Solar Tracking System Project Research

September 2021

1 Terminology

- Photovoltaic (PV) - Photo-voltaic panels that generate electricity from the sun
- Tolerance Angle - Angle between the optimal angle of the panel and the angle of the panel relative to the ground.
- Azimuth - Angle between north vector and astronomical object's vector on the horizontal plane.
- Zenith - Line perpendicular (vertical) to the earth's surface.
- Zenith Angle - Angle between the sun and the zenith.
- Angle of Incidence (AOI) - The angle which an incident line or ray makes with a perpendicular to the surface at the point of incidence.
- Apparent Solar Time (AST) - Time as calculated by the motion of the apparent sun.
- Altitude Angle - Angular height of the sun in the sky measured from the horizontal
- Tilt Angle - Angle between the zenith and the surface normal.
- Meridian - A circle of constant longitude passing through a location on the earth's surface and the terrestrial poles.
- Declination Angle - The angle between the equator and a line drawn from the centre of the Earth to the centre of the sun. Also known as seasonal tilt.
- Equinox - Time when the sun crosses the plane of the earth's equator, making night and day of approximately equal length occurring about March 21 (spring equinox) and September 22 (autumnal equinox).

- Solstice - Times when the sun is at its greatest distance from the celestial equator occuring on June 21 (summer solstice) or December 22 (winter solstice).
- Light Dependent Resistor (LDR) - A passive component that decreases resistance with respect to receiving light on the component's sensitive surface.
- Hydrophobic Spray - Spray that causes the target surface to be water repellent
- Carbon Footprint - Total amount of greenhouse gases generated by an action
- Solar Irradiance - Output of light energy from the sun measured on earth
- Direct Normal Irradiance (DNI) - Amount of solar radiation received per unit area measured on a surface normal to the direction of the rays from the sun.
- Diffuse Horizontal Irradiance (DHI) - Amount of diffuse solar radiation received per unit area measured on a horizontal surface.
- Cumulative Energy Demand (CED) - Total sum of energy used to manufacture, deliver, and install a product
- Energy Payback Time (EPBT) - Time required for a renewable source to generate its CED
- Life Cycle Assessment (LCA) - An analysis of the environmental impact of a product throughout every stage of manufacturing (result is typically the CED)
- Balance of System (BOS) - Refers to all the external equipment and components of the PV besides the solar panel itself
- Subduction Zone - area where multiple tectonic places collide and one under-thrusts or "subducts" beneath the other creating friction and tension which is eventually released in the form of seismic events.
- Solar Flares - huge eruptions of energy from the sun's surface and are considered to be the biggest explosions in our solar system. These massive energy releases can cause damage to GPS, Power Grids, Communications Systems, Solar Power Systems, Radios, and other electronic devices.
- Electromagnetic Pulse (EMP) - a short burst of electromagnetic energy. Such a pulse's origin may be a natural occurrence or human-made and can occur as a radiated, electric, or magnetic field or a conducted electric current. EMP interference is generally disruptive or damaging to electronic equipment.

- Faraday Cage - is an enclosure that is used to shield things from electromagnetic fields.
- Greenhouse Gases (GHG) - Gases such as carbon dioxide, methane, nitrous oxide that are known to cause the greenhouse effect of heating the earth and caused by the burning of fossil fuels, forest fires, factories, etc.

2 Financial Incentives

Purchasing and installing solar panel systems can be expensive. However, there are systems in place to lower that cost. There is a wide variety of incentives that help mitigate the cost of acquiring and installing solar panels in the form of federal and provincial financial grants, as well as tax breaks. British Columbia offers their own set of incentives for residents and businesses that can be used to lower the cost of installing solar panel systems. With the plethora of liquid incentives and quality information to ease the transition to green energy, beginning to use solar energy has never been easier in BC.

2.1 Federal Incentives

The federal government is offering residents up to 5,600 dollars "to help make more energy efficient retrofits to their homes" through the Greener Homes Grant [1]. This includes the implementation of solar PV energy systems that will help reduce greenhouse gas emissions. One may apply for this grant directly through the Government of Canada's website under the Natural Resource Sector.

Under the Smart Renewables and Electrification Pathways Program (SREPs) of the Government of Canada, organizations may apply for up to 50 million dollars in funding over four years for clean energy projects or grid modernization in the construction phase[2]. This grant is subject to heavy government monitoring and reporting.

2.2 Provincial & Municipal Incentives

Other incentives vary depending on province and municipality. Here in BC, there is a PST tax exemption for purchasing any equipment in a solar PV or solar thermal system[3]. Also in BC, there is a "net metering" program in which clean energy systems of no more than 100 kW tied to the grid will give a credit on your energy bill for producing an excess of energy required for your home or business[4]. This means that by producing your own electricity through solar panels, you will reduce your energy bill by the amount you produce. If you produce more than what is required for your needs, you will receive an energy credit which you may redeem for market value of the amount in excess[4].

3 Solar Angles

The power generated by solar PV panels is dependent on the intensity of incoming radiation from the sun. The intensity of the incoming radiation is largely dependent on the angle of incidence θ which is defined as the angle between the surface normal of the PV panel and the sun's rays[5]. The position of the sun in the sky is typically expressed in the azimuthal coordinate system using the altitude (elevation) angle α and the azimuth angle z as shown in Figure 1.

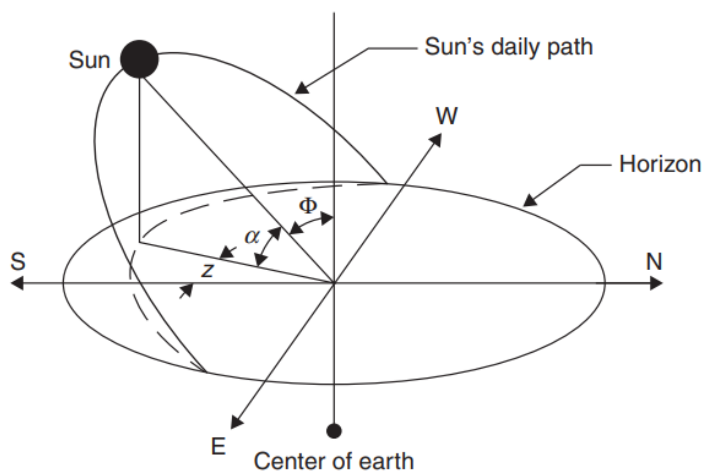

Figure 1: Position of Sun using Solar Angles [5]

3.1 Apparent Solar Time

Determination of the angles at each point of the day requires the use of the apparent solar time (AST) which is based on the apparent angular motion of the sun across the sky [5]. At solar noon (12:00 PM AST) the sun is located on the meridian of the observer, which typically does not align with the local noon of the location[5]. To convert the local time (LST) to AST, the day of the year number and longitude are used in conjunction with the equation of time. The expression for converting LST to AST is shown in (1)[5].

$$AST = LST + ET \pm 4(SL - LL) - DS \quad (1)$$

The terms in the AST conversion correspond to the standard longitude (SL), the local longitude (LL), the daylight savings time adjustment (DS) (which is either 60 minutes or zero), and the equation of time (ET). The equation of time term is expressed in minutes and calculated using (2)[5].

$$ET = 9.87sin(2B) - 7.53cos(B) - 1.5sin(B) \quad (2)$$

Where B is obtained using the day of the year number N and is expressed in degrees using (3)[5].

$$B = (N - 81)\frac{360}{364} \quad (3)$$

3.2 Solar Position

To determine the sun's position in the sky at any point during the year, the location latitude L, declination angle δ, and hour angle h must be known. The declination angle refers to the seasonal change in the altitude angle of the sun's path as the earth orbits around the sun and has a range of $\pm$ 23.45°[5]. In the northern hemisphere, the declination angle is negative during the winter months, positive during the summer months, and zero during the equinoxes[5]. The declination angle is calculated using the day number of the year N shown in (4).

$$\delta = 23.45sin[360/364(284 + N)] \quad (4)$$

The hour angle at a location refers to the relative rotation of the earth that would bring the sun directly onto the observer's meridian or offset from solar noon expressed in AST. Determination of the hour angle is simply ±15°per hour or 0.25°per minute, with positive hour angles denoting hours after solar noon[5].

Using the equations for declination angle, hour angle, and the local latitude of the location, the solar altitude angle α and azimuth angle z can be calculated using the following equations shown in (5) and (6)[5].

$$\alpha = sin^{-1}(sin(L)sin(\delta) + cos(L)cos(\delta)cos(h)) \quad (5)$$

$$z = sin^{-1}(\frac{cos(\delta)sin(h)}{cos(\alpha)}) \quad (6)$$

The incident angle θ is the angle between the surface normal of the PV panel and the sun's rays[5]. This angle is of importance in solar system design as it is typically used to determine the optimum orientation which produces maximum power generation. Determination of the incident angle requires the previously calculated solar angles as well as the surface tilt angle β and surface azimuth angle Z_s. The tilt angle is defined as the surface tilt from the horizontal and the surface azimuth is defined as the angle between the surface normal projection and the true south cardinal direction as shown in Figure 2[5].

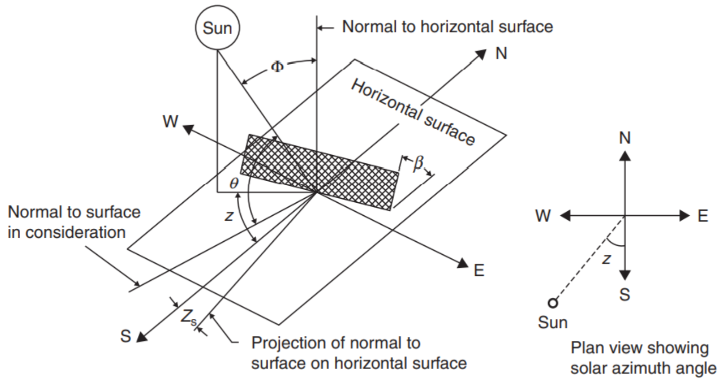

Figure 2: Incident Angle Determination and Associated Angles [5]

The incident angle for a south-facing tilted surface in the northern hemisphere can be calculated using (7) below[5].

$$\theta = cos^{-1}[sin(L - \beta)sin(\delta) + cos(L - \beta)cos(\delta)cos(h)] \tag{7}$$

4 Solar Panel Types

Solar panels are available in a wide variety of different types which have different strengths and weaknesses. While there are a ton of different types of solar panels, the three most common types of solar panels are: monocrystalline, polycrystalline, and thin-film. The monocrystalline panels consist of a crystal silicon lattice that is entirely continuous with no "grain boundaries" [6]. This lattice can then be cut into wafers for use. This style of solar panel has the advantage of being the longest lasting and most space efficient. However, the biggest disadvantage is that it requires a lot of silicon to produce, much of which ends up not being used, resulting in this type of solar panel being more expensive than alternatives. A variation of monocrystalline panels, known as passivated emitter and rear cell (PERC), adds a reflective layer underneath the silicon cell, which reflects the light back through the cell, increasing the amount of energy that gets absorbed [6]. This does increase the cost of the panels slightly, however the increase in efficiency is more than offsets this.

The polycrystalline uses multiple silicon lattices which are melted and placed into a mold [6]. This results in a lower silicon purity which corresponds to less efficiency overall, as well as a greater sensitivity to higher temperatures, which can further lower the efficiency. The biggest advantage to this type of panel is the lower overall cost when compared with the monocrystalline alternative [7].

