region will be analysed and further explored. This will ensure a more in-depth analysis can be made at a later stage in the report to determine what effect different environmental conditions in the Gladstone region will have on the overall efficiency of home-based solar PV installations. This will then allow maintenance strategies to be suggested and further explored.

It is also important that weather data is explored and further analysed for the Gladstone region, this will aid in the selection of appropriate maintenance strategies that can be implemented for the solar PV installations. Below a snippet of the weather forecast average can be seen. This will be analysed in further detail once the data analysis phase commences.

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Years		Plot	Map
Temperature																	
Mean maximum temperature (°C)	30.8	30.8	29.9	28.2	25.8	23.5	23.1	24.1	26.2	27.7	29.0	30.2	27.4	29	1993 2023		
Mean minimum temperature (°C)	23.0	23.0	21.9	19.2	15.7	13.3	12.0	12.7	15.6	18.6	20.5	22.2	18.1	29	1993 2023		
Rainfall																	
Mean rainfall (mm)	136.4	163.8	118.3	41.2	38.4	39.1	32.4	31.8	27.5	63.3	61.7	103.3	866.5	28	1994 2023		
Decile 5 (median) rainfall (mm)	118.6	105.6	63.2	27.4	19.2	18.9	14.6	15.4	16.4	53.2	46.2	88.2	786.3	29	1994 2023		
Mean number of days of rain ≥ 1 mm	8.5	8.3	7.3	3.9	3.6	3.8	3.0	2.6	2.8	4.9	4.8	7.1	60.6	28	1994 2023		
Other daily elements																	
Mean daily sunshine (hours)																	
Mean number of clear days														3	2007 2010		
Mean number of cloudy days														3	2007 2010		
9 am conditions																	
Mean 9am temperature (°C)	27.4	27.0	26.2	24.0	20.6	17.7	16.7	18.4	21.8	24.2	25.7	27.0	23.1	17	1993 2010		
Mean 9am relative humidity (%)	66	69	65	65	65	67	65	62	61	60	61	63	64	17	1993 2010		
Mean 9am wind speed (km/h)	17.0	15.9	16.2	14.5	13.0	12.4	12.1	12.2	13.9	15.9	16.2	15.9	14.6	17	1993 2010		
9am wind speed vs direction plot																	
3 pm conditions																	
Mean 3pm temperature (°C)	29.2	29.0	28.4	26.6	24.3	22.3	21.8	22.4	24.3	25.7	27.0	28.5	25.8	17	1993 2010		
Mean 3pm relative humidity (%)	60	62	57	55	51	50	46	47	52	56	57	59	54	17	1993 2010		
Mean 3pm wind speed (km/h)	24.1	22.7	23.6	21.7	17.8	16.9	16.8	19.6	21.0	22.6	23.0	23.2	21.1	17	1993 2010		
3pm wind speed vs direction plot																	

red = highest value blue = lowest value

Figure 12 - Gladstone Region weather forecast averages (BoM 2023).

Maintenance Strategies

Throughout the literature reviews various forms of maintenance strategies which have been developed for solar PV systems were elaborated on, specifically identifying the advantages, disadvantages, and efficiency of the solutions. As a part of the research being conducted, maintenance strategies are required to increase the efficiency of solar PV panel installations, and understanding what these strategies will look like once the installation has been complete. This has not been heavily explored, with most installations being neglected once installed due to the thought that they will be self-maintainable. Solar PV installations experience a loss in efficiency of the output power, due to environmental factors causing accumulation on the surface of the panels and potential lack of rainfall which would naturally clean the solar panel partially.

Maintenance strategies that will be further explored throughout this report include both passive and active systems. These systems will be modelled using MATLAB, allowing comparisons to be performed, and how these maintenance solutions will improve the efficiency for the various environmental conditions being explored. Below are the maintenance strategies identified from the literature reviews, that will be modelled.

Proposed Method	Mechanism	Pros	Cons	Efficiency improvement
Manual cleaning (Passive system)	It depends on laborers to clean the solar cell panels manually.	- Very efficient. - Cleans the system effectively	- Can put labors in danger. - Costly. - Time-consuming for large scale capacity	- Up to 98%
Dry-Cleaning system (Active system)	Cylinder with built-in nozzles to jet spray compressed air.	- No human intervention. - Efficient cleaning. - No need for water	- Loss of the power output - May scratch the panel surface	- Up to 15%
Acoustic waves (Active system)	Cleaning solar panels using Surface Acoustic Waves	- Low-cost - No surface damage	- Removing large dust particles with a size of 0.2 mm and above. - Depends on the tilt angle.	- Up to 54% improving in terminal voltage of Panel
Rainfall cleaning (Passive system)	It depends on the water droplets that come from rain	-It is free of charge	- Rains are not accurately - predictable - Is not suggested for dry regions with dusty air	- Varies and depends on adequate rainfall

Table 12 - Maintenance/Cleaning methods for Solar PV Installations to be Explored (Deb & Brahmbhatt 2018).

These proposed cleaning solutions above will be graphically compared, and from these models a suggestion for the most ideal solution to be implemented will be identified, and further elaboration will be had on how a maintenance strategy can be developed for people within the community, following the installation of these panels.

Storm Damage Protection

Due to the minimal research conducted on adequate storm damage protection for solar panel installations, the literature reviews will be utilised to further discuss and explore what options there are for storm damage protection. This will explore suggestions such as developing more reliable and heavy-duty solar panels, the potential for introducing enhanced protection or covers for the solar panels, or any other available options for extending and maintaining the life expectancy of the solar panels.

Solar Panel End of Life

At this current stage, there are not many options available for ensuring solar panels are recycled effectively. Options that can be further explored include design options for solar panels to be modular, allowing individual components to be replaced, rather than a whole solar PV panel being disposed of when a single part fails. Other options include government or solar PV panel industries initiating recycling facilities to ensure solar PV panel parts are disposed of in an environmentally friendly way. Other options involve preventing the initial failure of solar PV panels by ensuring they are designed to withstand environmentally harsh conditions. These options will all be explored and compared to identify opportunities for ensuring the carbon footprint created as a result of the disposal of solar PV panels is lowered, making the whole process of solar PV installations environmentally friendly.

Data Analysis

As explained throughout the methodology data collection for the environmental, maintenance strategies, storm damage protection and solar power end of life options, data will be analysed and compared using various data comparative tools. These tools will include using simulations and models in MATLAB, graphical analysis using MATLAB, tabular comparison using Microsoft Excel and Word, graphical analysis using flow diagrams or other analysis tools as required.

These tools will all contribute to the final research solution and will give a visual understanding of why this conclusion has been made, as well as the supporting evidence and data that can be used to further support this decision.

5. Design Stage

Solar Panel Efficiency

Solar Panel Selection for Testing

There are several types of solar panels available within Australia for installation in Home Based Solar PV systems. For the purpose of this report and testing, monocrystalline and polycrystalline solar panels will be simulated/modelled, with the results from these simulations being used for further analysis (Marsh, 2023).

Monocrystalline solar panels consist of monocrystalline solar cells which combine to form a solar panel. The advantages of monocrystalline solar panels include their increased efficiency when compared to various other solar panels available on the market. The reason for this efficiency is due to the panel being made up of single crystal cells, which allows the electrons present to move freely increasing overall efficiency. The panels have a slim design with black solar cell and will have a higher cost when compared to other panel options available (Marsh, 2023).

Polycrystalline solar panels comprise of multiple crystal silicon fragments which are combined to form a solar cell. Due to the multiple fragments, these cells may be referred to as multi-crystalline solar cells. When compared to monocrystalline panels, polycrystalline have lower efficiencies due to the increased fragments making up a single solar cell. This causes restrictions on electron movements within the solar cell decreasing efficiency. Polycrystalline panels are blue in colour and are less expensive to manufacture to the process being less complex and easier to produce (Marsh, 2023).

	Monocrystalline Panels	Polycrystalline Panels
Aesthetics	Solar cells have a black hue	Solar cells have a blue hue
Cost	More expensive	Less expensive
Efficiency	More efficient	Less efficient
Temperature Coefficient	Lower temperature coefficient/more effective when temperature changes	Higher temperature coefficient/less effective when temperature changes
Lifespan	25+ years	25+ years

Table 13 - Monocrystalline vs polycrystalline comparison (Marsh, 2023)

The specific solar panel brands chosen for the purpose of this research paper include the RNG-253D Monocrystalline solar panel and the RNG-253P Polycrystalline solar panel, both products from the popular and highly regarded solar panel brand Renology. These solar panels are available within MATLAB Simulink which will make simulation more achievable and simpler for these particular panels selected.

Irradiance Data for Gladstone

An important variable that needs to be considered for the location and placement of a solar photovoltaic installation is the irradiance data for the region these panels are being installed.

Irradiance is the measurement of radiant energy produced from the sun, which is directed towards the earth's surface (NASA, 2008). For the purpose of this research paper, Gladstone located in Central Queensland, Australia, is the location in which the home-based solar photo voltaic system will be situated. To ensure the simulation/model in MATLAB of the solar photo voltaic system is relevant to this location, historical irradiance data for Gladstone has been collected, spanning over the duration of a year, January through to December.

Show in table... Units MJ.m^{-2} kWh.m^{-2}

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Graph												
1st	5.1	7.8	6.9	6.2	5.1	4.4	2.1	3.9	4.9	6.7	2.1	3.5
2nd	7.9	8.0	6.8	6.1	4.0	4.4	1.8	3.4	4.8	6.1	8.0	6.7
3rd	8.3	5.8	6.4	6.2	5.0	4.4	1.9	4.8	5.4	6.2	8.1	8.3
4th	8.4	4.6	5.9	6.1	5.1	3.6	1.4	4.9	5.8	7.1	8.1	8.5
5th	8.5	7.3	6.1	6.1	4.9	2.7	1.5	4.4	5.7	5.4	7.9	8.5
6th	7.8	7.2	5.7	6.0	3.9	2.4	4.4	2.4	6.0	6.2	8.0	8.5
7th	8.2	7.0	6.2	5.8	3.5	2.6	4.4	4.4	3.8	6.4	7.6	8.5
8th	6.8	7.6	5.4	5.6	2.8	4.3	4.4	5.1	4.9	7.2	7.8	6.6
9th	5.7	7.9	3.8	2.1	4.3	4.3	4.4	5.1	2.9	3.9	8.1	8.4
10th	7.7	7.7	5.1	4.3	3.1	4.3	4.4	5.1	6.0	6.2	8.0	7.2
11th	6.3	8.0	2.9	5.9	1.4	4.3	4.4	4.8	6.2	6.0	8.2	7.7
12th	8.0	7.7	6.0	5.8	3.1	3.3	2.7	4.6	3.9	6.8		8.5
13th	8.4	7.6	6.6	5.7	1.3	4.3	4.5	3.8	6.3	6.7	8.2	7.1
14th	7.6	6.8	6.4	4.9	4.6	4.1	4.5	5.2	6.3	7.3	6.1	6.6
15th	8.3	6.0	6.8	5.7	4.2	3.8	4.5	5.2	6.2	7.1	7.3	8.6
16th	7.0	6.4	3.4	5.7	3.9	4.2	4.3	5.3	5.4	4.1	6.6	7.8
17th	7.5	7.7	6.9	5.6	4.6	3.7	4.5	5.4	1.7	5.5	7.7	8.5
18th	8.3	7.4	6.8	5.6	3.9	4.3	4.5	5.4	6.5	5.5	8.0	7.2
19th	8.2	7.6	6.7	4.5	3.8	4.3	4.6	5.4	4.2	2.6	7.1	8.2
20th	7.4	7.5	5.6	5.6	2.1	4.3	3.8	5.5	6.6	3.2	5.4	8.4
21st	6.8	7.6	6.7	4.0	1.0	4.3	1.6	5.5	2.7	5.4	6.5	8.3
22nd	8.3	7.3	6.3	2.6	4.5	4.3	3.2	5.4	5.1	5.6	6.0	8.5
23rd	8.4	6.5	6.6	5.1	2.4	4.3	4.7	5.3	6.5	7.7	6.5	6.9
24th	8.3	5.4	6.6	3.6	3.9	4.3	4.7	5.6	6.7	6.0	4.1	3.9
25th	6.5	6.1	6.4	4.1	4.2	4.3	4.7	5.6	6.8	5.9	8.3	4.3
26th	6.8	5.9	5.7	2.1	3.9	3.2	4.7	5.6	6.7	7.6	8.4	6.6
27th	3.6	6.1	4.2	4.2	4.4	4.1	4.8	5.5	5.2	7.4	7.1	6.6
28th	8.2	7.1	5.5	5.2	4.4	4.3	4.8	5.1	3.5	7.5	5.9	8.1
29th	8.3		6.2	5.1	4.4	2.9	4.7	4.7	3.2	7.8	1.1	8.6
30th	6.1		6.3	4.8	3.2	3.5	4.8	3.4	6.9	7.9	1.0	6.3
31st	8.2		6.2		4.2		4.3	4.8		7.7		7.7
Highest daily	8.5	8.0	6.9	6.2	5.1	4.4	4.8	5.6	6.9	7.9	8.4	8.6
Lowest daily	3.6	4.6	2.9	2.1	1.0	2.4	1.4	2.4	1.7	2.6	1.0	3.5
Monthly mean	7.4	7.0	5.9	5.0	3.7	3.9	3.9	4.9	5.2	6.2	6.7	7.4

Table 14 - Gladstone region irradiance 2022 (Australian Government 2023)

The purpose of this research paper is to understand the environmental influences on a solar panel, and therefore, the Gladstone irradiation data in Table 8 will be separated according to the various seasons experienced throughout the year. The data that will be used for the modelling of a solar photovoltaic system will be for the months below:

Summer – January

Autumn – April

Winter – July

Spring – October

The data for these specified months will be used for comparison and modelling of the solar system which will require monthly averages to be used. The data in Table 8, will also be converted to kWm^{-2} to allow these values to be input into MATLAB. The values that will be used during the testing stage can be identified in the below table.

Season	**Month**	**Monthly Average Irradiance (kWm^{-2})**
Summer	January	308
Autumn	April	208
Winter	July	163
Spring	October	258

Table 15 - Seasons Monthly Average Irradiance (Australian Government 2023)

Using the above values calculated in Table 10, and the selected monocrystalline and polycrystalline solar panels, comparisons will be made between the varying irradiation and the solar panel type. This will be conducted in Simulink and will allow an in-depth analysis to be performed comparing the effect different solar panels and irradiance can have on the overall power output of a solar panel.

Rainfall Data for Gladstone

The below table represents the rainfall data for the Gladstone region in 2022. This data will be used to identify how efficient natural rainfall is at cleaning the surface of a solar panel, depending on the amount of rainfall received throughout the year. For the purpose of this research, the rainfall data will be separated into seasons, more specifically 12-week periods, to display the effect dust accumulation has on the overall efficiency of a solar panel.