The thin-film can be made from multiple different types of materials, such as amorphous silicon, cadmium telluride, and copper indium gallium selenide [6]. These different materials can provide particular benefits, like a low carbon-footprint or low water production usage, however the most common advantage shared by all of them is their low cost, as they are on average the cheapest type of solar panel. However, this comes at the expense of efficiency as they are the least efficient solar panels [7].

When comparing monocrystalline panels with polycrystalline, the mono panels displayed a variation in efficiency of 12-16%, while the polycrystalline panels varied by roughly 20% based on solar radiation [8]. The monocrystalline panels are still the most efficient overall at roughly 20-25%, compared with the polycrystalline at 15-17%. The thin-film panels are the least efficient, ranging from 6-15%. In terms of production cost, not factoring in installation, the monocrystalline panels are the most expensive ranging from $1-1.5$ per watt, with the PERC dropping that down significantly to $0.32-0.65$ per watt. The polycrystalline averages $0.70-1$ per watt, while the thin-film averages $0.43-0.70$ [7].

5 Solar Panel Configurations

5.1 Fixed Panel Systems

Fixed PV panels are the most common configuration used in residential and commercial applications since the system is fairly simple and minimal maintenance is required. Due to the relative mechanical simplicity of these systems, they usually offer a longer lifespan than a dynamic system [9]. However, these static panels will generate significantly less power than a dynamic system over a given period of time [10]. To increase power generation, fixed panels are typically oriented facing due south in the northern hemisphere ($Z_s = 0$) with an optimized tilt angle based on the latitude of the location. The optimal tilt angle used for fixed panels is typically equal to the locations latitude to maximize the annual performance ($\beta_{opt} = L$). To maximize the fall and winter performance a tilt angle of $L + 15^{\circ}$ can be used, and conversely a tilt angle of $L - 15^{\circ}$ will maximize the spring and summer performance (Figure 3).

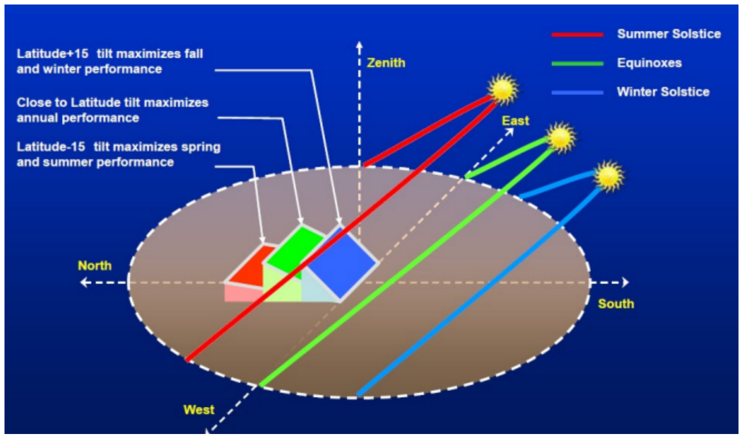

Figure 3: Fixed Panel Surface Tilt Angle Optimization[5]

Since the sun changes its azimuth and altitude angles during the day, a fixed panel does not effectively utilize the full radiation that is available during the morning and evening when the altitude angle is shallow.

5.2 Dynamic Tracking Systems

To optimize the power of the generation of PV panels throughout the day, the development of dynamic sun-tracking panels are considered which orient the panel in a way such that the incident angle is minimized. This maximizes incoming radiation to be incident on the panel and provides a reduction in scattered and reflected radiation from the panel surface. A study comparing the efficiency of dual axis tracking, single axis tracking, and fixed panels showed that the dual axis and single axis systems had a power gains of 43.87% and 37.53% respectively when compared to a fixed panel at the optimal tilt angle [11].

Tracking systems are classified by their relative motion which is either about a single axis or two axes[5]. Single axis systems are typically classified as E-W Polar (Figure 4(b)), N-S horizontal (Figure 4(c)), or E-W horizontal (Figure 4(d))[5]. Dual axis tracking, also known as full tracking, has the ability to continuously orient the surface such that the angle of incidence is always approximately zero (Figure 4(a))[5].

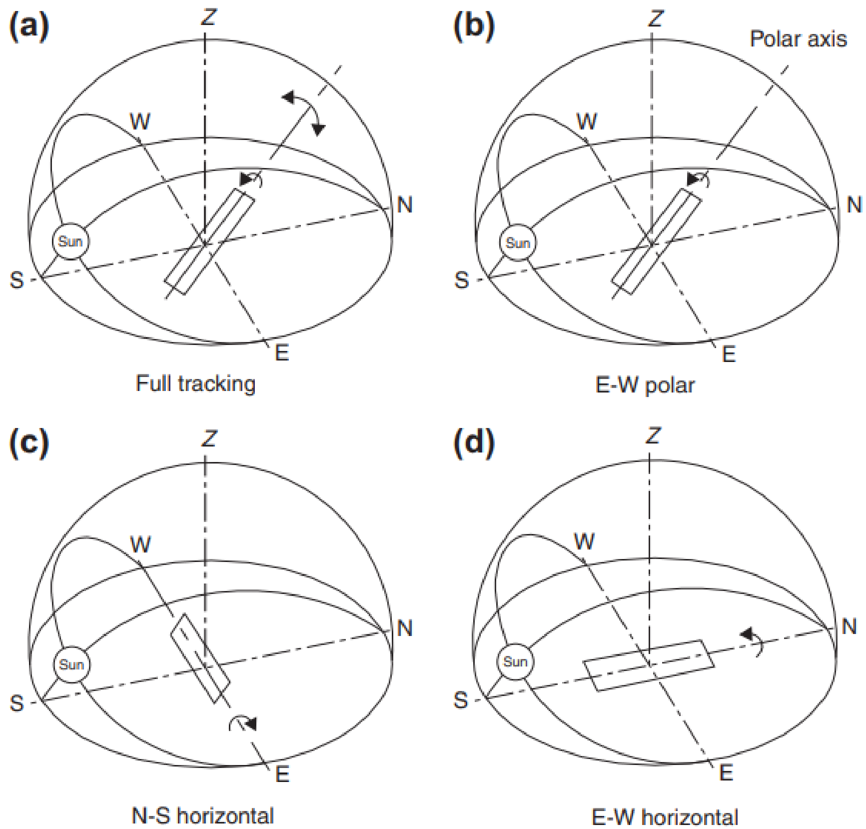

Figure 4: Tracking System Axis Configurations[5]

Each of the tracking methods shown in the above figure aims to maximize the amount of incident radiation reaching the PV panel surface by minimizing the angle of incidence. A comparison between the performance for each of the configuration types at the solstices and equinoxes is shown below in Figure 5 [5]. The performance analysis is completed using a radiation model with standard conditions at a latitude of 35°[5].

Tracking Mode	Solar Energy Received (kWh/m^2)			Percentage to Full Tracking		
	E	SS	WS	E	SS	WS
Full tracking	8.43	10.60	5.70	100	100	100
E–W polar	8.43	9.73	5.23	100	91.7	91.7
N–S horizontal	7.51	10.36	4.47	89.1	97.7	60.9
E–W horizontal	6.22	7.85	4.91	73.8	74.0	86.2

E = equinoxes, SS = summer solstice, WS = winter solstice.

Figure 5: Tracking System Configuration Comparison[5]

As shown in Figure 5, the full tracking configuration collects the maximum amount of solar energy and is the basis by which the single axis systems are compared. For the single axis tracking configurations, the E-W Polar (Figure 4(b)) and the N-S horizontal (Figure 4(c)) are the best performing configurations which show performance values close to those obtained with a full tracking system [5].

6 Dynamic Tracking Methods

Solar tracking systems can be classified based on the number of axis which are utilized for positioning as well as what method of control strategy is employed, either open-loop or closed-loop[12]. Open-loop control systems do not require feedback (sensor-less) whereas closed-loop systems rely on feedback from sensors. The two most commonly methods for dynamic tracking which utilize these control systems are as follows:

- **Open-Loop** - Tracking is based the location, date, and time of the panel. This method also typically incorporates typical meteorological year (TYM) data for the specified location. A computer calculates the solar position and corresponding incident angle based on these parameters and uses the motor to move the panel to the optimal position[13].
- **Closed-Loop** - Tracking is based the use of at least two optical sensors with different angle orientations, utilizing a microprocessor to determine the position of the sun in the sky. When a difference between the light intensity received by the sensors is present, a motor is activated using the microprocessor which rotates the sensors until they are electrically balanced[13].

Both types of dynamic tracking methods have been found to exhibit significant gains in the power generated when compared to a fixed panel system [12]. Both systems provide similar power generation efficiencies, with open-loop systems having a small increase in efficiency, but subject to certain limitations[12]. For closed-loop systems, weather and air quality conditions can affect the optical sensor's ability to determine the position of the sun due to light scattering and absorption[12]. In some cases, the diffuse radiation can actually cause the panels to point away from the direction of the sun[12]. Open-loop systems do not have this issue since the tracking schedule and movements are already predetermined by the computer but require accurate positioning, alignment, and calibration during installation[12]. For mobile applications where the panel frame may change orientation, the only effective method for tracking the sun is a closed-loop system.

Another less common method is what's known as passive sun tracking. This method does not use any mechanical motors, gears, or controls, so it is less likely to fail [14]. Using the sun's heat to evaporate a liquid with a low boiling point, this causes an imbalance in the panel system when exposed to solar radiation. The panel will tilt in the direction of the sun's rays on a single axis to re-balance the system [15]. This tracking system will be less effective at generating power than the previously mentioned open and closed loop systems, but will be less expensive to install and will require less maintenance over its life time[14].

6.1 Optical Sensors

The performance of the optical sensors used in the closed-loop tracking systems used can vary depending on which type of sensor is used. Numerous solar tracking applications have utilized light dependent resistors (LDR) which detect the visible light spectrum but exhibit disadvantages compared to optical sensors which rely on ultraviolet (UV) or infrared (IR) spectra [12]. During periods of high light intensity, LDRs can become saturated leading to low precision in tracking movements Figure 6[12]. During low visibility conditions such as cloudy, dusty, or rainy days, LDRs have difficulty determining the location of the sun due to strong visible light scattering[12].

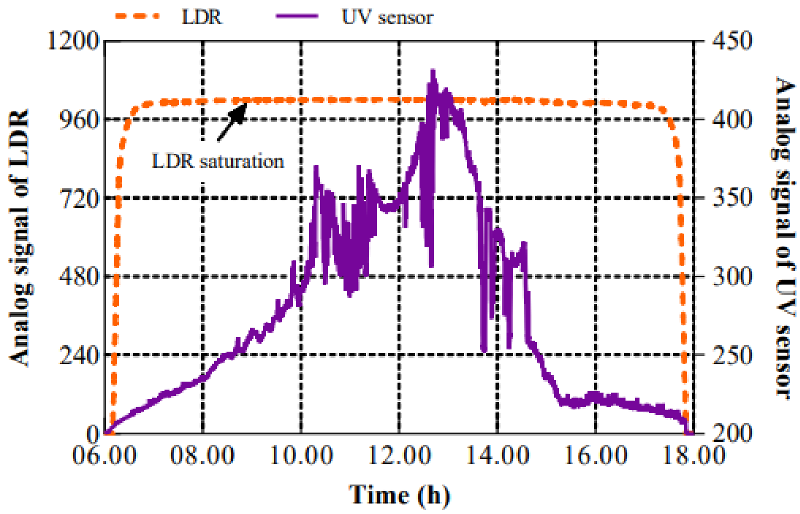

Figure 6: LDR and UV Analog Signals During Sunny Day[12]

A variety of different optical sensor systems and configurations have been studied with an aim at increasing tracking accuracy including using baffles, geometrical orientations, apertures, polarizing lenses, photodiode arrays, and four quadrant photocells (Figure 7). These configurations are found to increase the solar tracking accuracy compared to a fixed panel system but there have been no studies on the relative advantages or disadvantages between them.

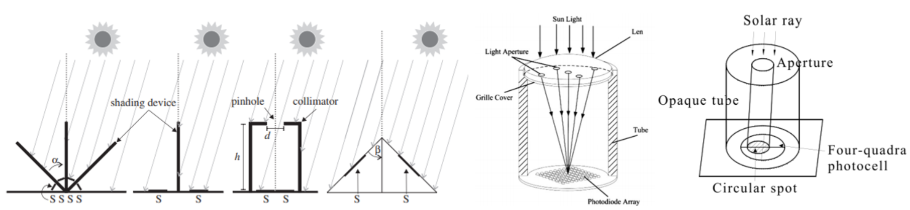

Figure 7: Optical Sensor Systems and Configurations [16][17][18]

Cloudy conditions reduce the total amount of radiation received on the earth's surface but some cloud formations can actually enhance UV radiation, making UV Sensors less susceptible to tracking errors[12]. On clear sunny days, the highest intensity of radiation received is in the visible spectrum whereas the intensity of the radiation in the UV spectrum is significantly lower (Figure 8) [12]. This allows for UV sensors to obtain better sensitivity and resolution during high intensities of incident radiation as shown in Figure 6 [12].

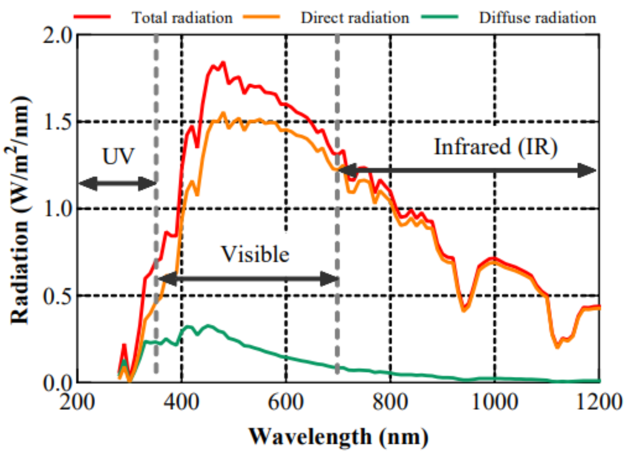

Figure 8: Incident Radiation Wavelengths[12]

A study completed over the course of 60 days was used to analyze the differences in power generation between a fixed panel and dual axis tracking systems which incorporated either LDR or UV sensors. The study found that the dual axis tracking systems generated significantly more power than a fixed panel system in all weather conditions[12]. Comparing the two tracking systems, the system using the UV sensors consistently outperformed the system which utilized LDRs as shown in Figure 9 [12].

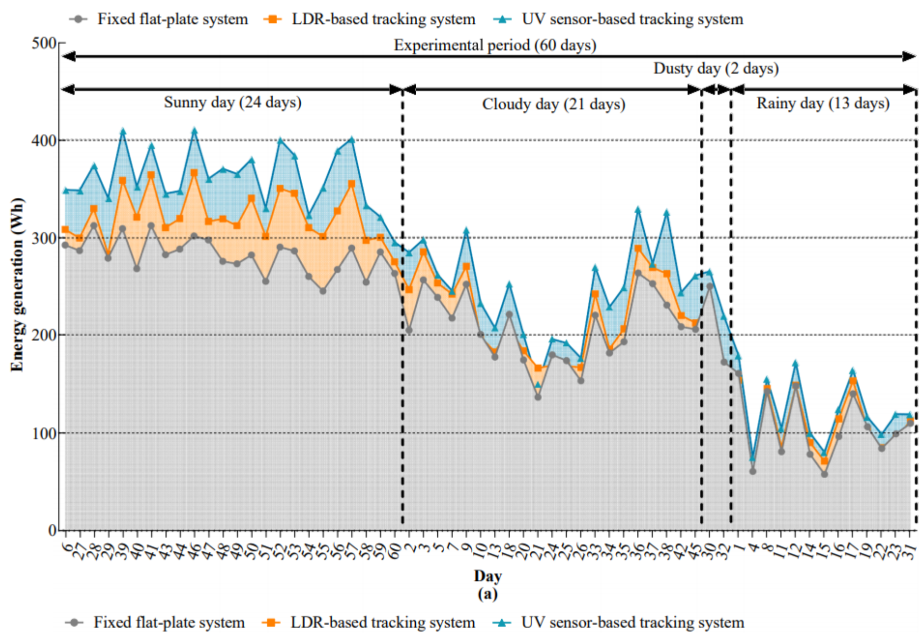

Figure 9: Comparison of Fixed vs Tracking System Energy Generation[12]

6.2 Net Energy Generation

One of the limitations of tracking systems is that they consume power in order to continuously change the orientation the panel to the optimal position. In adverse weather conditions such as cloudy days where the majority of incoming radiation is diffuse, continuous tracking can cause negative net energy generation since the motors consume a similar amount of power regardless of weather conditions (Figure 10)[12].

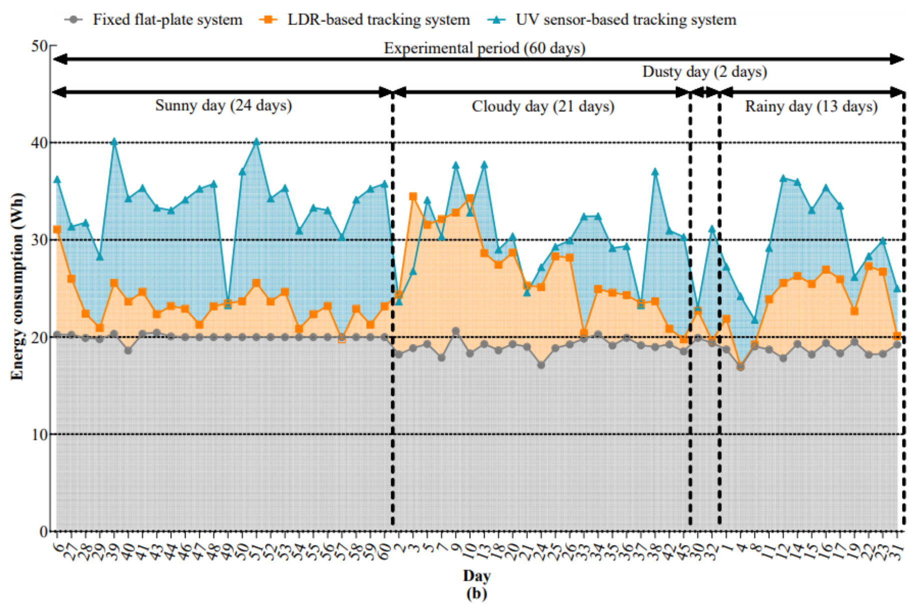

Figure 10: Comparison of Energy Consumption[12]

The study detailed in Section 6.1 showed that the large amount of diffuse radiation present during cloudy, rainy, and dusty days led to low net energy gains for the tracking systems. The UV tracking system net energy gains remained positive but were significantly lower compared to a sunny day due to the energy consumption from tracking. The LDR tracking system in all cases of adverse weather conditions was found to have net negative energy gains. A summary of the results of this study are shown in Figure 11[12].

Day	Tracking system	Generation (Wh)	ΔE (%)	Net Energy (Wh)	ΔE_{net} (%)
Sunny day	Fixed flat-plate system	230.65	-	211.66	-
	LDR-based tracking system	262.74	13.92	239.05	12.94
	UV sensor-based tracking system	326.32	41.48	289.28	36.67
Cloudy day	Fixed flat-plate system	177.57	-	158.27	-
	LDR-based tracking system	182.73	2.91	154.08	−2.65
	UV sensor-based tracking system	207.13	16.65	169.34	7.00
Dusty day	Fixed flat-plate system	172.36	-	152.97	-
	LDR-based tracking system	167.65	−2.73	148.01	−3.24
	UV sensor-based tracking system	219.00	27.66	187.84	22.80
Rainy day	Fixed flat-plate system	60.43	-	43.52	-
	LDR-based tracking system	54.21	−10.29	37.19	−14.55
	UV sensor-based tracking system	74.93	24.01	50.72	16.55

Figure 11: Comparison of Net Energy Generation[12]

7 Panel Tolerance

The efficiency of PVs is significantly affected by the tilt angle of the panels as PVs are most efficient when they are tilted orthogonal to the incoming solar radiation [19]. However, due to various limitations, it is important to examine the tolerance of PV panels to determine the amount of irradiance that is loss when we deviate from the optimal tilt angle [20]. The tolerance angle is the angle between the optimal tilt angle and the current tilt angle of the panel as can be seen in Figure 12. A n% tolerance angle refers to the tolerance angle that results in n% irradiance loss [20].

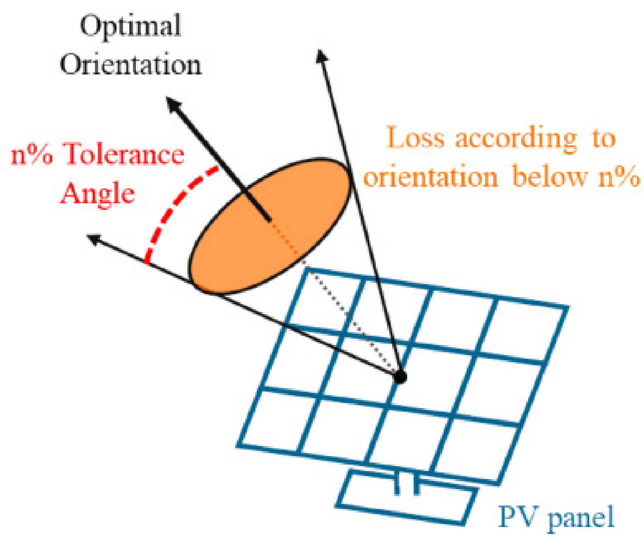

Figure 12: Figure Demonstrating Tolerance Angle of a PV Panel [20]

We can observe in Figure 13 and 14, that if we decided on a maximum irradiance loss of 10%, we could deviate from the optimal tilt angle by a maximum of 33°. This data is especially important when designing tracking systems and determining the intervals of tracking that would maximize efficiency and minimize irradiance loss [20].