Show in table...

Key: Units = mm 12.3 = Not quality controlled. ↓ = Part of accumulated total
28.0 Move mouse over rainfall total to view the period of accumulation.

2022	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Graph												
1st	0		0	0	0	0	0	1.4	0	0	6.0	29.4
2nd	0		0	0	0	0	25.2	0	0	0	12.0	0
3rd	0		0	0	0	0	6.2	0	13.2	10.4	0	0
4th	0		0.6	0	0	2.4	23.4	0	0	0	0	0
5th	0	2.2	1.6	0	0	0.2	25.2	0	0	0	0.6	0
6th	0	0	10.0	0	0	0.8	4.2	0.4	0	0	0	0
7th	8.0	0	1.2	0	0.8	0	0	2.2	0	0	0	0
8th	2.0	0	0.4	0	0	0	0	0	3.6	0	0	0
9th		0	2.2	0	5.0	0	0	0	0.6	0.2	0	22.4
10th		0	217.0	3.8	0.2	0	0	0	2.6	9.4	0	0
11th		0		0.8	17.2	0	0	0	0.2	0	0	0
12th		0	15.2	0.2	13.0	0	0	0	0	0	0	0
13th		0	0.2	0	38.4	0	0.6	0	0	0	0	0
14th		0	0	0	18.6	0	0.2	1.0	0	0	0	0
15th		15.2	0	0	0	0	0	0.2	0	0	0	27.4
16th		0	0	0	0	9.0	0	0	0	0	0	0
17th		0	0	0	0	0	0	0	4.0	0	0	0
18th		0	0	0	12.6	0	0	0	12.8	0	0	1.0
19th		0	0	8.2	0.2	0	0	0	0	7.8	0	0
20th		0	0	0	0.2	0	0	0	14.0	90.8	0	0.2
21st		0	3.0	0	53.2	0	5.0	0	0	0.4	1.2	0.2
22nd		0	0	6.0	19.6	0	34.6	0	0	9.4	1.2	0
23rd		1.0	0	2.8	1.6	0	0.2	0	0.4	0	0	0
24th		0.2	0	2.2	4.8	0	0	0.4	0	0	0	0
25th		0	0	0.4	0.8	0	0	0	0	6.8	1.4	7.0
26th		0	0	16.0		0	0	0	0	0	0	2.0
27th		1.0	9.2	1.6	0.2	0	0	0	0	0	0	0
28th		1.4	1.4	0.8	0	0	0	0	0.2	16.2	0	0
29th			1.6	0.6	0	0	0	0	8.2	8.8	31.0	0
30th			0	0.2	0	0	0	0	0.2	0	21.8	0
31st			0		0		0	1.4		0		0
Highest Daily	8.0	15.2	217.0	16.0	53.2	9.0	34.6	2.2	14.0	90.8	31.0	29.4
Monthly Total			263.6	43.6	186.4	12.4	125.0	7.0	60.0	160.2	75.2	89.6

Annual total for 2022 = n.a View all monthly data Plot year of daily data

Table 16 - Gladstone rainfall data 2022 (Australian Government 2023)

It is suggested that moderate to heavy rain will be sufficient enough to clean a solar panel. Moderate rain can be classified as an hourly rate of rain >2.8mm but <=7.6mm, and heavy rain is classified as an hourly rate of >7.76mm. Although these classifications are based off of hourly rainfall rates, the rainfall data only gives the total amount of rainfall received per day throughout the year, and therefore for the purpose of this research, it will be assumed that any total rainfall received that is >2.8mm will be moderate to heavy rainfall (Brittanica 2023).

Environmental Data for Gladstone

Gladstone region is an industrial town, with various pollutants and dust particles being produced as a result of the various industrial processes within the town. Typical pollutants and dust particles that could impact air quality or be identified in the community could include coal, alumina, caustic, dust, bauxite, carbon from burn-off, and typical dust generated from industrial, and development works within Gladstone. Although a portion of these processes are not located directly in the centre of the town, it is important to understand the impact these pollutants could have on solar installations in housing areas located near these facilities.

For the purpose of this research report, an analysis will be conducted based off data previously gathered in a study of the 'On-Site PV characterization and the effect of soiling on their performance' research paper, specifically focussing on the effect dust soiling can have on the overall performance and efficiency of a solar panel system (Kalogirou et al. 2013). This data gathered throughout the research is based off the location, Cyprus. Similar to Australia, where the most common types of solar panels are monocrystalline, polycrystalline, and amorphous. The most significant factors contributing to the decrease in efficiency of solar panels located in Cyprus is the settlement of dust on the surface of photovoltaic installations.

Using data gathered from the research conducted in Cyprus, a model was able to be simulated, in which Gladstone data could be input based of the efficiency trends identified in Cyprus. These models will identify the effect on varying irradiance conditions, with different solar panel installations. It will then further explore the effect dust accumulation will have on these installations, comparing the power output of a soiled solar panel with a clean and non-contaminated solar panel. The efficiency of these various solar installations and conditions will be further analysed and models will be generated to identify the effect dust accumulation has on the overall efficiency of a solar panel over a period of time. Using this data generated, various solar panel cleaning options can be implemented, allowing a maintenance strategy to be presented for the Gladstone region. This maintenance strategy will consider labour, cost, efficiency, and the practicality of the proposed maintenance strategy.

Solar Panel Maintenance Strategies

There are various researched methods that can be implemented for the continued maintenance and upkeep of solar panels, ensuring they maintain maximum efficiency over their lifespan. In residential solar panel installations, it has been identified that almost no regular maintenance is performed on a solar panel to ensure the environmental conditions these panels are exposed to isn't affecting their power output. Due to the lack of knowledge around maintenance for solar panels, it may be identified that panels are reaching their end of life quicker than specified. Regular maintenance will not only positively influence the output power of the solar panels, returning higher profits and power output for the consumer, but it will also ensure the panel is kept in good condition, promoting a lengthened life expectancy.

The types of active and passive cleaning/maintenance methods that will be further analysed and compared include, natural rainfall, manual cleaning, robotic arm, and super hydrophilic plane (SHIP) cleaning methods. Refer to the below table to understand the potential influence on power output efficiency if these cleaning methods are implemented as an effective maintenance strategy in residential home-based solar panel installations.

Cleaning Method	Efficiency increase percentage (%)
Natural Rainfall	3.26
Manual Cleaning	98
Robotic Arm	9.1
Super hydrophilic plane (SHIP)	5.4

Table 17 - Cleaning methods for solar panel installations (Derakhshandeh et al. 2021) (Deb & Brahmbhatt 2018).

The above cleaning methods will be included in the modelled solar panel graphs for different irradiances. These graphs incorporating the various cleaning methods will allow for an analysis of the most suitable and effective cleaning method, as well as providing the option to identify appropriate time periods between maintenance and cleaning of the solar panels, to ensure continued effective operation of the solar panels, both monocrystalline and polycrystalline. For the purpose of this research project, it will be assumed that Natural rainfall has an efficiency increase of 3.26%, a value gathered from the data revealing the efficiency increase for spraying water over a PV panel.

The maintenance strategy selection will also take into consideration the cost, labour, and effectiveness of the various proposed cleaning methods for solar panel installations. The proposed maintenance strategy must propose a solution which is practical and can be implemented in a home-based installation, as well as easily maintained by the house owner or a tradesperson, therefore it must be dependable and accessible. The cost of maintaining and operating the cleaning method proposed must also be considered, as the advantages of the method must outweigh the potential disadvantages of the method.

Solar Panel Simulation and Modelling

Solar PV System Calculations

MATLAB will be the software used to model the solar panel installation, more specifically using Simulink. The function 'PV Array' will be used to model the solar panel system, to mimic a real-life solar installation. As discussed earlier, the solar panels that will be further analysed are the monocrystalline RNG-253D and polycrystalline RNG-253P. Both of these solar panels are able to be selected as a preset PV module within the function 'PV Array'.

The function 'PV Array' is a five-parameter model, and the diagram of this circuit can be seen below:

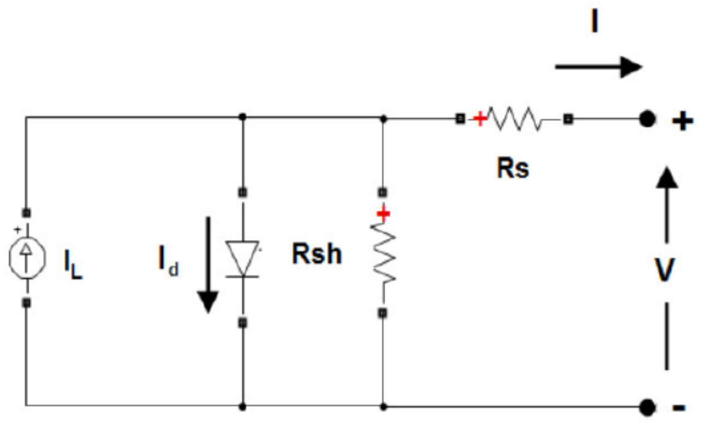

Figure 13 - Circuit diagram of function PV Array (MathWorks, 2023)

The IV characteristics of this circuit will be represented as per in Figure 15.

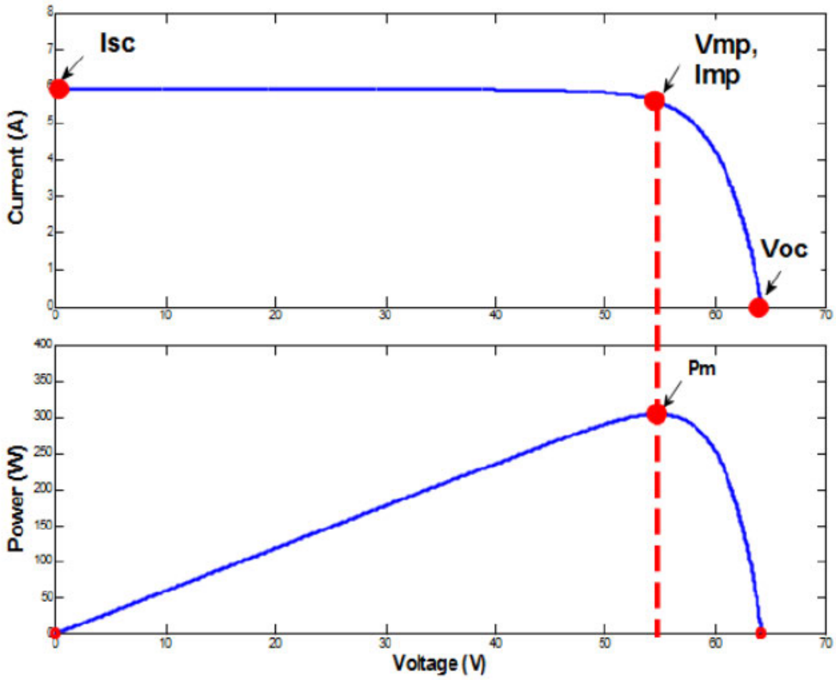

Figure 14 - I-V characteristics of PV Array function (MathWorks, 2023)

The I-V characteristic graph can be defined using the equations below:

$$I_d = I_0\left[\exp\left(\frac{V_d}{V_T}\right) - 1\right]$$

$$V_T = \frac{kT}{q} \times nI \times Ncell$$

Equation 1 - I-V Characteristic Equation for PV Array Function (MathWorks, 2023)

Where,

Variable	Description
I_d	Diode current (A)
V_d	Diode voltage (V)
I_0	Diode saturation current (A)
nI	Diode ideality factor, a number close to 1.0
k	Boltzman constant = 1.3806e-23 $J.K^{-1}$
Q	Electron charge = 1.6022e-19 C
T	Cell temperature (K)
$Ncell$	Number of cells connected in series in a module

Table 18 - Variables for characteristic equation (MathWorks, 2023)

The inputs for this PV Array function are irradiance values applied to the solar panel and the temperature of the cells in degrees Celsius. The output of this system will be a five-parameter vector consisting of, PV voltage array, PV array current, diode current, irradiance and temperature (MathWorks, 2023). These output elements will be used as the data for comparison of the solar panel types, differing irradiance conditions and cleaning method efficiency increase and their effect on a home-based solar panel installation.

Simulate a Solar Panel PV System

As discussed previously, the function 'PV Array' will be used in MATLAB Simulink to model the I-V and P-V characteristics of the selected panels, both monocrystalline and polycrystalline. Models will be established for both clean, and dirty solar panels, producing graphs for a range of different irradiance conditions experienced throughout different seasons.

For the solar panel simulation, the below data will be used to model the reduction in power output under extreme dust conditions. This extreme case is created by purposefully soiling a solar panel with a substantial amount of dust and comparing the data to a clean solar panel. The conditions will then be further evaluated, comparing a wet solar panel surface with a dry surface, in the extreme dust conditions (Kalogirou et al. 2013).

Power output reduction of solar panels experiencing extreme dust conditions.		
PV Type	**Wet surface power reduction (%)**	**Dry surface power reduction (%)**
Monocrystalline	44	14
Polycrystalline	49	15

Table 19 - Power output reduction of solar panels experiencing extreme dust conditions (Kalogirou et al. 2013)

Under normal environmental conditions, the below power output reduction percentages will be used to model the effect dust accumulation has on power output over a time period of 12 weeks in the summer period, for both monocrystalline and polycrystalline panels. Winter will not be considered in this model as it is assumed that the amount of rainfall received in the winter period is enough to adequately clean the solar panel and maintain its efficiency.

Week	Monocrystalline	Polycrystalline
1	4	2
2	6	5.7
3	8	7.9
4	9	8.5
5	9.8	10
6	11.5	11.9
7	12.9	12
8	13.5	13
9	14.1	13.2
10	14.2	13.8
11	14.6	14
12	15	14

Table 20 - Reduction in solar panel power output efficiency in summer (Kalogirou et al. 2013)

Spring will model the affect natural dust accumulation has on a solar panel over a period of four weeks. Autumn has very similar dust accumulation to spring and therefore the spring data will be referred to for both autumn and spring. This data that will be used for simulation purposes is based off Kalogirou et al. research and therefore Gladstone data will be used to replicate the reduction in efficiency of the solar panels identified in the studies previously conducted.

Week	Monocrystalline	Polycrystalline
1	2.2	2.5
2	3.1	3.4
3	3.6	4
4	3.7	4.1

Table 21 - Reduction in solar panel power output efficiency in spring (Kalogirou et al. 2013)

Home-Based Solar Installation Monitoring

<u>Purpose for Monitoring Installation</u>

Home-based solar installation monitoring systems use real-time data produced by solar panel installation to provide an overview of data being output from the installed system. This monitoring will provide information such as discrepancies between solar panel output energy, electrical faults and whether there is a potentially damaged panel.

Monitoring options ensure that energy output of solar installations can be monitored over an extended period of time, allowing users to understand the overall performance of their solar panel and financial returns. It also allows users to understand if their solar panels are operating as intended, and if not, monitoring should indicate what type of maintenance or fault finding will need to be performed on the panels to bring the efficiency of the panel back up to normal operation (Zientara 2023).

Available Monitoring Options

There are numerous options available for monitoring home-based solar installations. These various options will use devices installed on the solar panel or separately using a string inverter to measure the total power output of the solar panels. Generally, software and various interfaces are provided alongside these devices to enable easy monitoring and record keeping of solar panel output power rand other necessary data. To ensure these devices can effectively work, wireless internet connection and a smart-device or computer will be required to launch this software used to monitor these solar panels. The main types of monitoring options available include (Zientara 2023):

1. Monitoring devices supplied by the solar panel manufacturer.
2. Monitoring devices supplied by the installer of the solar panels.
3. Monitoring devices that are standalone from the solar panel installation.

Storm Damage Protection

Environmental Influences

As of February 2023, an estimated 10.8 million Australian homes have solar panel installations, equating to 31.46% of Australian households, with these figures exponentially increasing throughout the years (Solar Calculator 2023). Australia experiences a variety of different storms throughout the year, including:

1. Hail
2. Lightning
3. Cyclones
4. Heavy Rain
5. Strong Wind
6. Dust

With the increased installation of solar panels in residential areas, it is important that the overall solar panel integrity is maintained, when experiencing naturally occurring events such as storms. In residential areas, solar panels are generally installed on the roof of houses, and therefore they will be one of the first structures significantly impacted by storms, and this can lead to extensive damage to the panels if not appropriately protected from these events.

Storm Damage Protection Options

During storm events such as heavy rainfall and lightning storms, lightning strikes can cause significant damage to solar panels if they are contacted during the storm. To minimise the potential occurrence of lightning striking a panel, lightning rods can be installed on the rooftop of these households with solar installations. It is important that the solar panel rods installed are correctly rated for the equipment that needs to be protected, as a danger associated with lightning strikes is the potential for the installations to catch fire and damage the panels. These lightning rods will significantly reduce the outcomes and damage as a result of a lightning strike. It is also suggested that as a safety precaution sufficient grounding must be installed near the solar panel installation as this will protect both the surrounding people and equipment installed from harm and damage (Solar 91 2015).

During a storm strong wind may be present and are also a large contributor to the damage of a solar panel installed in a residential area. When initially installing the solar panels, sufficient and secure anchoring of the panels is essential to ensure the solar panels will not move during these storms. This will provide adequate stability to the installation and will prevent the bending and damage of the solar panel modules (Solar 91 2015).

Heavy rainstorms or cyclones will result in large quantities of rainfall on the solar installation. As a part of maintenance, it is important that the solar panels have sufficient seals to ensure these modules are waterproof. These seals can degrade over time as a result of daily sun exposure resulting in the degradation of these seals. Leaks as a result of these damaged seals can cause water leaks which will damage components within the solar panels, therefore regular inspection of the solar panel and seals is important to maintain the overall integrity of the installation and prevent damage. It is suggested that silicon-based sealants are a preferred option for the repair of solar panel seals, providing long lasting waterproof sealing of the panel (Solar 91 2015).

Solar panels are built to withstand a variety of different weather conditions that may be endured throughout its lifetime. However, large hail is a particular storm that will cause significant damage to a solar panel installation, specifically if the hail is above 25mm in diameter. The reasoning behind the extensive damage cause by large sized hail is the increased velocity and weight of the hail as it falls to the ground. Due to this impact of hail on the solar panels, damage is sustained to the glass of the panel resulting in significant damage to the panel and a reduction in the overall efficiency of the panel, generally requiring a complete replacement of the installation (Cranney 2020).

Suggestions for providing hailstorm and cyclone protection to solar installations includes, firstly selecting panels that can withstand potential hail conditions. If you are located in an area where hailstorms are common, choose a panel with product specifications that can withstand these potential conditions that could be experienced. It would also be important to ensure panels have warranty that could potentially cover hail damage, ensuring that if these panels are damaged during a hailstorm, they could be replaced or even repaired under warranty. Wire or mesh panel protection covers could also be installed to prevent damage during hailstorms. These covers are specifically made to prevent damage occurring from debris and hail during everyday use and operation of these residential solar panel installations. Ensuring adequately sized mesh is selected to prevent hail from contacting a panel causing damage will be important to ensure the cover is effective in its operation. Another suggestion for preventing hail damage, is installing an automated solar panel tilt system. This system will automatically tilt the panel to consistently receive sunlight, however this can also be adjusted to be vertical, making the panel less likely to experience direct hail impact. This system would require manual human intervention to adjust these panels when suspected hail is detected or when weather warnings are issued (Turky 2022).

Solar Panel End of Life

Purpose for Solar Panel Recycling

Research conducted by the Macquarie University has estimated that Australia will be responsible for one million tonnes of solar panel waste accumulation by the year 2047. As solar panels reach their end of life, homeowners need to understand what options are available for recycling, otherwise these damaged and old panels will end up in general landfill, adding to our current waste problem that already exists. These figures are also expected to increase as with continual technology advancements, people will be increasingly more likely to upgrading any existing panels installed in residential homes. Solar panels are considered hazardous waste as these panels contain various types of toxic chemicals which include lead that is utilised for the solar panel process. These chemicals present in broken and damaged panels are likely to leach into the environment where they have been disposed of as landfill waste. These chemicals are extremely toxic and harmful to the environment and therefore it has become increasingly important to understand how these panels can be recycled in a safe and environmentally friendly way. This will reduce the potential waste crisis that will be introduced as a result of aging panels (Wrigley 2022).

Parts for Recycling

Within a solar panel module there are various parts that can be effectively recycled, with it approximated that 95% of a solar panel can be effectively recycled. These parts include:

1. Glass
2. Aluminium frame
3. Polymer
4. Silicon
5. Copper
6. Silver Paste
7. Solar panel batteries

It is highly valuable to recover the aluminium frame and silver paste during the recycling process.

Available Recycling Options

Currently in Australia there are limited recycling options available and therefore this may require solar panel customers to transport or send these end-of-life panels to designated recycling facilities. Although this may acquire additional costs to the customer, it is important that these recycling measures are taken, as this will significantly reduce the total landfill generated as a result of solar panel end of life disposal. Batteries used within solar installations are also able to be recycled, and therefore ensuring these items are sent to an appropriate recycling plant for batteries is important as lithium-ion contained within these batteries can have significant impacts on the environment if disposed of in landfill.

6. Testing Stage

Simulation in MATLAB

Below is an example of the simulation used to graph the I-V and P-V properties of the monocrystalline and polycrystalline solar panels in different irradiance conditions. These panels were then plotted in both wet and dry panel surface conditions to allow for further analysis to be conducted regarding the effect of rain or water on the efficiency of the solar panel (Tan, 2016).

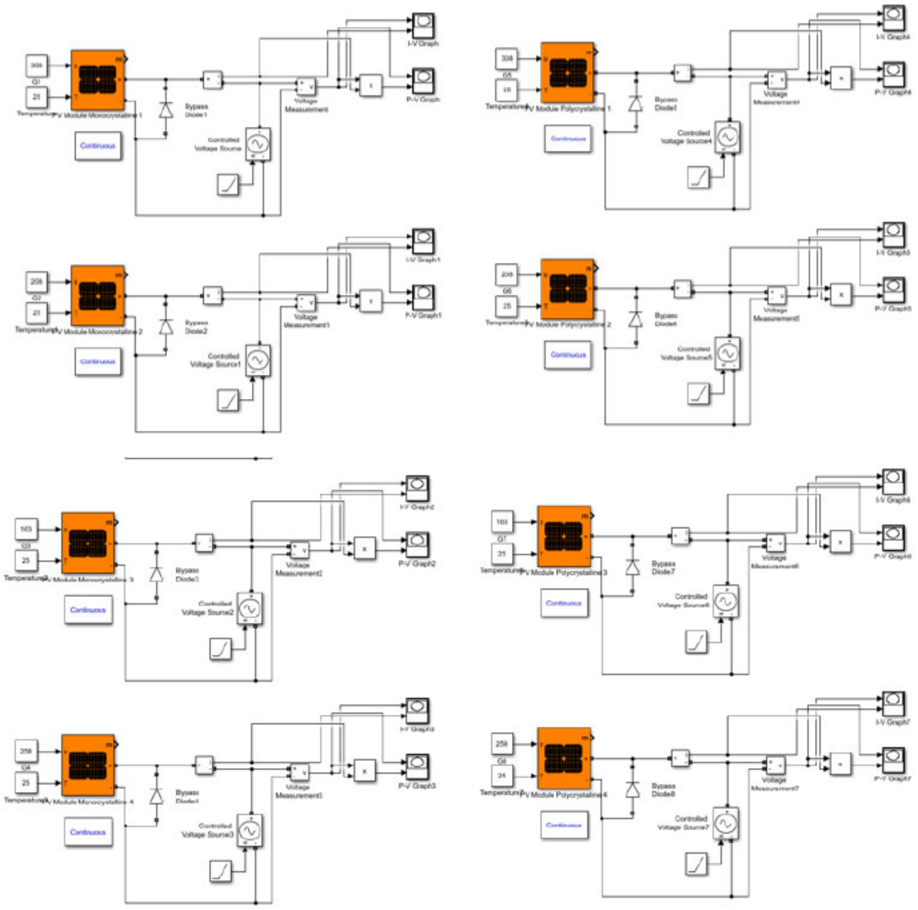

Figure 15 - Simulation used to model I-V and P-V characteristics of the solar panels (Tan, 2016).

Monitor/Record Simulated Data

I-V and P-V characteristics of the clean Renology RNG-235D monocrystalline solar panel, for the selected monthly average irradiances in Table 10.

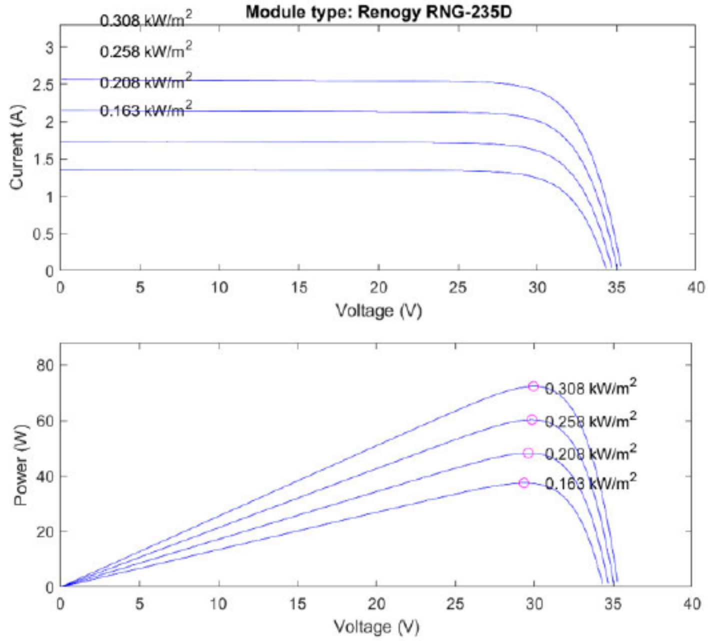

Figure 16 - I-V and P-V characteristics of the Renology RNG-235D monocrystalline solar panel under normal conditions (clean panel)

I-V and P-V characteristics of the clean Renology RNG-235P polycrystalline solar panel, for the selected monthly average irradiances in Table 10.

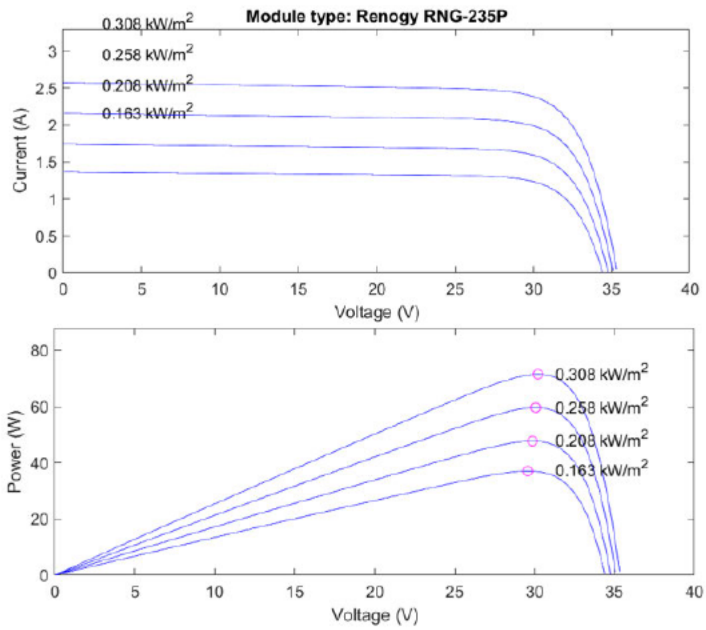

Figure 17 - I-V and P-V characteristics of the Renology RNG-235P polycrystalline solar panel under normal conditions (clean panel)

<u>I-V and P-V characteristics of the Renology RNG-235D monocrystalline solar panel, for extreme cases of dust soiling with a wet solar panel surface.</u>

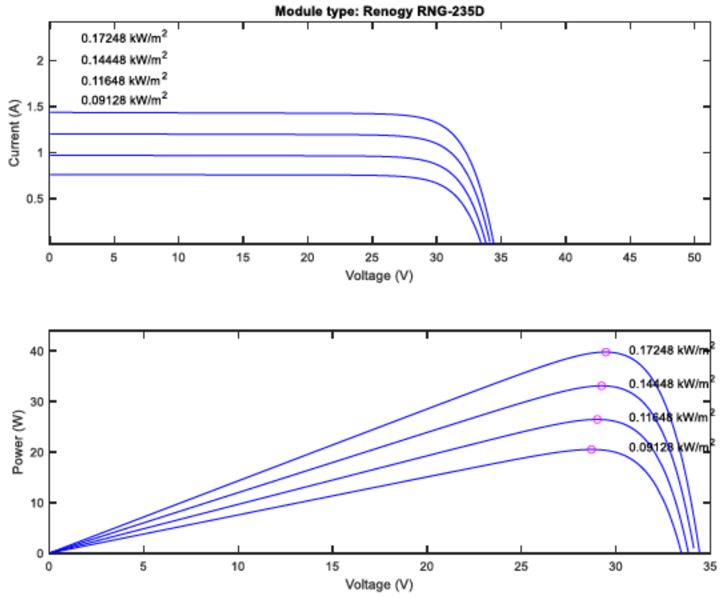

Figure 18 - I-V and P-V characteristics of the Renology RNG-235D monocrystalline solar panel under extreme dust conditions with a wet surface (purposefully soiled)

<u>I-V and P-V characteristics of the Renology RNG-235P polycrystalline solar panel, for extreme cases of dust soiling with a wet solar panel surface.</u>

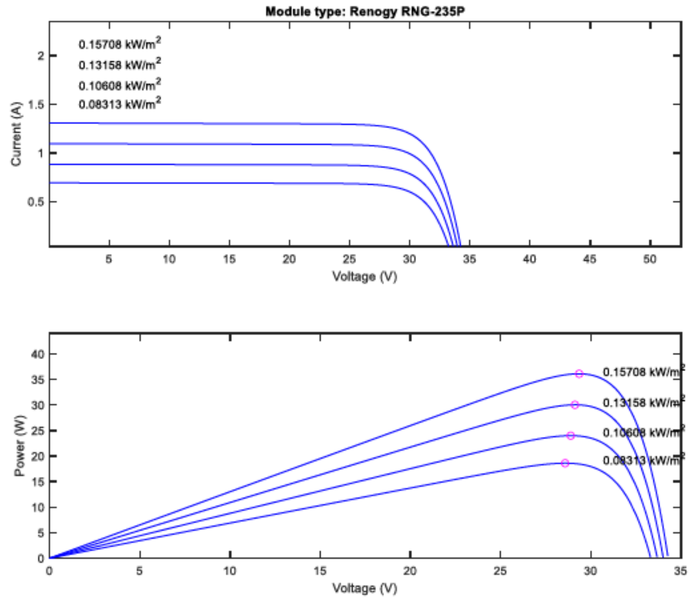

Figure 19 - I-V and P-V characteristics of the Renology RNG-235P polycrystalline solar panel under extreme dust conditions with a wet surface (purposefully soiled)

I-V and P-V characteristics of the Renology RNG-235D monocrystalline solar panel, for extreme cases of dust soiling with a dry solar panel surface.