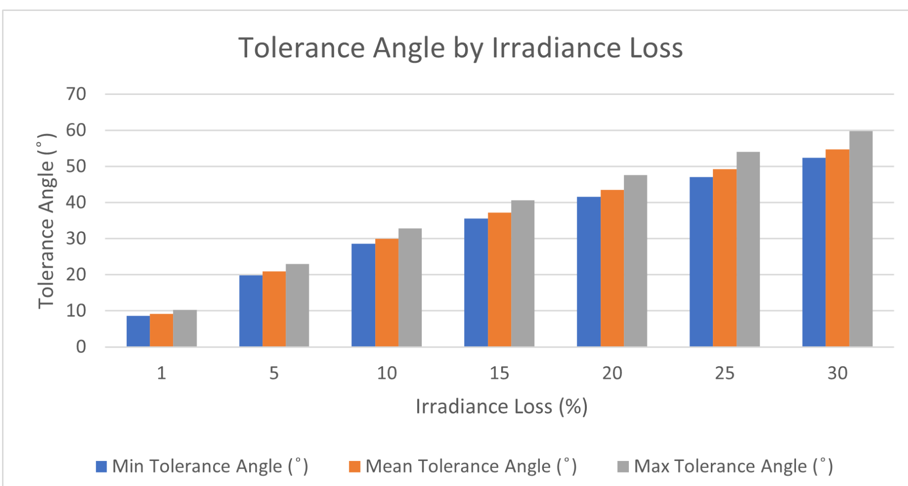

Figure 13: Tolerance Angle by Irradiance Loss [20]

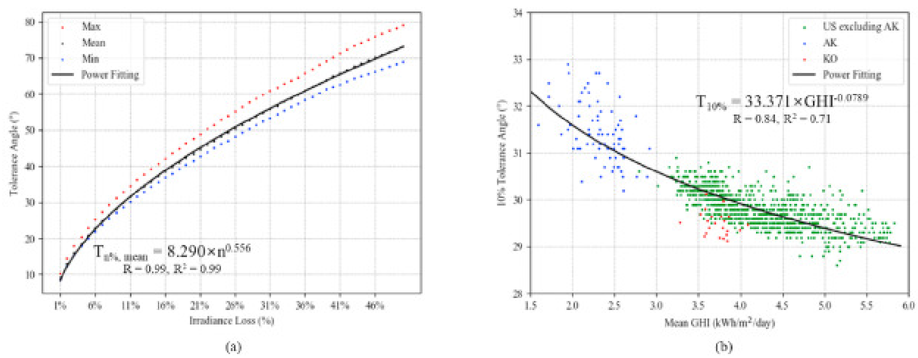

Figure 14: 10% Tolerance Angle by Irradiance Loss and Mean GHI [20]

Furthermore, as the latitude increases, the tolerance angle increases which allows for a greater deviation from the optimal tilt angle while maintaining the same amount of irradiance loss [20]. We can view this in Figure 15. We can also see that Hartley Bay has a 10% tolerance angle around 31°[20].

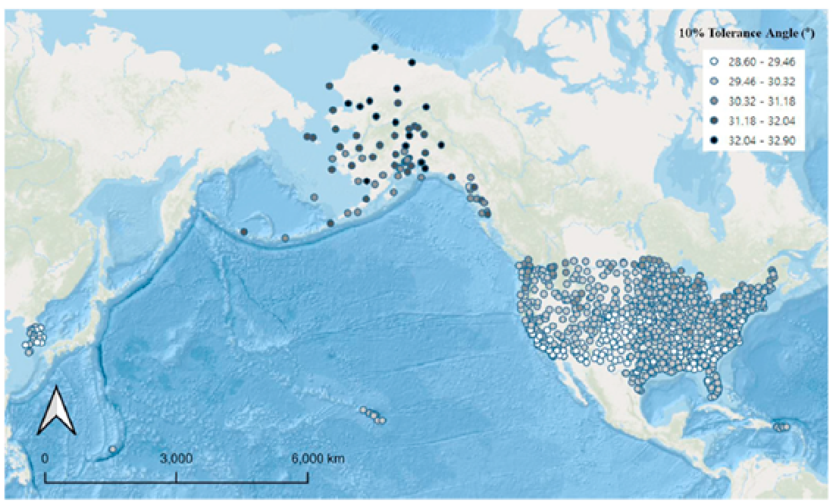

Figure 15: 10% Tolerance Angle by Location [20]

8 Environmental Factors

As we transition towards sustainable power sources such as photovoltaics (PV), the effects of climate, weather, and other environmental factors need to be examined and considered to ensure that maximum efficiency of the PVs can be obtained [21], [22]. Meteorological effects such as dust, humidity, temperature, rain, and snow can have significant effects on the efficiency of PV panels [21], [22].

8.1 Dust

Dust is characterized as minute solid particles with a diameter of less than 500μm that is lifted into the air by wind, animals, pollution, and natural events [21].

This dust can then deposit and accumulate on the surface of PVs which blocks solar radiation [21]. The location of the PV panels, tilt of the panels, dust density, wind speed, and rainfall determines the effect of the dust on the efficiency of the PVs [21]. The higher the density of the dust, the lower the efficiency of the PV module as more solar radiation is blocked by the dust particles [23]. A study by Sayyah, Horenstein, and Mazumder found that the "radiation intensity is reduced by both absorption and scattering by the accumulated particles. Particles with high absorption coefficients, such as soot and iron oxides (0.2–2.0 m in diameter), absorb incoming radiation, and fine particles with their size comparable to the wavelength of light will scatter light more efficiently than others. Finer particles also have large specific surface area. Thus fine particles deposited on the collector cause more energy loss compared with the same mass concentration of large particle deposition," [24]. The relationship between dust density and PV efficiency can be seen in Figure 16 [24].

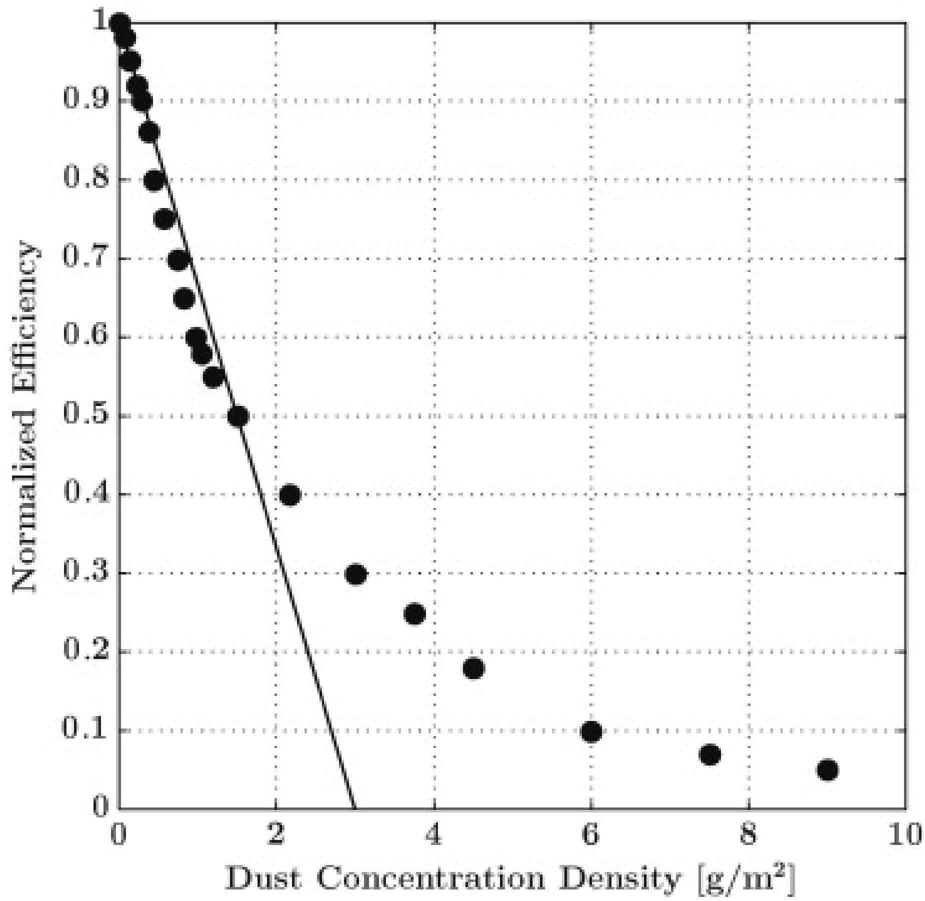

Figure 16: Efficiency of PV Module Depending on Dust Density [24]

Tests conducted in Dahran, Saudi Arabia where the dust density was 6.184 gm^{-2} and PV panels were tilted at 26°determined that a single dust storm and 6 month period of desert exposure can reduce the power output of a PV module by 20% and 50% respectfully [23]. We can conclude from this data that in an environment where dust accumulation occurs, PV panels need to be cleaned regularly to ensure that the efficiency of the PVs does not decrease [25].

8.2 Humidity

Humidity is an important factor that impacts the efficiency of PVs [21]. Mekhilef, Saidur, and Kamalisarvestani found in their study that "almost always humidity causes degradation in solar cell efficiency," [21]. As can be seen in Figure 17, the power, voltage, current, and efficiency drop as the humidity increases. The relative humidity affects the performance of the PV module as the "air water vapour contents affect the solar irradiance level and reduce the solar intensity by scattering the radiation," [26].

Humidity %	Current (A)	Voltage (V)	Power (W)	Efficiency %
67.28	4.50	23.23	104.54	13.76
75.42	4.14	22.30	92.322	13.62
80.33	3.82	19.90	76.02	11.40
85.56	3.65	19.20	70.08	11.24
88.47	3.60	18.60	66.96	12.65
92.11	3.30	18.00	59.40	12.49
95.59	2.50	17.40	43.50	9.80
Correlation Factor R	-0.93639	-0.98245	-0.98395	-0.71935
Determination coefficient R^2	0.876828	0.965215	0.96816	0.517464

Figure 17: Properties of PV Module Depending on Humidity [26]

Furthermore, as can be seen in Figure 18 and 19, a study by Kazem found that the power and efficiency decrease rapidly as the humidity increases [26]. This data is especially important when installing PV modules in climates such as the one in Hartley Bay where the humidity hovers above 90% regularly.