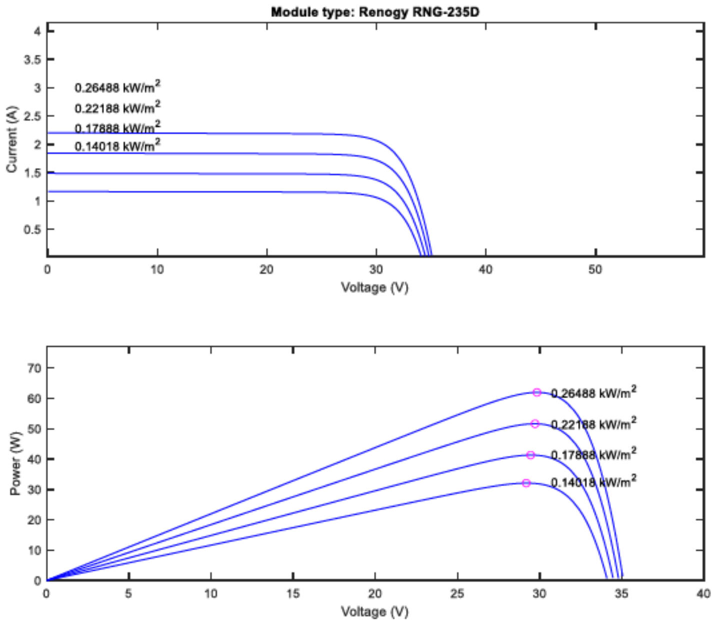

Figure 20 - I-V and P-V characteristics of the Renology RNG-235D monocrystalline solar panel under extreme dust conditions with a dry surface (purposefully soiled)

I-V and P-V characteristics of the Renology RNG-235P polycrystalline solar panel, for extreme cases of dust soiling with a wet solar panel surface.

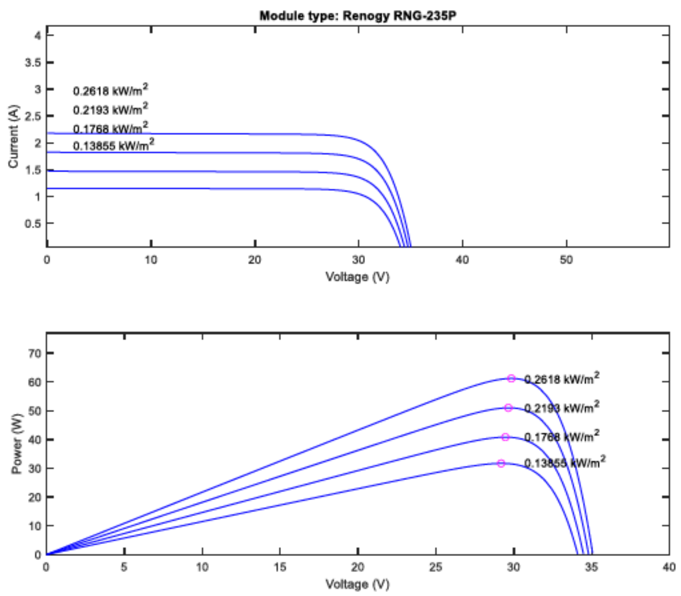

Figure 21- I-V and P-V characteristics of the Renology RNG-235P polycrystalline solar panel under extreme dust conditions with a dry surface (purposefully soiled)

Weekly accumulative decrease in solar panel output power expressed as a percentage for a monocrystalline and polycrystalline solar panel under normal dust accumulation conditions in Summer – 12 weeks.

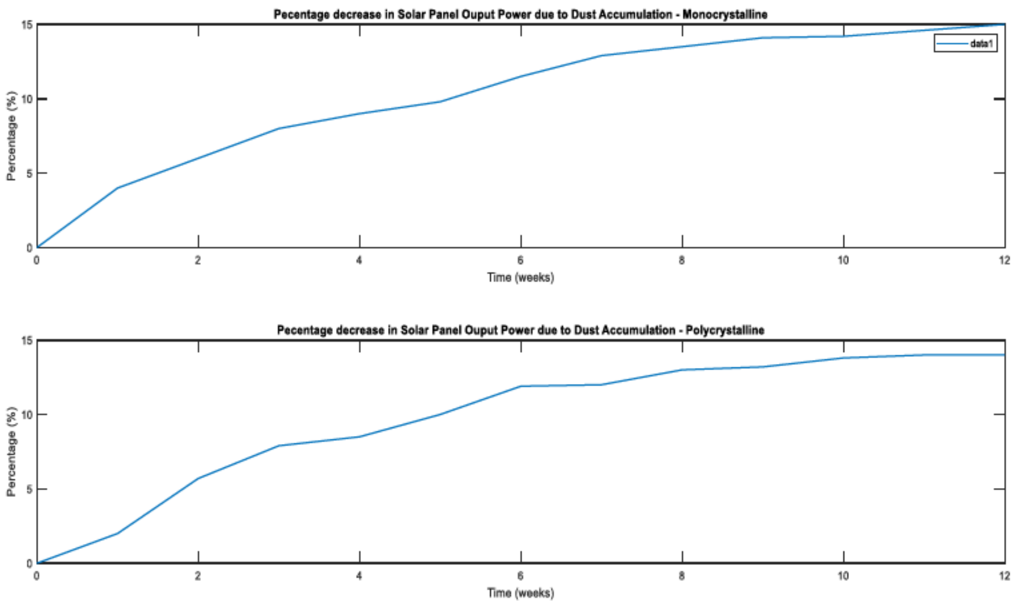

Figure 22 - Percentage decrease in solar panel output power due to natural dust accumulation - Summer.

Weekly accumulative decrease in solar panel output power for a monocrystalline and polycrystalline solar panel during various irradiance conditions and under normal dust accumulation conditions in Summer – 12 weeks.

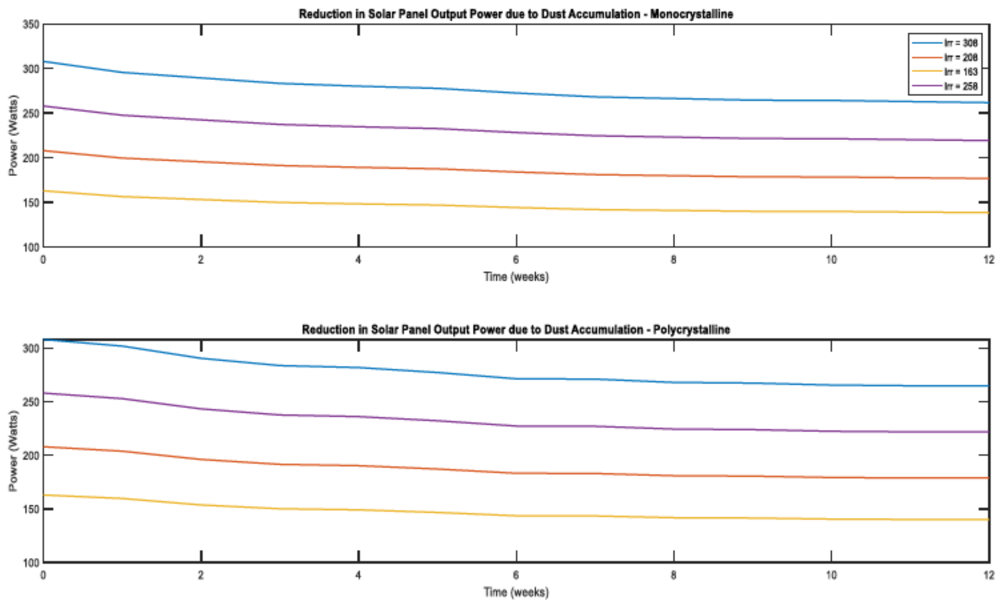

Figure 23- Decrease in solar panel output power due to natural dust accumulation - Summer.

Weekly accumulative decrease in solar panel output power expressed as a percentage for a monocrystalline and polycrystalline solar panel under normal dust accumulation conditions in Spring – 4 weeks.

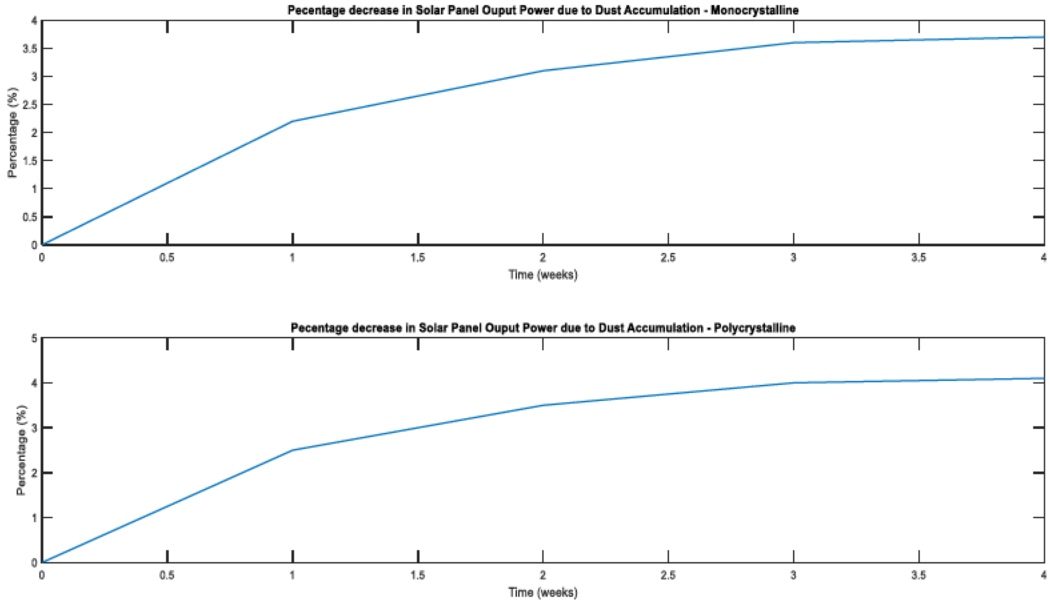

Figure 24 - Percentage decrease in solar panel output power due to natural dust accumulation - Spring.

Weekly accumulative decrease in solar panel output power for a monocrystalline and polycrystalline solar panel during various irradiance conditions and under normal dust accumulation conditions in Spring – 4 weeks.

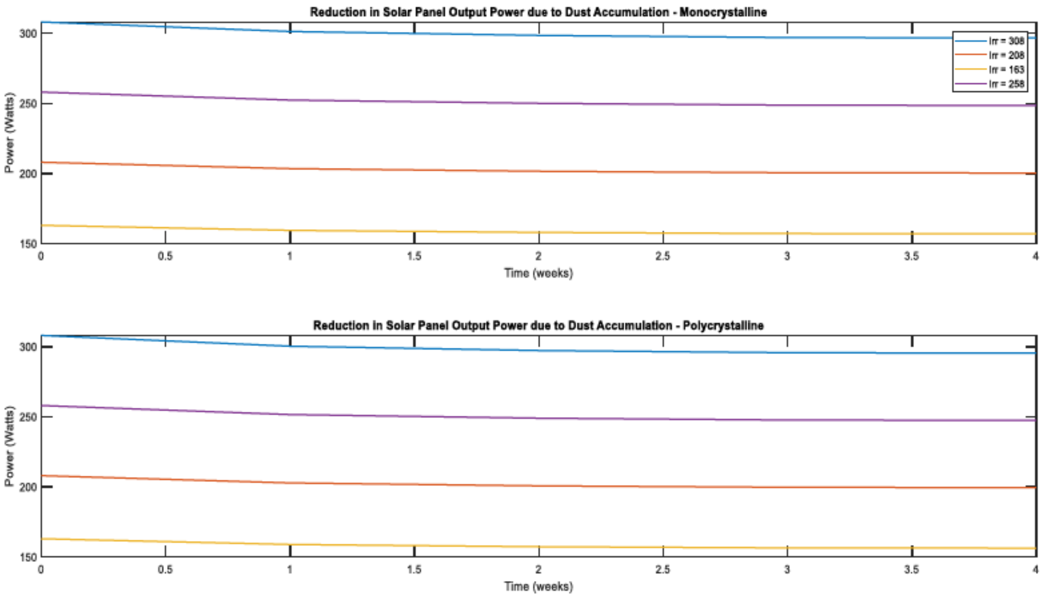

Figure 25 - Decrease in solar panel output power due to natural dust accumulation - Spring.

Review Potential Maintenance Strategies and Effect on Efficiency

To identify the trend of the percentage decrease in solar panel output power, an equation was established using the 'basic fitting tool' in MATLAB. This tool was able to produce a cubic equation based off the existing plot, which can be used to predict the dust accumulation over any given period of time. This was specifically used for the 12-week period to prove what effect maintenance implementation has on a solar panel.

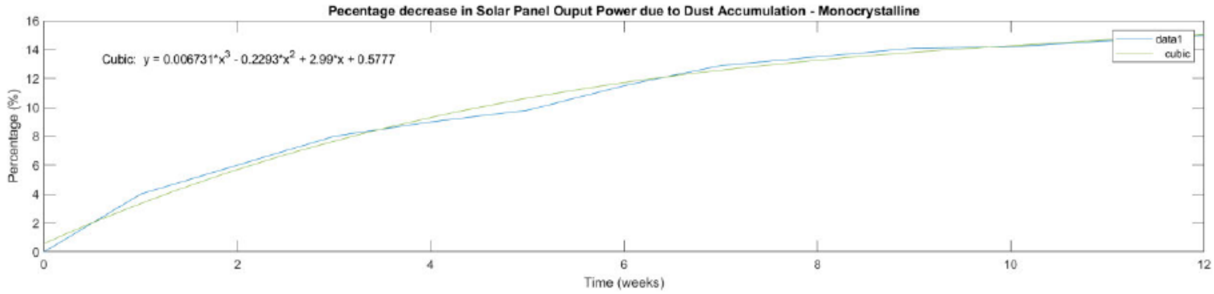

Figure 26 - Percentage decrease in solar panel output power due to natural dust accumulation and cubic equation - Monocrystalline

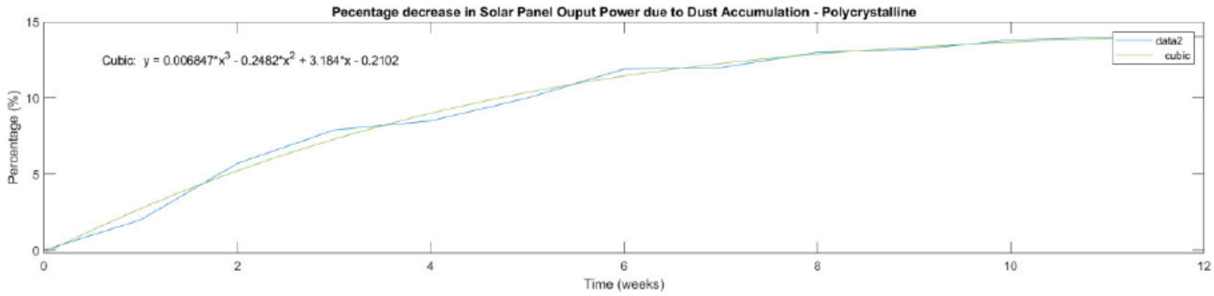

Figure 27- Percentage decrease in solar panel output power due to natural dust accumulation and cubic equation - Polycrystalline

Using the cubic equation for both the monocrystalline and polycrystalline solar panels predict the percentage decrease in solar panel output power when the maintenance strategies are implemented from Table 11, at different cleaning/maintenance intervals of 2-, 4-, 6- , 8- and 12-week periods for both the Robotic Arm and Manual Cleaning maintenance strategies. Rainfall was plotted based off the 12-week seasons that are experienced, and the SHIP maintenance strategy shows the difference between no coating and when SHIP has been applied to a panel.

<u>Weekly accumulative decrease in solar panel output power expressed as a percentage for monocrystalline and polycrystalline solar panel under normal dust accumulation conditions with Robotic Arm maintenance.</u>

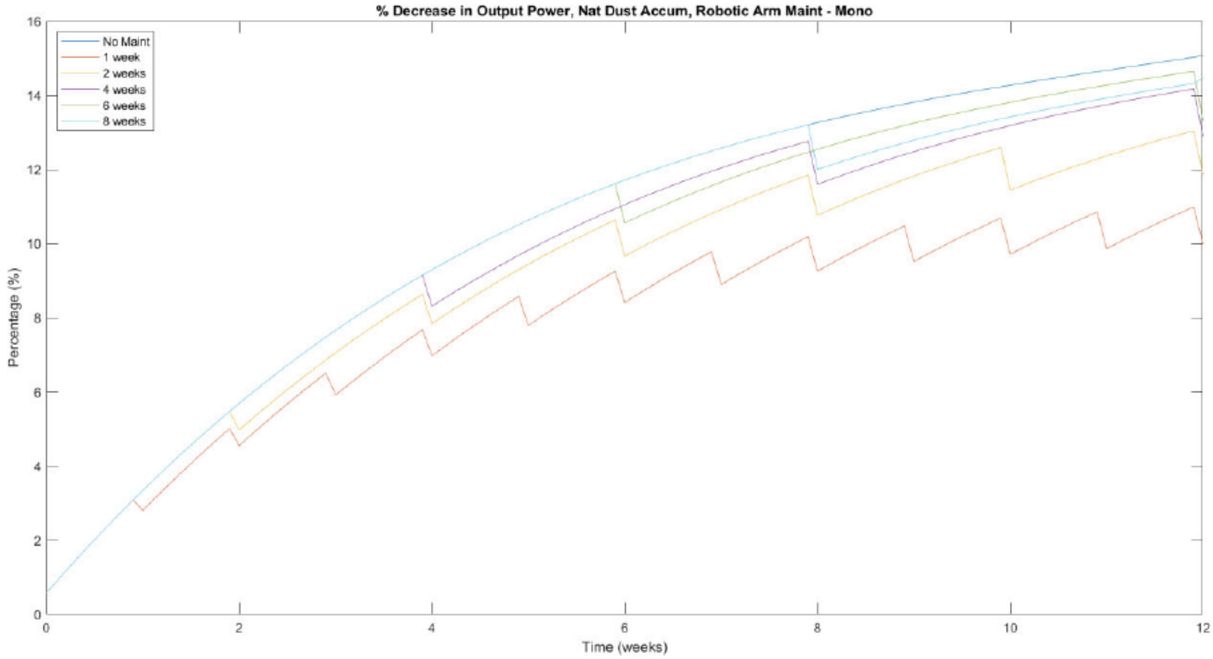

Figure 28 - Percentage decrease in output power, with natural dust accumulation and robotic arm maintenance - monocrystalline

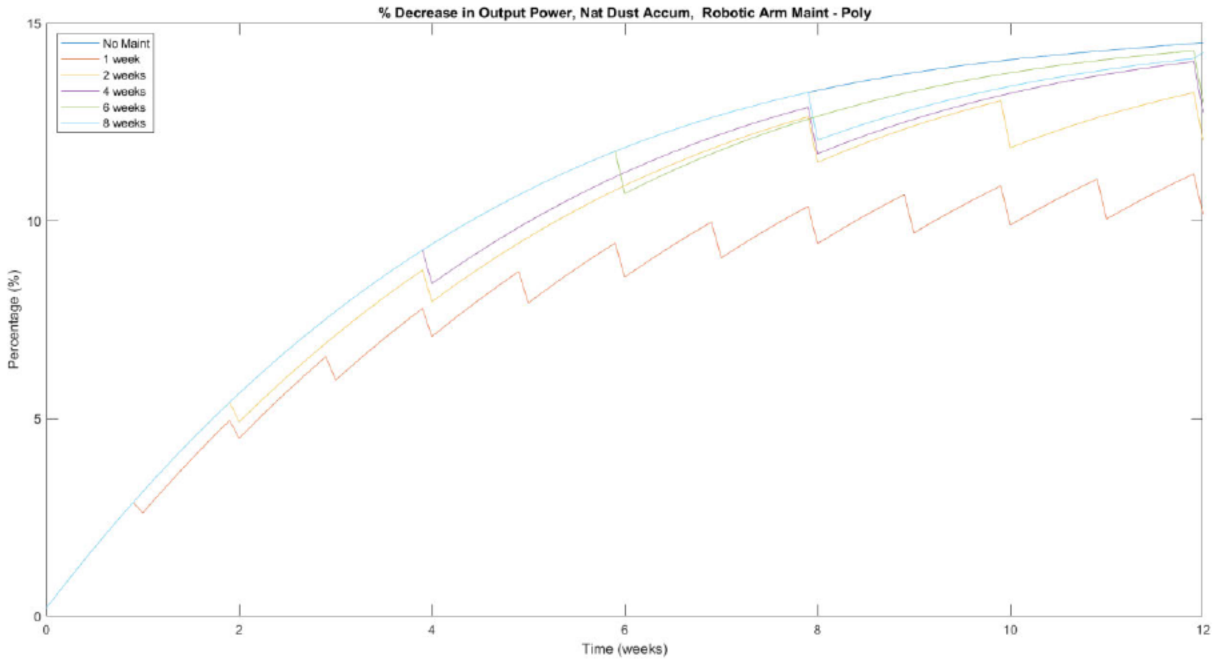

Figure 29 - Percentage decrease in output power, with natural dust accumulation and robotic arm maintenance – polycrystalline

Weekly accumulative decrease in solar panel output power expressed as a percentage for monocrystalline and polycrystalline solar panel under normal dust accumulation conditions with Manual Maintenance.

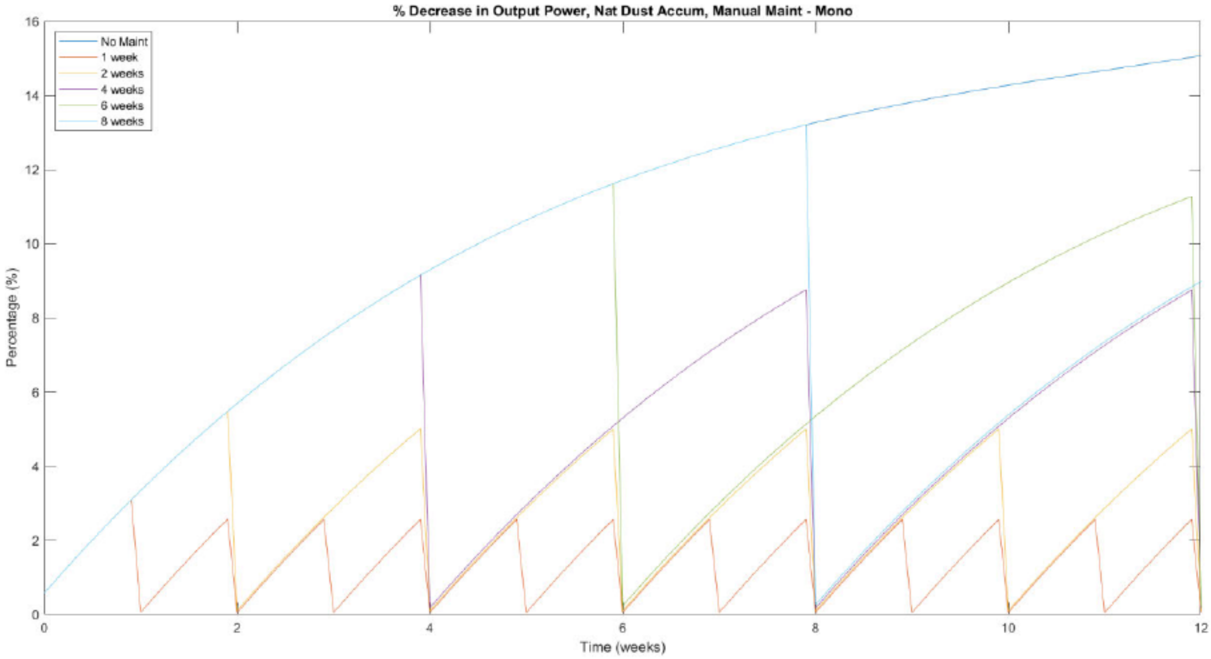

Figure 30 - Percentage decrease in output power, with natural dust accumulation and manual maintenance – monocrystalline

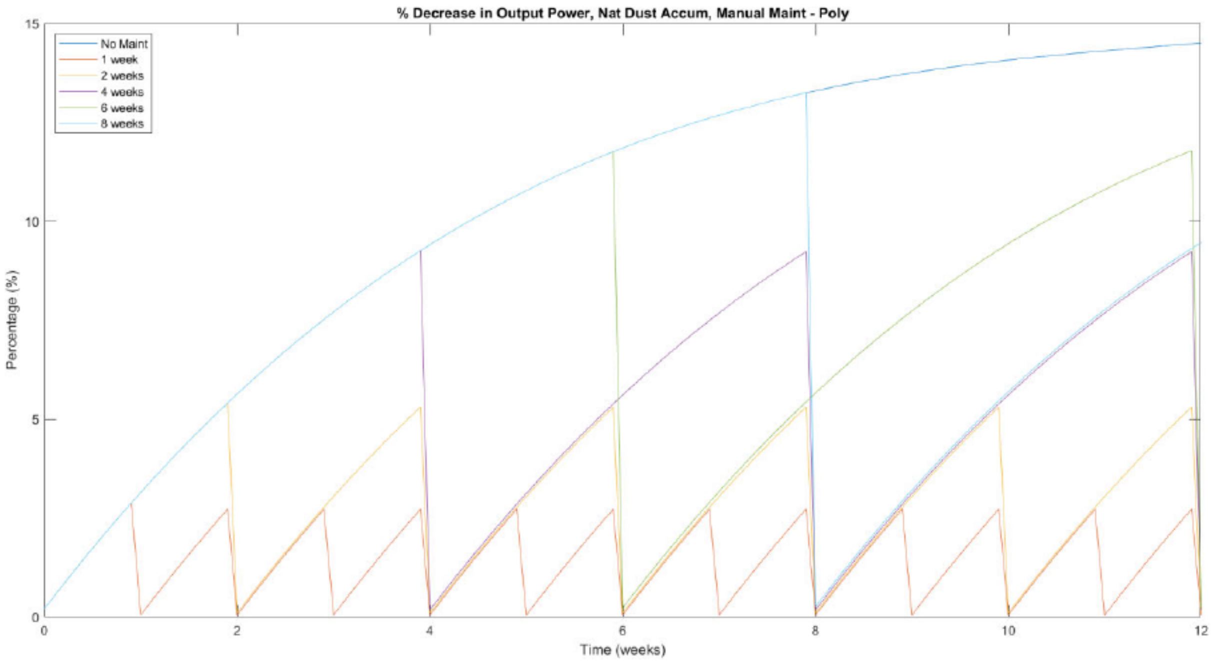

Figure 31 - Percentage decrease in output power, with natural dust accumulation and manual maintenance – polycrystalline

<u>Weekly accumulative decrease in solar panel output power expressed as a percentage for monocrystalline and polycrystalline solar panel under normal dust accumulation conditions with SHIP coating.</u>