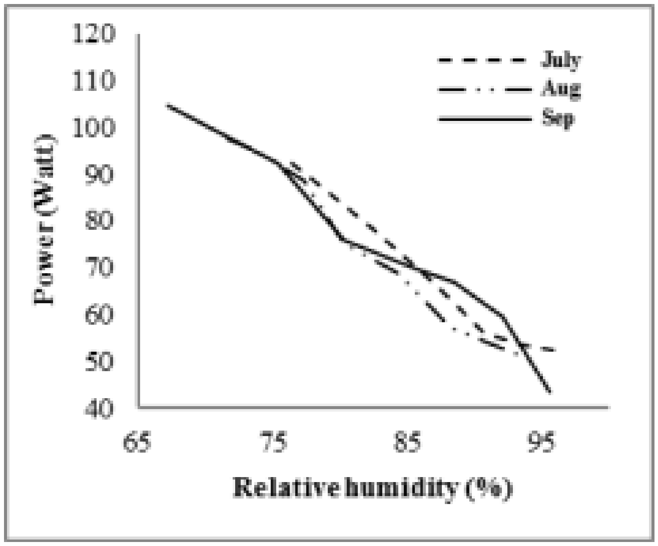

Figure 18: Power Output of PV Module Depending on Humidity [26]

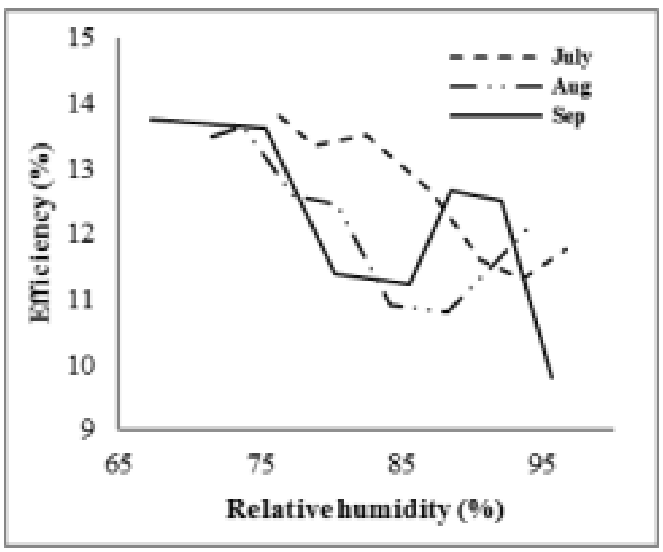

Figure 19: Efficiency of PV Module Depending on Humidity [26]

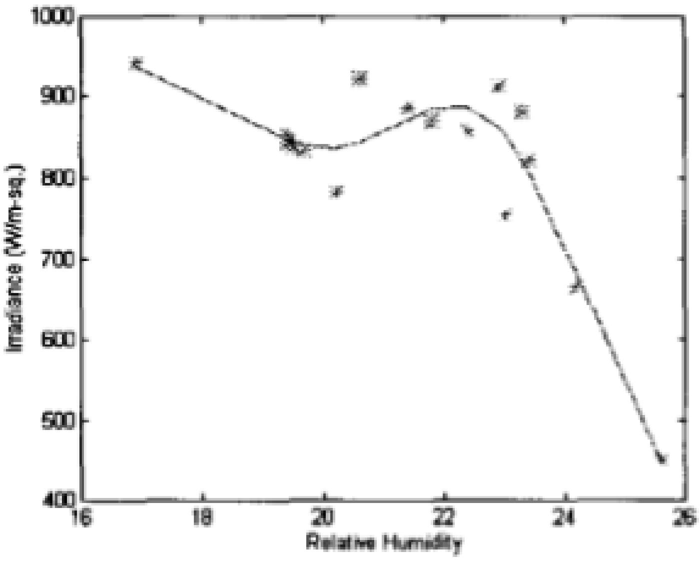

Figure 20: Irradiance of PV Module Depending on Low Relative Humidity [27]

8.3 Temperature

The temperature of PV cells plays an important role in the efficiency of PVs as the efficiency of PVs decreases as the temperature increases [28]. As stated by Fesharaki and Dehghani, "the present work clearly indicates a decrease in the efficiency of the PV module with increase in temperature," [29].

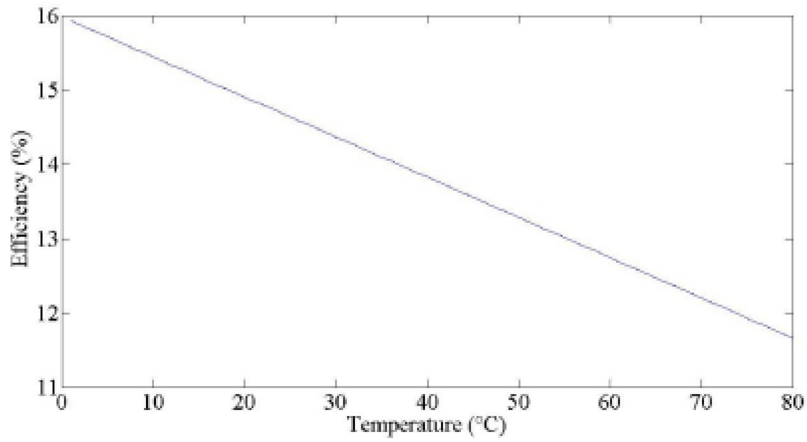

Figure 21: Efficiency of PV Depending on Temperature [29]

A regular PV module will only convert 6-20% of solar radiation into electricity while the rest is converted into heat which raises the cell temperature and therefore lowers the efficiency of the PV [28].

We can mathematically model the efficiency of PV modules using the Evans and Florschuetz linear relationship for the PV electrical efficiency. This linear relationship is characterized by [30]:

$$\eta_T = \eta_{Tref}[1 - \beta_{ref}(T_c - T_{ref})] \tag{8}$$

The η_T refers to the solar cell power conversion efficiency,the β_{ref} is the solar radiation coefficient, and the the η_{Tref} is the module's electrical efficiency at the reference temperature T_{ref}, and at solar radiation of 1000 W/m^2 [29] The β_{ref} and η_{Tref} are usually given by the manufacturer [29], while the η_T can be calculated using [28]:

$$\eta_T = \frac{P_{max}}{P_{in}} \tag{9}$$

The T_{ref}, η_{Tref}, and β_{ref} of various PV modules by material can be observed in Figure 22.

T_{ref} (°C)	η_{Tref}	β_{ref}	Comments
25	0.15	0.0041	Mono-Si
28	0.117	0.0038	Average of Sandia and commercial cells
25	0.11	0.003	Mono-Si
25	0.13	0.0041	PVT system
		0.005	PVT system
20	0.10	0.004	PVT system
25	0.10	0.0041	PVT system
20	0.125	0.004	PVT system
25		0.0026	a-Si
25	0.13	0.004	Mono-Si
	0.11	0.004	Poly-Si
	0.05	0.0011	a-Si
25	0.178	0.00375	PVT system
25	0.12	0.0045	Mono-Si
25	0.097	0.0045	PVT system
25	0.09	0.0045	PVT system
25	0.12	0.0045	PVT system
25	0.12	0.0045	PVT system
25	0.127	0.0063	PVT system
25	0.127 unglazed	0.006	PVT system
25	0.117 glazed	0.0054	PVT system

Figure 22: Properties of PV Panels by Material [29]

Furthermore, we can view in Figure 23 that the efficiency ratio of PVs decreases as the temperature increases [30].

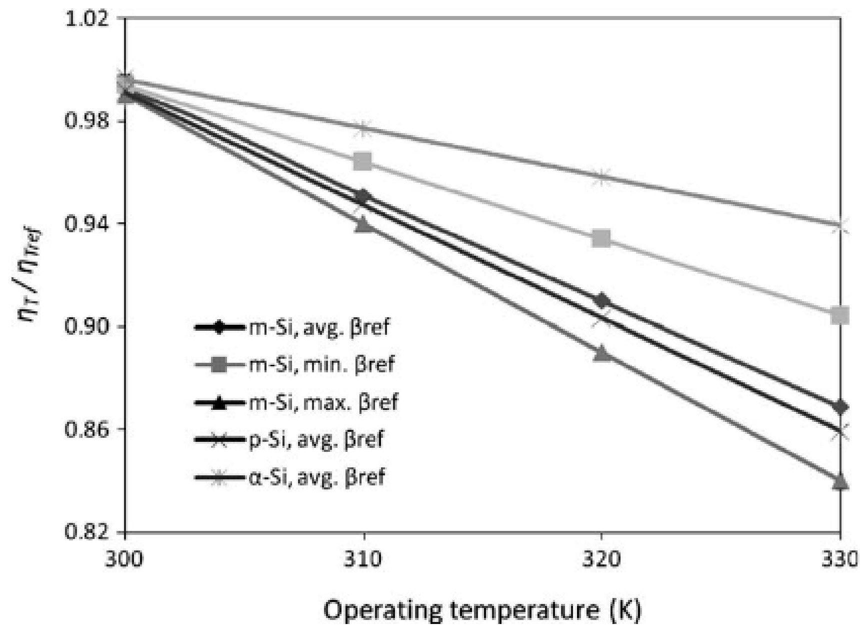

Figure 23: Efficiency Ratio of PV Depending on Temperature [30]

The higher the ratio of $\frac{\eta_T}{\eta_{Tref}}$, the greater the efficiency of the of the PV module [30], therefore Figure 23 demonstrates that the efficiency of PV modules decreases as the temperature rises.

8.4 Rain

The effect of rain on PV panels is almost always positive as the colder temperature of the rain cools the PV cells and therefore increases efficiency of the PV module [22]. Del Paro, Aste, and Leonforte found that "it is possible to state that rain has for sure a positive influence on the yearly performance of c-Si PV systems, with mean values during spring/summer period ranging from 2% up to 10%, depending on the context; such gain is the greater the more are the rainfalls of convective type in spring and summer seasons, thus characterized by intense precipitations and frequent alternation with partially-sunny conditions," [22]. Furthermore, rain can dislodge and clean PVs, removing debris that is blocking solar radiation and therefore increasing efficiency of the PV [22].

8.5 Snow

PVs are increasingly being installed in environment that experience snowfall and therefore the effect of snow accumulation on the panels needs to be examined [31],[32]. The effect of snow on PVs is directly related to the tilt angle of the panel [31], [32].

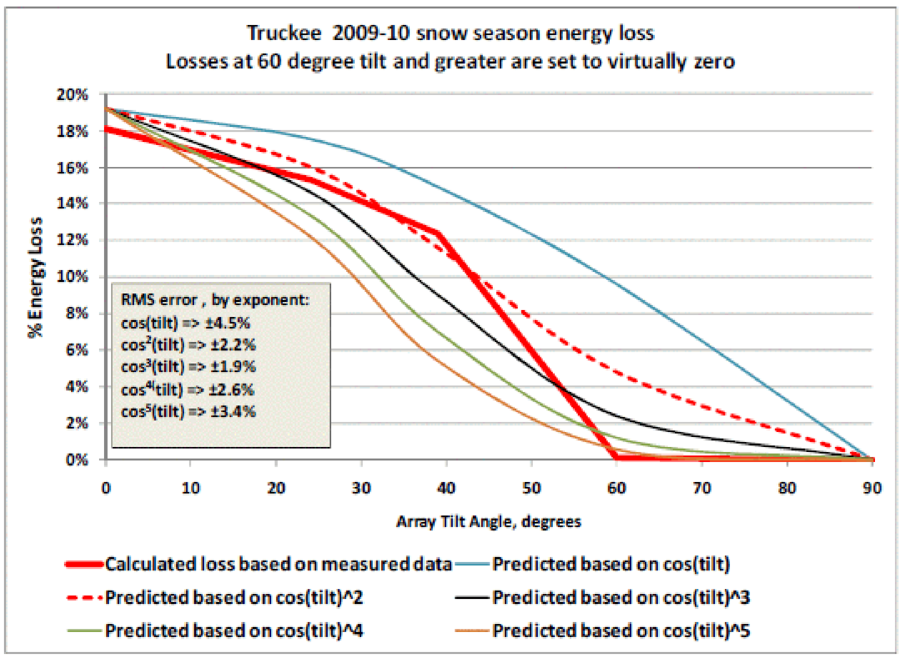

Figure 24: Energy Loss Due to Snow Accumulation Depending on Tilt Angle [32]

A study conducted in Michigan, USA, by Heidari found that the minimum snow related energy loss ranged from 5-12% [31] which they found by measuring the difference between power outputs of snow covered panels and clear panels at 4 different tilt angles, 0, 15, 30, and 45° using (10).

$$E_{Loss}(t) = (P_c * t) - (P_m * t) \tag{10}$$

The study examined two sets of PV modules, one set elevated 1.5m above the ground which is labelled as the unobstructed panels while the set installed on the ground are labelled as the obstructed panels [31]. As can be seen, increasing the tilt angle from 0° to 45° for PVs installed 1.5m above the ground lowered the amount of annual energy loss from 35% to 5% as can be seen in Figure 25. The panels installed on the ground did not see a significant decrease in energy loss between tilt angles [31].