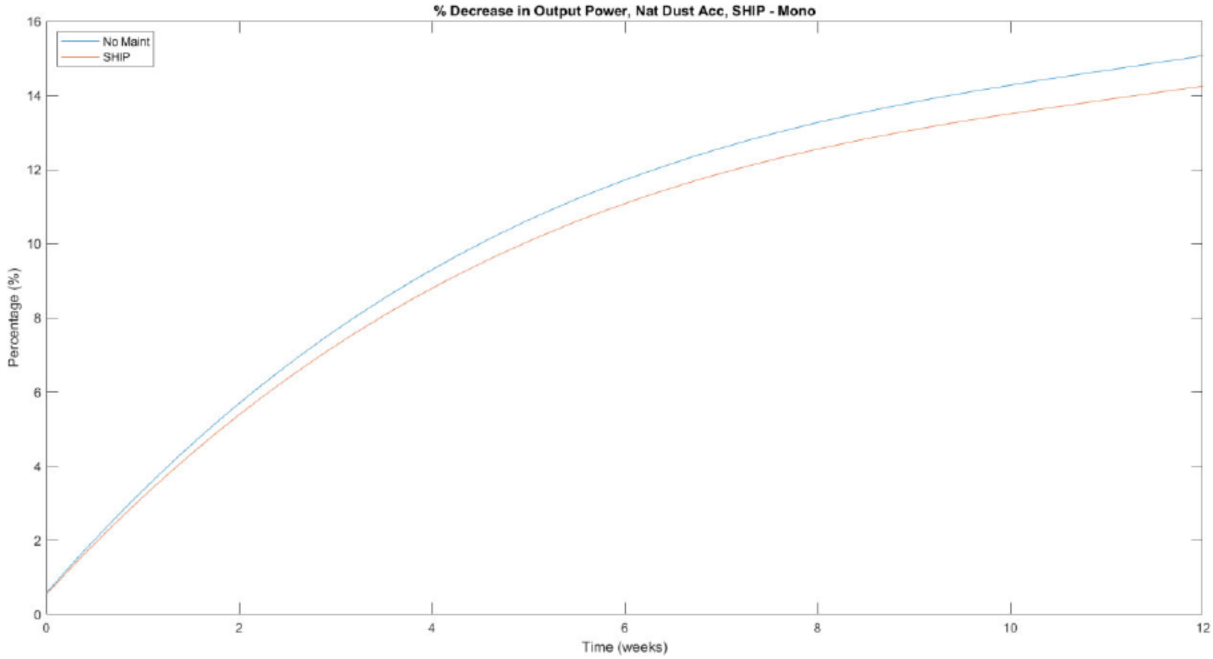

Figure 32 - Percentage decrease in output power, with natural dust accumulation and SHIP coating – monocrystalline

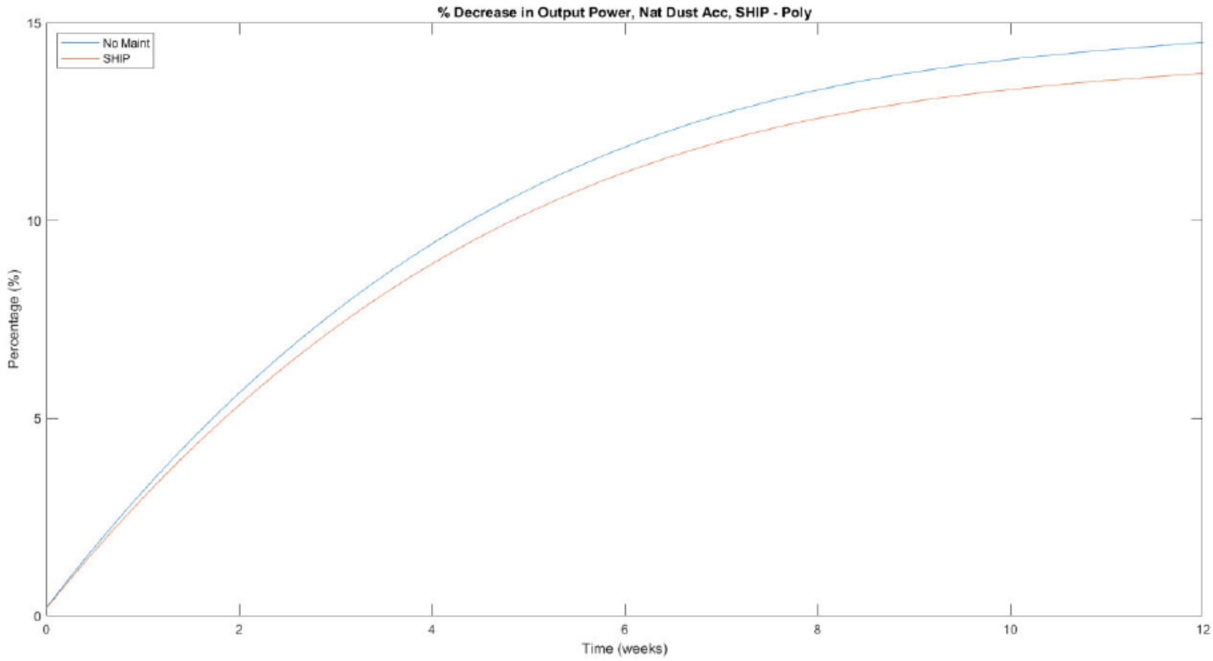

Figure 33 - Percentage decrease in output power, with natural dust accumulation and SHIP coating – polycrystalline

<u>Weekly accumulative decrease in solar panel output power expressed as a percentage for monocrystalline and polycrystalline solar panel under normal dust accumulation conditions with naturally occuring rainfall.</u>

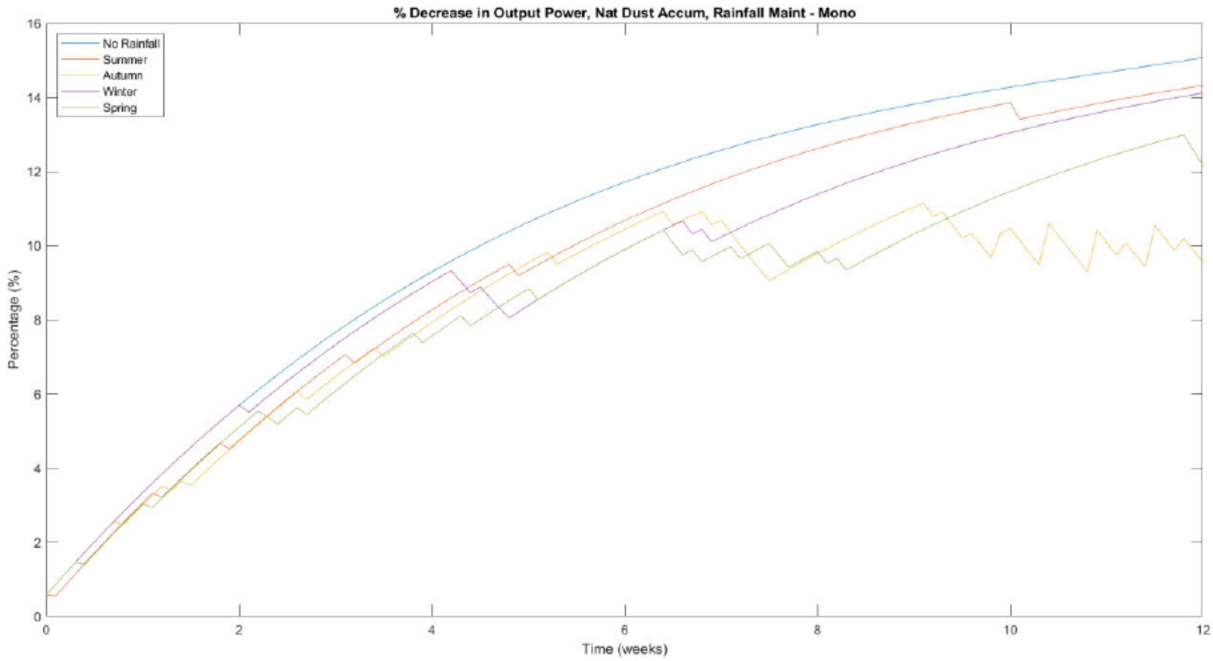

Figure 34 - Percentage decrease in output power, with natural dust accumulation and rainfall – monocrystalline

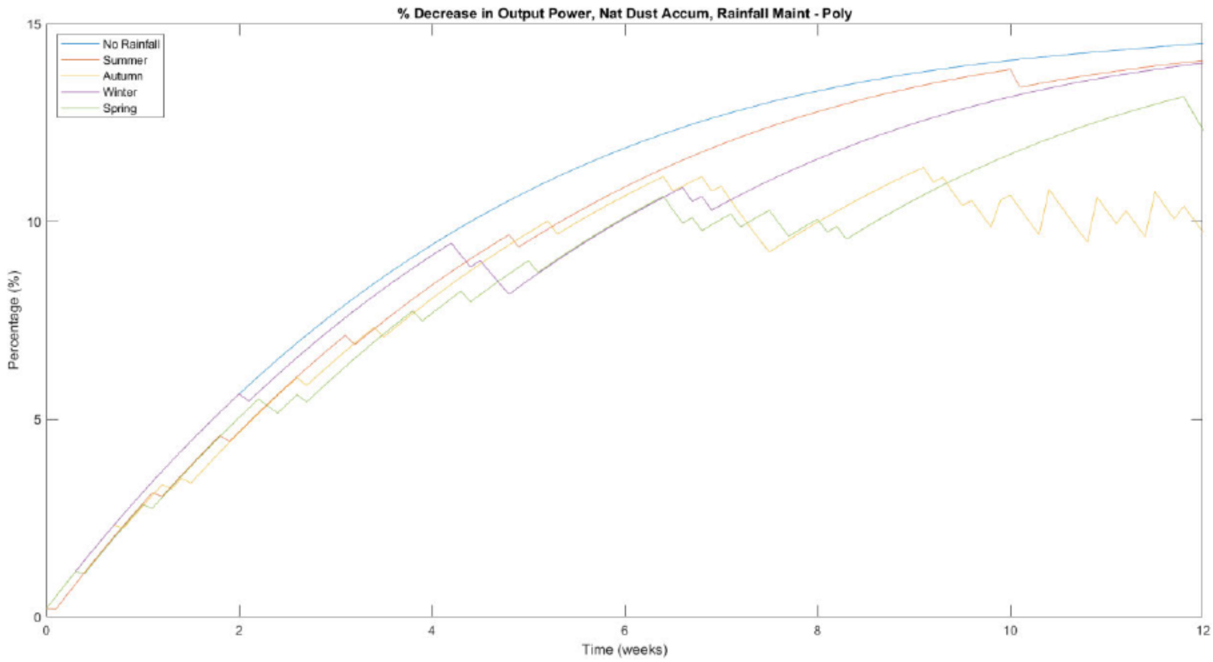

Figure 35 - Percentage decrease in output power, with natural dust accumulation and rainfall – polycrystalline

7. Data Analysis Stage

Compare Different Solar Panel Types and Efficiency

As discussed during the design stage, two types of solar panels were simulated in the testing phase to simulate a home-based solar panel installation in the Gladstone region. These panel types include, monocrystalline and polycrystalline panels, with it being previously determined that monocrystalline panels are more efficient, due to the construction and characteristics of the panel.

From the data simulated in Simulink for a Renology monocrystalline and polycrystalline panel, it can be identified that the monocrystalline panel has a higher peak output power of 72.33 Watts, when compared to the polycrystalline panel with a peak output power of 71.57 Watts. This proves the earlier efficiency statement made regarding the difference in efficiencies between the two panel types.

Throughout the duration of the testing stage, both panel types were modelled, and therefore the results and data gathered will be very similar as there is not a significant difference between the two panels. The models all look similar as the behaviour of the panels are exactly the same, just producing slightly different output values. This will require particular attention when observing the output values being produced, as the characteristics of the graphs produced will appear identical from a visual perspective.

Irradiance Effect on PV Efficiency

The data used for the simulation of the output power, of the two solar panel types was irradiance data from the Gladstone region obtained for the seasons experienced, Summer, Autumn, Winter, and Spring. January data was used to represent Summer irradiance conditions, with an average irradiance produced of 308 W/m^2. April data was used to represent Autumn irradiance conditions, with an average irradiance produced of 208 W/m^2. July data was used to represent Winter irradiance conditions, with an average irradiance produced of 163 W/m^2. October data was used to represent Spring irradiance conditions, with an average irradiance produced of 258 W/m^2.

From the data it can be observed that a decrease in irradiance, results in a decreased output power. This is proportional for all irradiance conditions and follows the same output power trend as a clean solar panel, just at a proportionally lower output power value. Both monocrystalline and polycrystalline panels behave identically to the change in irradiance conditions, however the power output values will be slightly different when comparing the two panels' data. The polycrystalline panel (Figure 18) experiences slightly lower output power values for the different irradiance conditions when compared to the monocrystalline panel (Figure 17) which is more efficient. The irradiance conditions used for this analysis are based off solar exposure experienced throughout the month. Events and scenarios that can affect the solar irradiance conditions include, the time of day, location of the solar panel, season, weather and environmental conditions and landscape conditions. Throughout the day the sun will move as the earth rotates, changing the exposure of the panel to this light source, the sun. Depending on the position of the sun, the irradiance conditions will vary, with the peak irradiance conditions generally being experienced in the middle of the day when the sun is more perpendicular to the panel. For the simulation, average monthly data values were used for the irradiance conditions, rather than high or low values experienced throughout the month. Due to the earths tilt, and orbit around the sun, the solar panel will experience a range of irradiance conditions, depending on the location's seasons experienced. This is why the seasonal irradiance data for the Gladstone region was utilised for the simulation, as it gives a good indication of the different irradiance conditions that may be experienced depending on the season. Different weather conditions can affect the amount of irradiation received by a solar panel. Rainfall, cloud coverage, and other extreme weather conditions such as snow, hail, and natural disaster events are all contributing factors to the decrease in irradiance. Lastly the position in which the solar panel is located can have an effect on the irradiance, and therefore the location of residential solar panels installation mat result in different power output as elevation of the landscape and obstructions such as trees and surrounding infrastructure can block the sun's rays from reaching the solar panels (Opie, 2022).

Extreme Dust Conditions

Using data gathered, a simulation was able to be produced for extreme dust soiling conditions on a solar panel surface. This simulated condition is man-made and was used to show the effect large deposits of dust on the surface of a solar panel can have on the efficiency and power output. This simulated data compared monocrystalline and polycrystalline solar panels, and the four irradiance conditions representing the different seasons experienced by the Gladstone region. These extreme dust conditions were further refined, revealing the difference in power output when the surface of the solar panel is wet or dry. A wet solar panel surface is utilised to indicate what would be experienced after light rainfall which is not capable of fully cleaning the solar panel of dust accumulated on the panel surface.

Wet Panel Surface

Figure 19 & 20 represents the effect extreme dust soiling conditions and a wet panel surface have on the power output for irradiance conditions 308 W/m^2, 208 W/m^2, 163 W/m^2 and 258 W/m^2 for a monocrystalline and polycrystalline solar panel. A wet monocrystalline solar panel surface exposed to extreme dust conditions will experience an approximate 44% reduction in output power efficiency. This will result in an output power of 39.79 Watts for an irradiance of 308 W/m^2. A wet polycrystalline solar panel surface exposed to extreme dust conditions will experience an approximate

49% reduction in output power efficiency. This will result in an output power of 36.11 Watts for an irradiance of 308 W/m^2. The remaining efficiencies experience a proportional output power decrease.

As a result of the solar panel surfaces being wet, it can be assumed that this allows dust to stick to the panel, causing significant efficiency loss. When this surface dries, so will the dust which has soiled the panel, potentially creating a more hardened product on the surface of the panel which is difficult to remove naturally. If the panel was dry, it would be assumed that this introduced dust would either fall/slide off the panel or blow off more easily on a windy day.

Wet Panel – Extreme Dust Accumulation			
Monocrystalline (44% loss)		**Polycrystalline (49% loss)**	
Irradiance (W/m^2)	**Power (W)**	**Irradiance (W/m^2)**	**Power (W)**
172.48	39.79	157.08	36.11
144.48	33.11	131.58	30.04
116.48	26.46	106.08	24.00
91.28	20.52	83.13	18.61

Table 22 - Wet Panel dust accumulation initial irradiance and power (Kalogirou et al. 2013)

Dry Panel Surface

Figure 21 & 22 represents the effect extreme dust soiling conditions and a dry panel surface have on the power output for irradiance conditions 308 W/m^2, 208 W/m^2, 163 W/m^2 and 258 W/m^2 for a monocrystalline and polycrystalline solar panel. A dry monocrystalline solar panel surface exposed to extreme dust conditions will experience an approximate 14% reduction in output power efficiency. This will result in an output power of 61.96 Watts for an irradiance of 308 W/m^2. A dry polycrystalline solar panel surface exposed to extreme dust conditions will experience an approximate 15% reduction in output power efficiency. This will result in an output power of 61.22 Watts for an irradiance of 308 W/m^2. The remaining efficiencies experience a proportional output power decrease.

When comparing the decrease in output efficiency for a wet and dry monocrystalline panel, this is significantly different, with a 40% different in efficiency. For a polycrystalline wet and dry panel there is a 44% difference in efficiency which is an even larger difference between panel conditions experienced with extreme dust soiling. This clearly proves the effect a wet surface has on the efficiency, revealing that dust is more likely to remain on the panel if the surface is wet before soiling occurs.

Dry Panel – Extreme Dust Accumulation			
Monocrystalline (14% loss)		Polycrystalline (15% loss)	
Irradiance (W/m^2)	Power (W)	Irradiance (W/m^2)	Power (W)
264.88	61.96	261.80	61.22
221.88	51.62	219.30	51.00
178.88	41.32	176.80	40.82
140.18	32.08	138.55	31.70

Table 23 - Dry Panel dust accumulation initial irradiance and power (Kalogirou et al. 2013)

Dust Accumulation – Normal Dust Conditions

Dust accumulation doesn't occur in one day, and therefore research conducted by Kalogirou et al. physically implemented a solar installation and monitored the decrease in efficiency due to naturally occurring dust conditions over a specific period of time. Efficiency data for the dust accumulation in summer from the research conducted will be used along with Gladstone region irradiance data to calculate the output power and the effect this naturally occurring dust soiling has on both monocrystalline and polycrystalline solar panels.

It was assumed through the previous research data collected that Spring an Autumn would produce similar results for dust accumulation as these seasons experience similar environmental conditions, for example rainfall. And therefore, only data was gathered over a 4-week period in Spring with the assumption that this will be similar for Autumn. It was also decided though the previous research that Winter is a season that generally experiences a greater amount of rainfall, with it being enough to keep a solar panel clean from any naturally occurring dust accumulation.

Using the data from this previous experiment by Kalogirou et al, both models were established from the physical experiment for a 12-week period in summer, and a 4-week period in Spring using the data in Table 20 and Table 21. These models showing the percentage decrease in efficiency over a given time period for both monocrystalline and polycrystalline panels were used to create a cubic function equation shown in Figure 27 and Figure 28 that could be used to model Gladstone region data. For the further exploration of adequate maintenance strategies that can be implemented for a home-based solar panel installation, only the Summer model will be used, as this was developed over a longer time period. Both 12-week and 4-week models would display similar characteristics and therefore, this required only one of these time periods to be used, however, continuing to compare both the monocrystalline and polycrystalline solar panels.

<u>Summer</u>

For Summer, data was established over a 12-week period, with natural dust accumulation. From the graph it can be observed that the decrease in efficiency gradually increases over the 12-week period, with a total decrease in efficiency of 15% at 12 weeks for a monocrystalline panel and 14% for a polycrystalline panel.

Spring

For Spring, data was established over a 4-week period, with natural dust accumulation. From the graph it can be observed that the decrease in efficiency gradually increases over the 4-week period, with a total decrease in efficiency of 3.7% at 4 weeks for a monocrystalline panel and 4.1% for a polycrystalline panel.

Maintenance Strategies

Dust accumulation and other debris soiling is a naturally occurring phenomenon, and therefore maintenance strategies are crucial to ensure the continued efficient operation of solar panels in home-based installations. For the purpose of this research paper, only dust accumulation was analysed, however it must be noted that there are various other contributing factors that can reduce the efficiency of a solar panel. The following maintenance strategies were incorporated into the previous dust accumulation models to visually show the effect each maintenance strategy implemented at different time intervals has on maintaining or improving efficiency over the 12-week period monitored for naturally occurring dust accumulation.

Robotic Arm

The model for the percentage decrease in output power over a 12-week period with natural dust accumulation on a monocrystalline panel with robotic arm maintenance can be observed in Figure 29. The robotic arm maintenance can be seen implemented at time intervals of 1, 2, 4, 6 and 8-week intervals, being compared to the original natural dust accumulation over a 12-week period with no maintenance at all. Through previous research conducted it was identified that the implementation of a robotic arm will result in a 9.1% improvement of a solar panels efficiency (Derakhshandeh et al. 2021).

It is ideal to compare these different time intervals at the 8-week mark, as this will ensure fair comparison is made as a majority of the time intervals will have been implemented at least once during this period of time. It can be seen that the 1-week interval is the most effective maintenance time-interval for the robotic arm, reaching a peak output power decrease of 10.19%, being 3.02% more efficient over an 8-week period when compared to no maintenance being conducted at all. This is followed by the 2-week time interval period, which has a peak of 11.85% power decrease over an 8-week period. This is a 1.35% increase in output power efficiency when compared to no maintenance being conducted and a 1.66% decrease in efficiency when compared to the 1-week interval maintenance. The time interval 6-weeks will have a power output decrease of 12.47%, being 0.74%

more efficient then no maintenance at all. Lastly, the 8-week period has a decrease in efficiency of 12.76%, proving it to be 0.45% more efficient then no maintenance at all, and 2.57% less efficient then 1-week maintenance intervals.

Overall, a robotic arm doesn't require any human intervention to conduct cleaning, and will be a fully automated system, therefore time intervals of 1-week between the operation of the robotic arm is achievable. It can be identified from Figure 29 that 1-week intervals not only increase the efficiency of the monocrystalline solar panel significantly, but also stabilise this efficiency improvement over time, proving this strategy will maintain dust levels to a position which is maintainable. This will ensure the dust accumulation is not slowly increasing until it reaches maximum efficiency decrease which can occur when maintenance isn't enough to keep up with the maintenance efficiency reduction over time.

The polycrystalline panel exhibits almost identical characteristics and comparisons between different time intervals for the operation of a robotic arm for maintenance. The main difference is that the polycrystalline panel experiences higher decrease in efficiency of power output due to being less efficient than the monocrystalline panel. This will result in higher values of power output loss, due to this difference between panels.

Manual Labour

The model for the percentage decrease in output power over a 12-week period with natural dust accumulation on a monocrystalline panel with manual labour maintenance can be observed in Figure 31. Manual labour maintenance can be seen implemented at time intervals of 1, 2, 4, 6 and 8-week intervals, being compared to the original natural dust accumulation over a 12-week period with no maintenance at all. Through previous research conducted it was identified that manual labour will result in a 98% improvement of a solar panels efficiency (Derakhshandeh et al. 2021).

Due to manual labour maintenance being almost 100% effective in cleaning solar panels from any dust or debris accumulation, the intervals between cleaning show peaks and troughs which are almost identical each time. Therefore, using the peak at any time interval will be suitable for the comparison of the various intervals graphed for manual maintenance. It can be observed that at the 8-week interval, 1-week manual maintenance has decrease in efficiency of 2.56%, which is 10.56% more efficient then no maintenance at all during that period of time. This is followed by the 2-weekly manual maintenance period, which has a decrease in solar panel efficiency of approximately 5%, proving to be 8.21% more efficient then no maintenance at all during the 8-week period, and 2.44% less efficient then 1-week intervals conducted for maintenance. A 4-week interval between manual maintenance will result in a consistent peak of 8.76% decrease in solar panel efficiency, followed by a 6-week interval peak of 11.62% decrease and finally an 8-week maintenance interval with a 13.21% decrease in solar panel efficiency.

Overall, manual maintenance requires human intervention and labour to conduct thorough maintenance on these solar panels. It must be understood that human labour is not a once off cost like robotic arm installed on a panel, and therefore the cost of human labour and the cost in improving efficiency must be compared to understand what a reasonable timeframe between visits is to ensure the savings in efficiency outweigh the costs associated with human labour to clean these residential solar panel installations. From the data, it would be assumed that a 4-weekly interval would be reasonable to ensure that the cost of labour is worthwhile, as over a 12-week period, this could save on efficiency losses of up to 6.31%.

The polycrystalline panel exhibits almost identical characteristics and comparisons between different time intervals for manual labour maintenance. The main difference is that the polycrystalline panel experiences higher decrease in efficiency of power output due to being less efficient than the monocrystalline panel. This will result in higher values of power output loss, due to this difference between panels.

SHIP

The model for the percentage decrease in output power over a 12-week period with natural dust accumulation on a solar panel with a SHIP coating can be observed in Figure 33 and Figure 34. SHIP coating will be implemented when the panel is installed, and this coating and its effect on efficiency of the solar panel is compared to the original natural dust accumulation over a 12-week period with no maintenance at all. Through previous research conducted it was identified that if a SHIP coating is applied, this will result in a 5.4% improvement of a solar panels efficiency (Derakhshandeh et al. 2021).

In Figure 33 it can be identified that over a 12-week period a SHIP coating on a monocrystalline panel will result in a decrease in output power of 14.26%, which is 0.81% more efficient then no maintenance conducted at all during this time period.

In Figure 34 it can be identified that over a 12-week period a SHIP coating on a polycrystalline panel will result in a decrease in output power of 13.73%, which is 0.78% more efficient then no maintenance conducted at all during this time period.

Overall, a SHIP coating applied to a panel, whether it is monocrystalline or polycrystalline is a simple solution if customers don't want to invest in long term maintenance of solar panels. Although this method is clearly not as efficient as a robotic arm installation, and definitely not comparable to manual maintenance it is s good option for obtaining simple and effective way of slightly increasing the efficiency of a solar panel even when affected by natural conditions such as dust accumulation and debris soiling of the panel.

Natural Rainfall

The model for the percentage decrease in output power over a 12-week period with natural dust accumulation on a monocrystalline panel with natural rainfall in the Gladstone region can be observed in Figure 35. Natural rainfall data was identified for the Gladstone region and was compared to the original natural dust accumulation over a 12-week period with no maintenance at all. Through previous research conducted it was identified that natural rainfall will result in a 3.26% improvement of a solar panels efficiency, given that it was moderate to heavy rainfall received (Derakhshandeh et al. 2021). Moderate to heavy rainfall was identified as a total rainfall of >2.8 mm (Brittanica 2023).

The decrease in output power due to naturally occurring rain was separated and graphed according to seasonal data gather for total rainfall in the seasons, Summer Autumn, Winter, and Spring. This allows the efficiency to be compared depending on the season, as generally rainfall will significantly change depending on the season and time of year, and therefore cannot necessarily be relied on to provide consistent rainfall.

From the data, it can be identified that Autumn is the season which provides sufficient rainfall to keep the efficiency of the solar panel significantly lower than the other seasons, stabilising at around a 10.6% decrease in efficiency over the 12-week period a season experiences. Spring is the next season which experiences a substantial amount of rainfall with a peak decrease in efficiency of 12.99% over a 12-week period. Winter experiences a few days of rainfall over a 12-week period, with a peak efficiency decrease of 14.12% at the 12-week point in the season. Lastly, Summer is the season that has received the least amount of rainfall when compared to the remaining seasons. At the 12-week point in the season, it can be observed that the panel decrease in efficiency experienced is 14.33%, the highest output power decrease in efficiency experienced when comparing all of the seasons. It must be noted that the data graphed assumes the panels are clean at the beginning of each 12-week period modelled. In reality, seasons will be continual and span over the period of 52 weeks.

When comparing the data modelled for the Gladstone region, this provides an opposite suggestion to Kalogirou et al. research which suggested Winter is the season experiencing the greatest amount of rainfall. From the data winter ranked, third least efficient when compared to the three other Gladstone region seasons, experiencing a small amount of rainfall throughout the season. When comparing Spring and Autumn, both seasons follow similar trends, only experiencing different rainfall towards the end of the season, suggesting Kalogirou et al. research comments regarding Spring and Autmn experiencing similar rainfall to be moderately accurate for the Gladstone region. Finally, it was suggested that Summer is the season experiencing the least amount of rainfall, which is a true comment, when visually analysing Figure 35 & 36.

The polycrystalline panel exhibits almost identical characteristics and comparisons between different time intervals for natural rainfall. The main difference is that the polycrystalline panel experiences higher decrease in efficiency of power output due to being less efficient than the monocrystalline panel. This will result in higher values of power output loss, due to this difference between panels.

Maintenance Recommendations

Based off the presented data and analysis it would be reasonable to suggest that natural rainfall in the Gladstone region is enough to reduce some efficiency losses experienced by dust accumulation on a solar panel throughout various seasons. This would be a simple and cost-effective strategy to rely on, as no physical installations or manual labour is required to assist cleaning this panel, only natural rainfall. It would be recommended that visual checks are conducted regularly on the solar panel for situations specifically where trees and other environmental factors such as bird droppings etc soil the panel at a faster rate by dust accumulation. This would result in manual labour becoming an option periodically to give the solar panel a thorough clean, as rainfall is not as effective as a manual clean at getting all of the dust accumulation off the panel. A suggested interval period for maintenance would be annually upon initial installation, with more regular intervals implemented if it became evident that the efficiency of the solar panel was being significantly impacted by dust accumulation and environmental pollution.