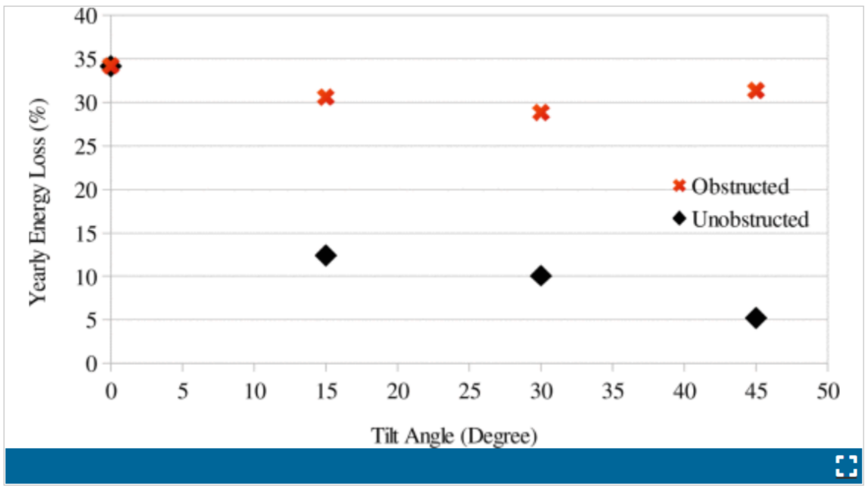

Figure 25: Yearly Energy Loss Due to Snow Accumulation Depending on Tilt Angle for Obstructed and Unobstructed Panels [31]

Furthermore, when we examine the energy loss during the snow season (November - May), we can notice that the panel tilted at 45° and lifted 1.5m off the ground had a 57% decrease in energy loss compared to the panel installed horizontally during the snow season [31]. The panels installed at ground level only differed by 9% energy loss for the different tilt angles, demonstrating that the panels must be installed higher than the snow level to decrease energy loss [31].

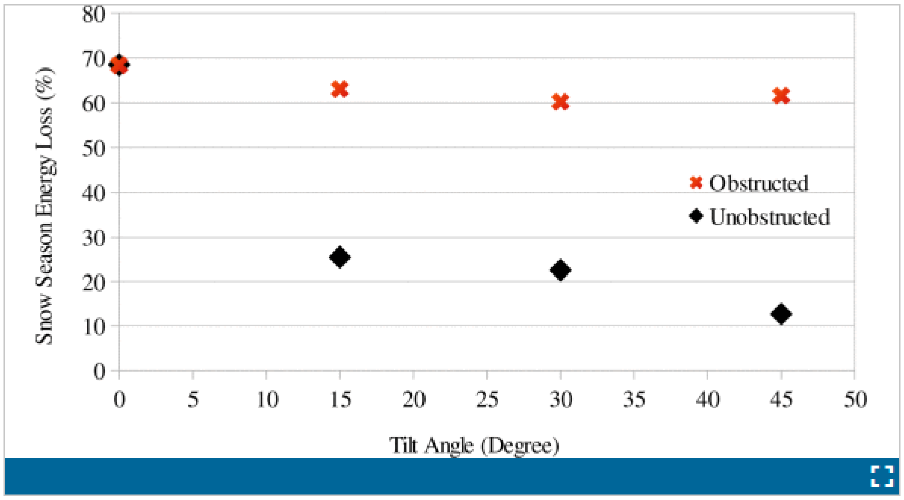

Figure 26: Snow Season Energy Loss Due to Snow Accumulation Depending on Tilt Angle for Obstructed and Unobstructed Panels [31]

We can further observe the difference between panels installed at ground level and 1.5m above ground level in Figure 27 and 28. The data clearly shows that the panels installed at ground level experienced significantly more energy loss throughout the winter months compared to the panels installed at 1.5 m above ground level [31].

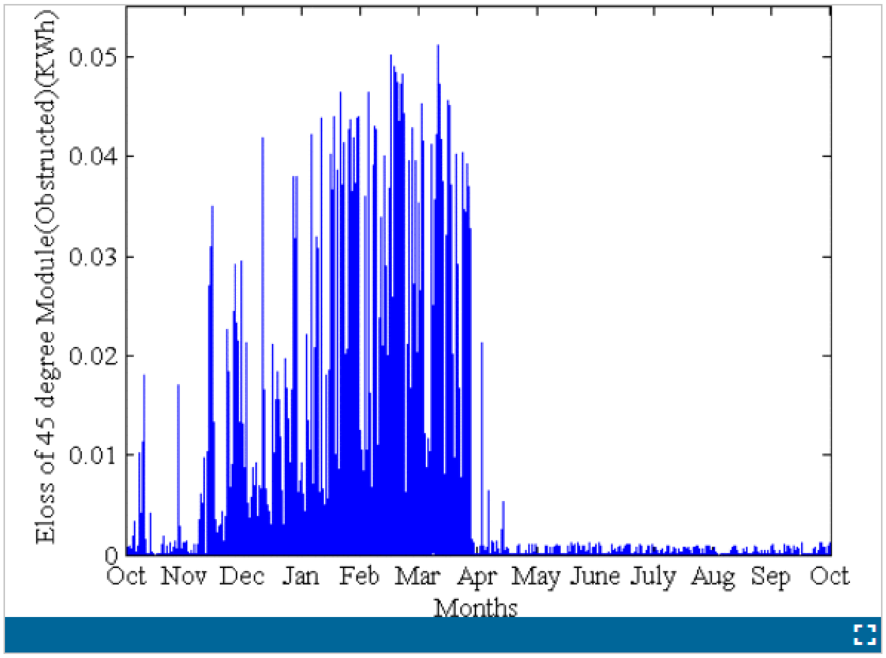

Figure 27: Yearly Energy Loss of a PV Module Installed at Ground Level Due to Snow [31]

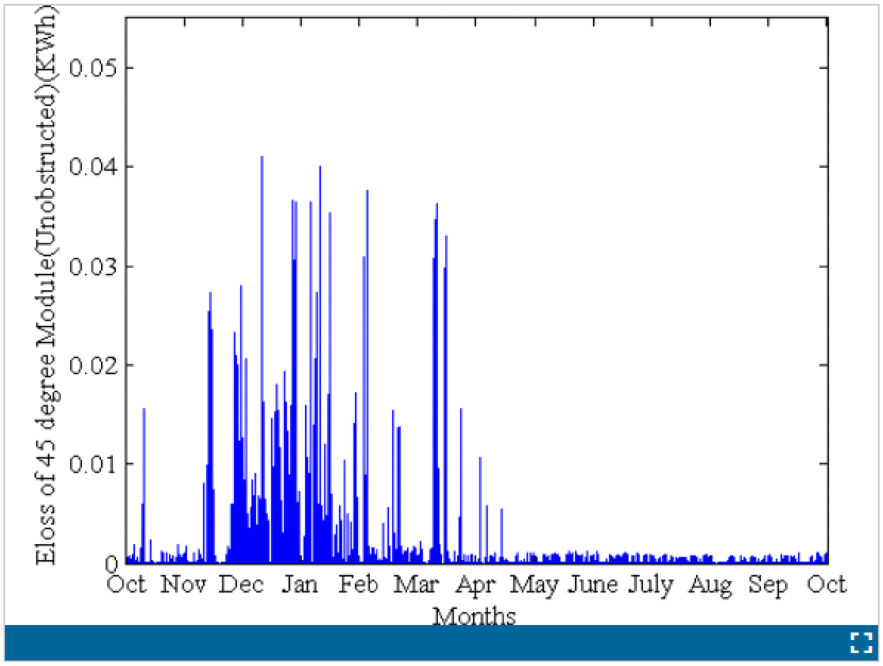

Figure 28: Yearly Energy Loss of a PV Module Installed at 1.5m Due to Snow [31]

9 Emergency Response Ability

The design and development of solar panel systems must consider the natural risks of building these systems in specific locations. This includes the possibility of a natural disaster occurring and damaging the system. For instance, if a system is being built along the west coast of BC, a region with high plate tectonic activity [33], the developers should account for a potential earthquake and tsunami. The specific natural disasters that developers and engineers will need to consider can significantly vary region to region, so adequate research on the history of disasters in the region must be conducted. The previously discussed environmental factors will likely play a role in a natural disaster. For practical purposes, we will be focusing on the region specific conditions for coastal communities in BC since this will be our scope of our initial operations.

9.1 Earthquake

The last mega-thrust earthquake to rock the west coast of BC and Vancouver Island occurred on January 26, 1700 [34]. These super-earthquakes of the Cascadia Subduction Zone on the south coast of BC, down to northern California, are expected to occur anywhere between 400 to 600 years, indicated by geological evidence [35] When minimizing the potential impact of an earthquake on our solar panels, we must consider the strength and stability of our materials, as well as the surrounding environment and how either of these factors could be affected by an earthquake of a 9.0 magnitude (the expected degree of the next mega-thrust quake). Steps to ensuring the panel system's preparedness for the inevitable "big one" include using strong materials that can resist a significant shake, along with selecting a location for the system that will not be affected by falling trees, buildings, or other large natural or man made objects that could hit the system and damage it.

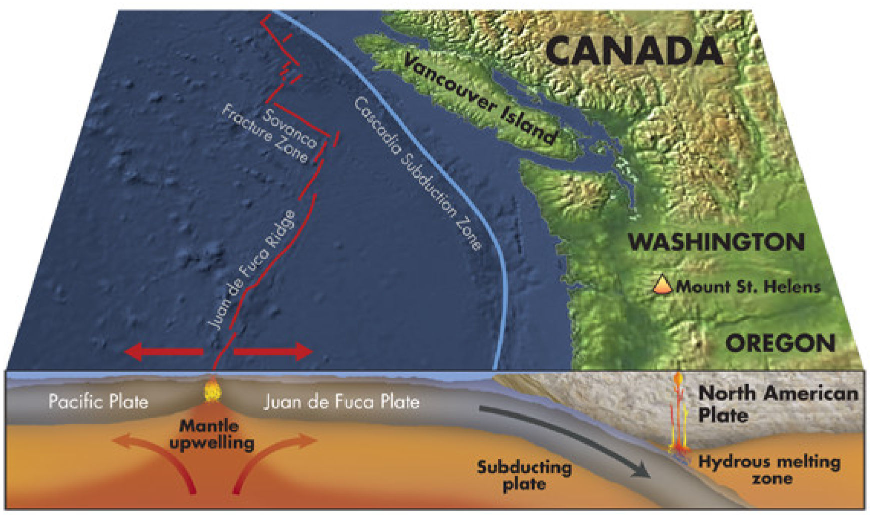

Figure 29: Cascadia Subduction Zone [36]

9.2 Tsunami

Directly linked to the possibility of an earthquake, is the chance of a tsunami hitting coastal communities. A tsunami in this area could be triggered from a nearby earthquake along the Cascadia Subduction zone, or from a relatively far away earthquake near Chile or Alaska [37]. We have seen the coast of BC be affected by many of these far travelling tsunamis in the last hundred years with some reaching heights as large as 7.7 meters [37]. The height of a tsunami is extremely difficult to predict due to the many factors that can impact its size [38]. With maximum heights ranging from a few centimetres to over 50 meters since 1997 [38], considerations of the panels' elevation from sea level should be taken based on the geological threat of a tsunami.