Solar Panel Monitoring

As discussed in the design stage of the report, there are various options available for solar panel monitoring, both pre and post installation. It would be recommended to get a solar monitoring device installed that is the same brand as the panels being installed. This will ensure all compatibility and capability features of the device match the solar panel and are utilised to their full extent. Having these devices installed at the same time will save money rather than having to source labour to install these devices at a later date. Installing these devices with the panel will also allow immediate monitoring of these panels to commence, ensuring adequate data is captured over the complete lifespan of the panel, increasing the accuracy of the data obtained.

Storm Damage Protection

Overall, the installation of storm damage protection will positively contribute to extending the expected life expectancy of the residential solar installations, preventing any damage from occurring to the panels during storms. It would be recommended that the solar panels selected firstly meet the expected storm conditions for the Gladstone region, which would include rain and wind. Cyclones and hailstorms are less common in the Gladstone region; therefore, it would be better to identify what warranty is available with the panels in the event one of these uncommon natural disasters occurs. It would be suggested that sufficient anchor points are mounted to the panels to ensure wind and heavy rainfall does not cause any damage to the structure of the solar panel. It would also be important to have regular maintenance conducted on the panel to ensure the seals are sufficient and maintaining their waterproof qualities. This will prevent any early damage do the panel electrical components due to leaks from deteriorated seals.

It is also be recommended that adequate lightning protection systems are installed on residential solar panel installations. This will prevent lightning strikes causing significant electrical and physical damage to the solar panel installations. This is a simple solution that can be easily implemented and maintained, ensuring adequate protection is provided to the installed panels.

An annual maintenance period would be suggested following the installation of the panel and could be increased accordingly depending on the condition of the seals. The Gladstone region experiences high amounts of UV exposure, and therefore these maintenance periods will need to be determined depending on the housing location and quality of the panel and the seals. Introducing maintenance intervals for the inspection of seals is a relatively simple task, and therefore the cost of labour would be significantly outweighed when compared to the replacement costs of a whole residential installation if water leaks occur.

Solar Panel Recycling

Solar panel recycling is an industry that needs a lot of improvement, especially when taking into consideration the number of solar panels being installed daily across Australia. When recycling solar panels within the Gladstone region, it would be recommended that a professional company recycles these panels rather than attempting to separate all of the parts within the solar panel at home. This will ensure that any toxic chemicals contained within the panel are managed and disposed of appropriately, significantly reducing the potential exposure to health and safety risks. If there are no local recycling facilities available, the next option would be to have these panels transported to a recycling facility elsewhere within Australia. Although this may be a slight expense for the customer, this will ensure that solar panels are responsibly recycled rather than being sent to landfill where various environmental hazards will be introduced from the toxic chemicals contained within these panels.

8. Further Testing and Research Recommendations

There are various areas within this research topic that could be further explored and tested. For the purpose of this report, only the Gladstone region has been used for data and analysis purposes. Further research could be conducted in various locations around Australia as every town has different weather and environmental conditions that could significantly change the outcome of the data when compared to Gladstone region. This would be due to potentially heavier or less rain, different natural weather conditions (cyclones and hail), dust present in the area and various other factors.

It would be recommended that further study is conducted to understand what effect other pollutants such as bird droppings, tree debris, etc, has on the overall efficiency output of the solar panel. For this specific study only the pollutant dust was considered, however there are various other pollutants that can cause efficiency loss on a solar panel, depending on the location and environmental conditions.

This research and data analysis used data from Cyprus in Egypt, and therefore these dust accumulation figures may not be as accurate when comparing to the Gladstone region dust accumulation. To further refine and present more accurate findings, it would be suggested that similar physical testing to the research data utilised in this report is carried out in the Gladstone region. This will develop data that is accurate for the region, and potentially might be slightly different to what was presented in this report. Physically testing a solar panel installation could be beneficial as houses within Gladstone are subject to various different industrial processes, and therefore, a comparison between the various location within Gladstone may present different findings and trends for analysis.

Due to Gladstone being an industrial town, there are various types of dust product that could accumulate on a solar panel installation, not only residentially, but in commercial and industrial installation. This would be a good research topic to further analyse, identifying the impact different dust and airborne products have on the efficiency of a solar panel based off their particle size and composition. This could be tested using a physical solar panel installation at various industrial sites and locations within the town that may experience this dust pollution as a result of the heavy industry present in the town.

Using data gathered from various sources, the efficiency improvements once maintenance methods were implemented were based off these pre-determined data values. To further confirm the increase in efficiency once these maintenance devices and strategies are installed, the physical implementation and maintenance could be conducted on a physical set up in the Gladstone region over a designated period of time. This would give real time data, experienced throughout the time periods established. To align with the data presented in this report, the physical implementation could be run over the course of a year, to identify how to solar panel behaves throughout the four seasons experienced. This data could be compared to the data developed in this specific research paper, to identify any discrepancies in the data obtained. The seasonal data used within the report was based on location outside of Australia, so this would provide more accurate data to represent the Gladstone region.

If a physical solar panel installation was implemented, solar panel monitoring devices could be installed to prove the advantages and benefits of these devices for proving the efficiency and overall behaviours of the solar panel installation. Purposeful 'storm damage' could be physically simulated, to prove how the monitoring devices would identify these issues experienced. The monitoring device could be utilised to prove what maintenance intervals are sufficient for maintaining the overall efficiency of the solar panel.

9. Conclusion

Overall, based off the data and analysis performed in this report, there is a distinguished trend between dust accumulation and increased loss of efficiency over an extended time period. This data highlights the importance of implementing effective maintenance strategies to ensure this solar panel efficiency isn't compromised over the life of a solar panel installation in a residential setting. Although the data provided good insight into the trends incorporating dust accumulation and efficiency, it would be suggested that further research is conducted with physically implemented solar installations in the Gladstone region. This would provide a more accurate representation of the dust accumulation in the Gladstone region, over the seasonal periods and with the various industrial sites present within the town. This research paper has identified the influence maintenance strategies at different time intervals has on maintaining and improving the overall efficiency of a panel, proving to be an important aspect that should be considered by all homeowners when installing solar panels in a residential setting. The further suggestions regarding storm damage protection, monitoring and recycling options ensure the consumer have a thorough understanding of how to maintain the life and quality of the solar panel, as well as appropriately disposing these panels to ensure negative health and environmental impacts are mitigated through the solar panel disposal process.

Appendices

Appendix A

ENG4111/4112 Research Project

Project Specification

For: Ainsley Cooper

Title: Industrial based solar power grid system monitoring, service, storm damage protection and recycling

Major: Electrical and Electronic Engineering

Supervisors: Professor Paul Wen

Enrolment: ENG4111 – EXT S1, 2023

ENG4111 – EXT S1, 2023

Project Aim: To investigate a solar panel, inverter and batteries lifespan and how this can be improved by implementing effective maintenance practices and storm damage protection. The system performance will be analysed, specifically understanding the effect environmental factors contribute to performance efficiency and further, how recycling can be initiated for solar panels at their end of life.

Programme: Version 1, 7th March 2023

8. Review and research relevant technical information and background information regarding the solar panel its current installation/maintenance practices.
9. Understand/research potential environmental factors that may be encountered in an industrial setting. Solar panel efficiency and potential influences because of these conditions would need to be further analysed.
10. Design a solar panel prototype (small scale) and identify different areas on site where this can be placed, based off different environmental conditions.

11. Monitor/record data over an extended period in different industrial site conditions. Create a model to represent this system for easy simulation.
12. Review potential maintenance strategies which could be implemented and then replicate these in a real-life situation.
13. Research potential storm damage protection options and provide a solution which is practical in an industrial setting.
14. Understand and demonstrate options for recycling solar panels which have reached end of life.

If time and resources permit:

15. Implement storm damage protection designs/options and understand whether effective in maintaining the solar panels physical integrity and efficiency.

ENG4111/4112 Research Project

Project Plan

Task Name	Duration	Start	Finish
1. Scope/Prework Stage	0 days	Wed 8/03/23	Wed 8/03/23
1A. Research relevent technical information	7 days	Wed 15/03/2:	Thu 23/03/23
1B. Identify equipment required and purchase	2 days	Wed 15/03/2:	Thu 16/03/23
1C. Identify potential environmental conditions for testing phase.	3 days	Fri 24/03/23	Tue 28/03/23
1D. Identify suitable maintenance strategies.	3 days	Wed 29/03/2:	Fri 31/03/23
2. Design Stage	0 days	Fri 31/03/23	Fri 31/03/23
2A. Design a small scale solar panel system	7 days	Mon 3/04/23	Tue 11/04/23
2B. Design arduino monitoring	7 days	Wed 12/04/2:	Thu 20/04/23
3. Testing Stage	0 days	Thu 20/04/23	Thu 20/04/23
3A. Test solar installation in varying environmental conditions'	21 days	Fri 21/04/23	Fri 19/05/23
3B. Test proposed maintenance strategies	14 days	Mon 22/05/2:	Thu 8/06/23
4. Data Analysis Stage	0 days	Thu 8/06/23	Thu 8/06/23
4A. Compile output data from solar panels	7 days	Thu 8/06/23	Fri 16/06/23
4B. Compare data from different environmental conditions	7 days	Thu 8/06/23	Fri 16/06/23
4C. Compare data from different maintenance strategies	7 days	Thu 8/06/23	Fri 16/06/23
4D. Revisit testing stage if further data is required.	28 days	Mon 19/06/2:	Wed 26/07/2:
4E. Analyse efficiency of solar panel and visually display results from test stage	4 days	Thu 27/07/23	Tue 1/08/23
4F. Analyse condition of solar panel after testing stage.	3 days	Wed 2/08/23	Fri 4/08/23
5. Report Write-Up Stage	0 days	Fri 4/08/23	Fri 4/08/23
5A. Prepare draft dissertation	28 days	Mon 7/08/23	Wed 13/09/2:
5B. Suggest further testing/research which would support this study	3 days	Thu 14/09/23	Mon 18/09/2:

ENG4111/4112 Research Project

Project Resources

- Need to purchase solar panels and any associated equipment.
    - Will need to understand delivery times or pickup locations if locally available.
    - Need to identify how many solar panels I will require for this testing. Will consider cost. More solar panels will make testing more efficient and cut down on time to conduct this.
- Need to obtain an Arduino unit and associated equipment.
- Need to understand what alternative locations can be used if Boyne Smelters doesn't give me access to specific locations for testing.
    - Will need to get permission from somebody on site to conduct testing.
    - If alternative location is required, will consider local residential area for solar panel placement.
- Will need to utilise online resources for research and information.
- Will need access to a computer to write dissertation and use software.
- Will require Arduino software to simulate data being recorded.
- Will require software to simulate solar installation/system.
    - To be further discussed with supervisor on options available through USQ.
- Will require Microsoft excel, project, and word.
- Possible resources will be required to replicate storm damage protection (if time permits). Will review closer to the time.
- Resources will be required to conduct maintenance on the solar panels for testing purposes. This will be visited closer to the testing stage.
    - Should only require simple products which can be obtained locally.

ENG4111/4112 Research Project

Communication/Supplementary Material

1. Initial conversation with examiner to understand project and review the project specification to address any concerns or suggestions going forwards.

2. Ongoing fortnightly communication via email.

3. Occasional Zoom call if required. Will depend on circumstance.

This communication interval confirmation is still to be discussed with supervisor. Will update once conversation has been had. Awaiting email response currently (10/3/2023).

This Project Specification has not been reviewed by supervisor. Will be revised once email communication has occurred (10/3/2023).

Appendix B

NUMBER	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
2474	Home based solar power grid system monitoring, service, storm damage protection and recycling.		Low	Low

DOCUMENTS REFERENCED

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Ainsley Cooper	14/05/2023	22/05/2023	22/05/2024

THIS IS A RESTRICTED RISK ASSESSMENT

RISK FACTOR(S)	EXISTING CONTROL(S)	PROPOSED CONTROL(S)	OWNER	DUE DATE
Potentially faulty charging cable and outlet.	**Control:** Designed to have a cable sheath, also protected by an RCD.	**Control:** Conduct preoperational/usage checks of the equipment being used. This will ensure sheath is in good condition and appliance has no exposed or faulty parts visible.		
Sprains and strains from sitting at computer.	**Control:** Take breaks to ensure movement of the body.	**Control:** Set a timer and take regular breaks. **Control:** Set aside time to stretch and move the body, maintain good posture whilst working for extended periods of time.		
Slips, trips and falls	**Control:** Ensure clear pathway around workstation.	**Control:** Remove any potential trip hazards or equipment that does not belong in area. Keep eyes on path.		
Dehydration	**Control:** Take regular hydration breaks throughout the day. Keep a water bottle at workstation.	**Control:** Use aircon in office if cool area is required. **Control:** Set timer for reminders to take regular hydration breaks. Come up with a hydration plan.		

Figure 36 - Risk Assessment

Appendix C

Consequential Effects

Sustainability

The research being undertaken for this project will not pose any serious sustainability risks. Reports will be computer based, and no printing of any material will be required, therefore substantially reducing any sustainability challenges that could affect this project. All the modelling will be conducted using a computer software and no physical installations or testing in the field will be conducted for the duration of this project.

It is important to ensure that people utilising this information for the future installation or implementation understand their own sustainability and environmental impacts when conducting this work. Ensuring materials are adequately recycled and excessive waste is not generated of highest importance. Only licensed professionals should be performing these future works.

Risk Assessment

A risk assessment was conducted to ensure that adequate measures have been put in place to ensure that any work carried out has good controls out in place to ensure the safety of people and the environment is maintained throughout the duration of the research project. This can be identified in Appendix B.

Ethical Responsibility

As an Engineer it is important that Ethical responsibility is taken when conducting research, aligning with the Engineers Australia Code of Ethics. Whilst practicing an Engineer we must, demonstrate integrity, practice competently, exercise leadership and promote sustainability (Engineers Australia 2022).

All information provided in this report will be factual and all research will acknowledge the appropriate authors or publishers. Only information based off adequate knowledge and research will be utilised in this research paper to ensure the validity of the information provided. As a part of this research paper, sustainable practices will be further explored, to ensure the health, safety and wellbeing of the surrounding environment and community is maintained (Engineers Australia 2022).

The information used throughout this paper is public knowledge and therefore no privacy or ethical issues should be encountered because of this paper being published (Engineers Australia 2022).

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