Tsunamis can also be triggered by landslides, as was realized by the peoples of the Kitimat First Nations settlement BC 1975 [39]. This submarine landslide sparked an estimated maximum 8.2 meter tsunami in the northern part of the Kitimat Arm passage and was not the result of any seismic event [40]. The history of the area's seafloor dynamics should be analyzed to determine the risk of this occurring and what measures can be taken to reduce its impact on the system. These landslide induced tsunamis also can sometimes be triggered by human activities [41], which should also be considered.

9.3 Wild Fires

The impact of large scale forest fires and the large clouds of ash they create can be devastating to the output of solar PV panels [42]. The amount of power generation loss depends on the intensity and duration of the smoke clouds and ash, with many places reporting a 10-20 percent loss in production and some losses even as high as 66 percent [42] [43] [44]. The actual fires themselves do not pose nearly as great of a risk since the system should be in an area with few trees to begin with due to their sun-blocking capabilities and their chance of falling and damaging the panels. However, we will likely see an increasing amount of impact from the ash of the fires due to climate change [45], which could have long term impacts on the solar panels' long term performance[42].

9.4 Solar Flares and EMP

Solar Flares and EMPs are most commonly known to damage wires within or connected to devices. The panels themselves are not at a high risk if they are not connected. Solar inverters and charge controllers, what converts and stores solar energy into usable power, are Unfortunately, most susceptible to damages from a solar flare or EMP [46]. To reduce the effects of a solar flare, one could build a large mesh Faraday cage to house their charge controllers and inverters [46].

10 Carbon Footprint of Solar Panels

Although solar panels are proven to be a renewable energy source, there exists a stigma that tarnishes its reputation as a greener alternative to fossil fuels. The manufacturing and installation of solar panels are fossil fuel heavy as seen by the invasive mining of quartz silicon to the overseas shipping from Asia of where almost 80 percent of all photovoltaic modules come from it is easy to see a Cumulative Energy Demand (CED) that doesn't seem green at first [47]. In this section of the report, we will go over the long-term carbon footprint of solar energy and how a solar tracking system can come into play, while also providing insight into the Energy Payback Time (EPBT) of this kind of system.

10.1 The Effects of Tilt Angle on EPBT

A study performed in 2020 by Gul and Al-Hussein [48], involved the installation of fixed monocrystalline solar panels throughout the northern latitudes of Alberta between 2010 and 2015. This study provided an analysis of the EPBT of the residential fixed solar systems and what were the biggest effects on the PV performance [48]. Based off the LCA performed in this study, Gul and Al-Hussein estimate the average energy required to manufacture and install a PV system to be 4973 MJ per square meter of solar panel that produces an average annual yield of 1380.95 kWh/kWp [48]. This resulted in an average EPBT of 7.93 years for northern locations [48].

Although the effect of geolocation of the PVs was a major topic of discussion in the study, it was found, as stated by Gul and Al-Hussein, "the most effective factor for minimizing the EPBT and GHG emissions resulting from solar PVs is the tilt angle, or in other words, the inclination of the receiving surface from the local latitude; the closer the tilt angle to the latitude the lesser the EPBT and GHG emissions, and the greater the aggregated annual energy generation." [48] The level of impact the tilt angle has on the energy generation of each solar panel used in the study is shown in 30 [48].

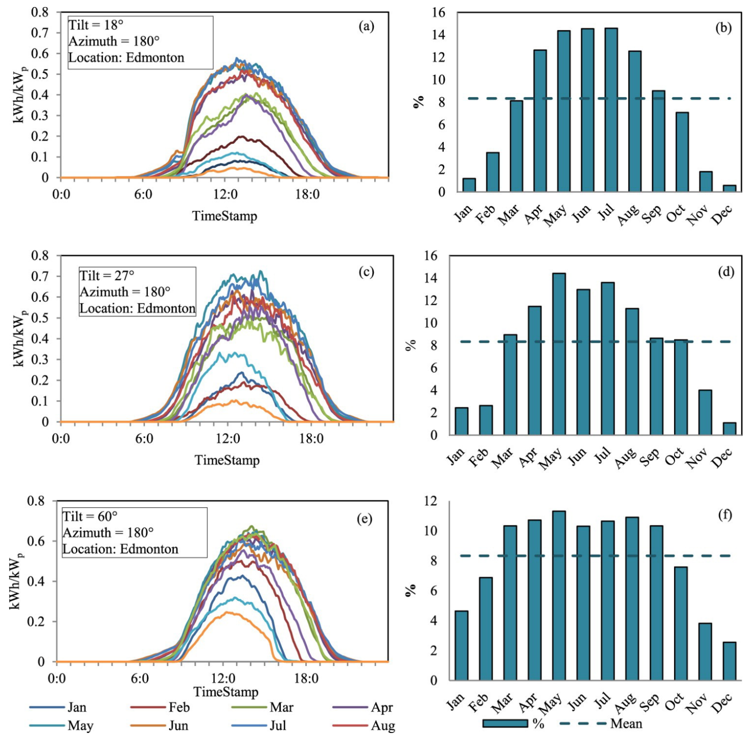

Figure 30: Energy Generation for each month of the year for tilt angles of 18°, 27°, and 60°located in Edmonton, AB [48]

It was also found that, "Provided that the most-likely North American roof-sloping practice varies between 30°(7:12) and 40°(10:12), a range which is approximately below the local latitude by 15°to 25°, it is concluded that by changing the solar PV system's tilt angle from the current practice to a tilt angle that is equal to the local latitude, the EPBT and GHG emission rate decreases by 29.48 percent." [48]

Seeing that tilt angle is extremely important for improving the average energy yield of a PV, implementing a tracking system would eliminate the guess work of finding the optimal panel position and maintain it for longer periods of time.

10.2 The Environmental Cost of Overseas Solar Panels

To minimize the carbon footprint caused by the manufacturing of solar panels, the country of manufacture can drastically effect the environmental production costs. From a study done in 2012, China is responsible for the production of 62 percent of all solar panels worldwide, while only generating 5 percent of the total solar energy capacity worldwide [49]. Although we are seeing a decrease in GHG emissions by 30-40% for roof-top installed monocrystalline, polycrystalline, and ribbon solar panels as production is becoming more efficient, eliminating unregulated overseas manufacturing could drastically reduce the carbon footprint of manufacturing solar panels even further [49].

A study done in 2014, outlined the CED, EPBT, and carbon footprint between solar panels manufactured and installed in Europe compared to those manufactured in China and shipped to Europe [49]. The CED and EPBT are detailed below in (31) and (32) showing a clear distinction between the two locations of manufacturing.

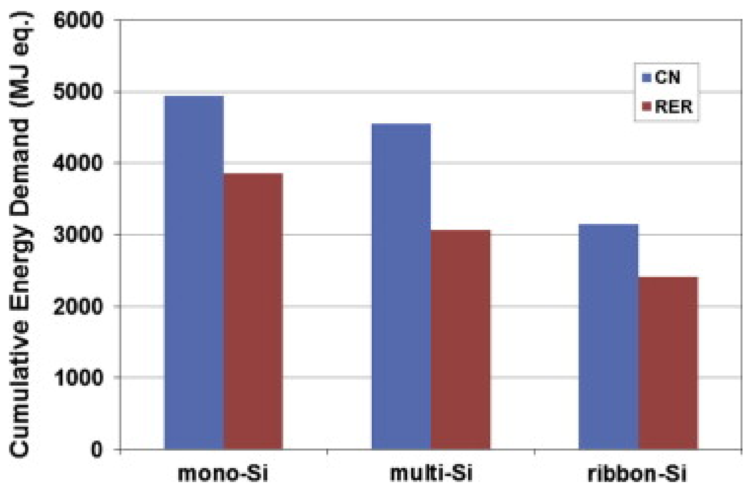

Figure 31: Cumulative Energy Demand Comparison Between Chinese(CN) Manufactured Solar Panels and European Manufactured Solar Panels(RER) [49]

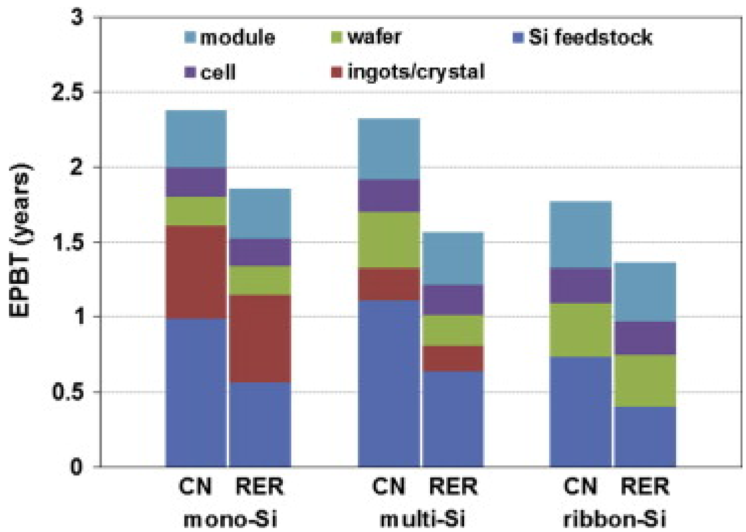

Figure 32: Energy Payback Time Comparison Between Chinese(CN) Manufactured Solar Panels and European Manufactured Solar Panels(RER) [49]

According to this study, "two of the most important factors underlying these differences are electricity mix and energy efficiency. China generates 80% of its electricity from coal, while renewable energy resources (e.g., hydropower plants) have a larger share in Europe. Moreover, the large share of coal in energy generation also causes the efficiency level in China to stand below the world average." [49] This combined with the resources required to ship the panels leads to the carbon footprint of Chinese solar panels to be double compared to the European panels as shown in (33) [49].

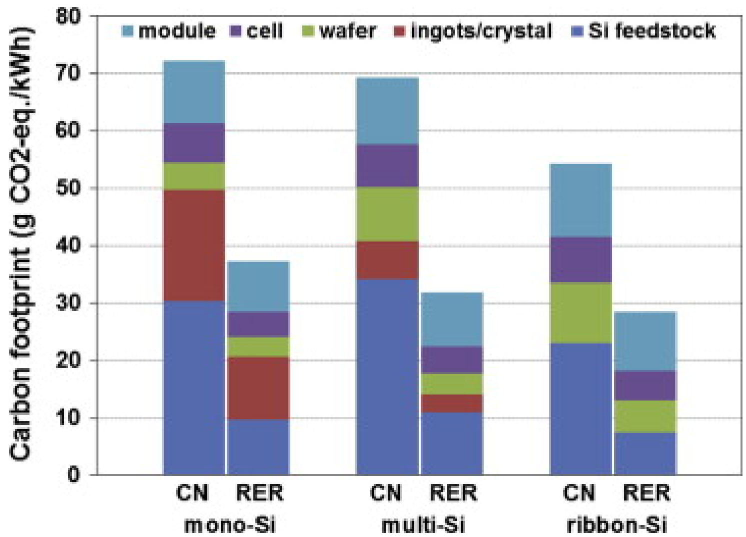

Figure 33: Carbon Footprint Comparison Between Chinese(CN) Manufactured Solar Panels and European Manufactured Solar Panels(RER) [49]

Another study performed in 2018 compared the energy requirements in manufacturing solar panel components in China with those manufactured in Canada [50]. Their results were as follows: "The results of the GaBi analysis found that the existing China and Ontario PV supply chain requires a total primary energy demand of 3.12E+3 MJ or 8.67E+2 kWh to produce a CS6X-P module, whereas the hypothetical Ontario-only supply chain would have a primary energy demand of 2.41E+3 MJ or 6.70E+2 kWh." [50] From these results it was concluded that in order to dramatically reduce the initial environmental impact of manufacturing solar panels, finding a local manufacture would decrease the EPBT and total GHG emissions, but at a higher cost for each panel.

10.3 Solar Panel Recycling Options

Over the past few decades, PV systems have improved dramatically in efficiency, total power generation, and cost. These improvements make solar power more attainable, reducing our dependency on non-renewable energy sources. Although using solar panels is a great alternative to fossil fuels, they are known to have a lifetime of 25 years [51]. After this point their ability to convert solar radiation into electricity is reduced. Because of this, "the worldwide ratio of solar PV waste to new installations is expected to increase considerably over time. It will reach between 4% and 14% of total generation capacity by 2030 and approximately rise over 80% by 2050." [51]

To mitigate this problem, recycling used solar panels for reusable components such as the glass, frame, and other components will become a necessity to reduce the amount of waste generated. Currently there are three different forms of recycling solar panels that each aim to harvest certain components of damaged or used panels. One of these forms are physical, which involves the separation of the glass, aluminum frame, and cells into separate forms to be reused and recycled [51]. The thermal form of recycling mainly involves the recuperation of the glass which through the physical process is smashed and ground up into fine pieces and then heated in a furnace [51]. A 91 percent recovery rate of the glass was determined after the thermal process [51]. The last process is chemical which uses different organic solvent combinations like trichloroethylene to reclaim the rare metals used in the PV cells [51]. These different processes are detailed in (34).

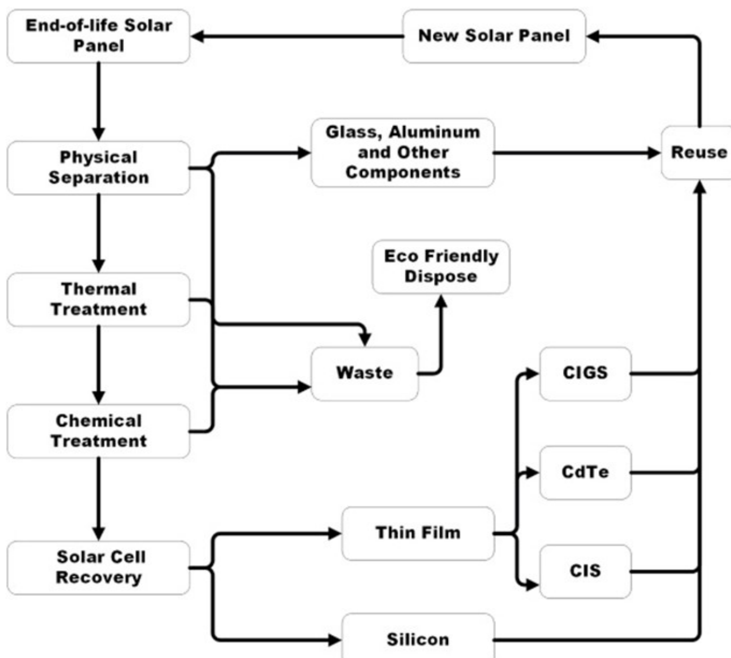

Figure 34: Different Forms of Recycling Solar Panels [51]

Even though, the processes used to recycle and renew used solar panels involve toxic chemicals, high energy processes, and high costs, they are necessary to keep solar as an environmentally friendly energy source.

10.4 GHG Emissions Comparison and Relation Between Solar Panels and Diesel Generator

In Canada, there exists 182 remote communities that are inaccessible by road [52]. Resources like medical supplies and fuel must be transported by boat or plane. Isolated from any power grid, 85 percent of these communities depend on diesel as a source of power [53]. This results in an estimated annual fuel consumption of 215 million litres or 600 kilotons of CO2 between every community [53]. Using durable and efficient solar panels with solar tracking technology, the shipments of fuel for electricity can be eliminated reducing the amount of GHG emissions, allowing for more efficient trips to remote communities, and providing them with clean energy.

To put into perspective, a study from 2012 measured the carbon dioxide emitted from a Sarawak diesel generator with a constant load demand of 1.05 kW/hour for 6 hours of operation [54]. The rated power provided by the generator was varied between 2.0kW and 5.0kW [54]. This resulted in a carbon footprint detailed in (35).

Rated Power of Diesel Generator (kW)	Efficiency of Diesel Generator	Fuel Consumption		Carbon Footprint in terms of CO_2 Emissions	
		(liters/day)	liters/kWh)	(kg/day)	(kg/kWh)
2.0	0.52	2.56	0.42	7.67	1.22
3.0	0.35	3.06	0.49	9.18	1.46
4.0	0.26	3.57	0.57	10.70	1.70
5.0	0.21	4.07	0.65	12.21	1.94

Figure 35: Carbon Footprint Data by a Diesel Generator [54]

From this data a linear relationship was determined in Excel to provide a variable estimate of the amount of GHG emissions in kilograms of CO2 per kWh relative to the kW power rating of the off-grid generator.

$$GHG_{diesel} = 0.24(P_r) + 0.74 \tag{11}$$

Using this equation, a comparison can be made between the green house gas emissions between a PV system of varying peak-wattage capability and a diesel generator with a similar power output. Determining the green house gas emissions of a solar system on the other hand contains many more factors than that of the diesel generator. Since solar panels generate zero GHGs as it produces energy, a LCA must be performed to determine the GHG emitted to produce, install, and recycle a PV system. Through the LCA performed in 2020 by Gul and Al-Hussein [48], the carbon footprint of various fixed monocrystalline silicon solar panels from various manufactures with a peak wattage between 225Wp and 260Wp that detailed a minimum carbon footprint of 37.93 grams of CO2 per kWh, a maximum carbon footprint of 66.78 grams of CO2 per kWh, and an average of 49.33 grams of CO2 per kWh [48].

Using (11) we can calculate the resulting emissions of a diesel generator outputting a similar peak wattage between 225Wp and 260Wp is between 794 grams of CO2 per kWh and 802.4 grams of CO2 per kWh. Comparing these results with the data calculated from Gul and Al-Hussein's [48] average carbon footprint of 49.33 grams of CO2 per kWh we see that solar panels produce about 16 times less CO2 then a conventional diesel generator. By providing other options besides fossil fuels, the amount of GHG emissions can be drastically reduced while also providing a more reliable and efficient energy system for those off the grid.

11 Hydrophobic Coating

The coating used on the panels is important to take into consideration, as it can be used to improve the longevity and reliability. Since these solar panels are intended to be used in marine environments, a hydrophobic coating is essential, since a build up of rainwater on the panel would reduce performance. The hydrophobic coating works by decreasing the surface tension between the panel and the water, allowing the droplets to simply slide off the panel [55]. Additionally, this has the added benefit of helping reduce the build up of snow as well, since the coating should cause the same result. Which makes the coating even more impactful, as the panel being covered in snow would render it unable to produce any power at all until cleared.

According to a 2019 study, trichloro-perfluorooctylsilane can be applied to the surface of the panel via a vapour spray [55]. The application process begins by applying micro-abrasions to the surface of the panel with an abrasive such as a polycrystalline diamond solution, which is harder than the panel surface. The panel is then cleaned before being placed in a humidity-controlled environment (16%) for the hydrophobic spray to be applied. The panel remains in this environment for twenty minutes until the application is complete, before being removed and thoroughly cleaned with isopropanol alcohol [55]. This is also a scalable process.

One important consideration is the effect of hydrophobic coatings on the performance of the panels. It is important that the coating does not significantly reflect or absorb the incoming light. The trichloro-perfluorooctylsilane solution does not significantly alter how the panel interacts with light, and Figure 36 demonstrates how the treated panel displays almost identical levels of transmission compared with an untreated panel [55]. The coating results in an efficiency reduction of less than 1% for tilt angles of 45°and 60°[56].

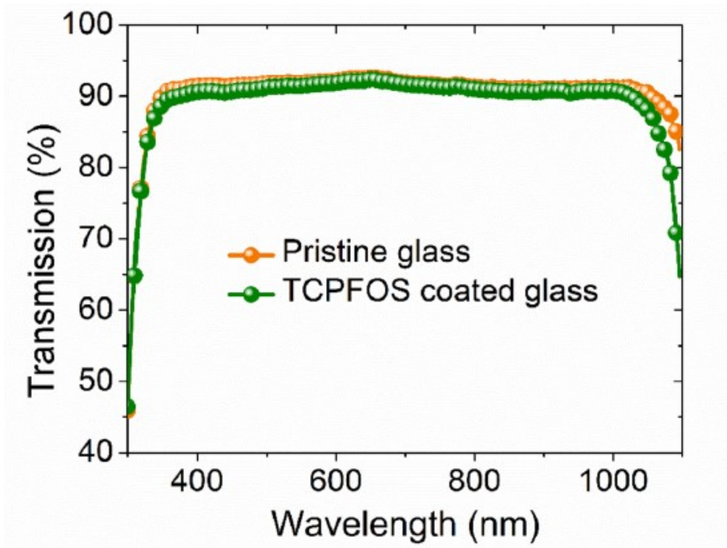

Figure 36: Light Transmission Through Glass At Various Wavelengths, Hydrophobic Coated Glass Versus Non-Coated [55]

Given that the panels are intended to operate in marine environments, it is important to consider the impact of factors such as salt water. One of the benefits of using hydrophobic coatings is that they can also help protect the panels from degradation caused by these environmental factors. Salt can accumulate on the panels as a result of dew formation in the morning, which can be difficult to clean and cause deteriorated performance if left to build up [55]. Figure 37 shows a comparison between a panel with the coating versus one without, with both panels being coated in a saline solution multiple times a day over the course of a week. The panel with the coating shows almost no salt buildup versus the panel without which has a substantial amount.

Figure 37: Salt Build-Up on Hydrophobic Coated Solar Panel Versus Non-Coated Solar Panel [55]

12 Installation

The cost of installing a solar PV or thermal panel system will depend on many factors. In BC, the average system will cost $ 2.54 - $2.69 per kilowatt[3]. Of course, a more complex and efficient system will require a larger cost than a less complex system. Due to this, this "cost" should be perceived more as an investment, where a higher value investment should yield a higher return in the long run. Having said this, the investment amount can be significantly reduced by local funding opportunities and grants that were previously mentioned in 2.

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