Optimizing Tilt Angle for Maximum Photovoltaic Potential in Qatar

Word Count: 5303

Abstract:

Qatar remains the world's biggest exporter of Liquified Natural Gas (LNG). Unfortunately, given the nonrenewable nature of LNG, it is simply unsustainable and furthermore cannot ensure self-sufficiency in terms of electricity consumption. Solar power may be a viable alternative, however no research is done to ensure that maximum electrical output can be achieved through finding an optimal tilt angle of a PV cell in Qatar. As a result of this, Qatar has not been reliant on Solar Power simply because it remains too expensive of an option in terms of how much electricity it can produce. By creating a theoretical function that can model the effect of tilt angle of a PV cell on power output, and comparing that to experimental data at a given time and a given date in 10 degree increments, a comparison can be made that will show whether or not this function is statistically accurate to find the optimal tilt angle in Qatar at a specific time and date. From this study, it was observed that power changed through the alteration of the tilt angle, based on the assumption that the relationship was sinusoidal in nature. The experimental data was not significantly different from the theoretical model, and therefore, this model can predict the optimal tilt angle at Qatar within the confines of this study.

Intro

1.1 Qatar’s current Energy Policy

Currently, Qatar is the largest exporter of Liquified Natural Gas (LNG) in the world, with the revenues generated from it amounting to almost 60 percent of Qatar's Gross Domestic Product (GDP)[1] according to Alan S. Weber, a professor at Weill Cornell Qatar (Weber, 2013). While this has shown to be a major source of economic success as well as provide ample energy to every household and commercial building in the country, there is growing speculation on the sustainability of this practice. As a result of this, alternative plans have been created for the sole purpose of still being able to maintain the vitality of Qatar's economy without compromising the country’s access to energy. The creation of the Qatar National Vision 2030 mimics this mentality in terms of looking towards sustainable means of energy production (Weber, 2013). One such alternative is Solar Power, as Qatar’s climate consists of a very sunny and arid nature, something optimal for most Solar Panels according to Varnas et al., all of which are members of the Stockholm Environment Institute, an organization recognized for their analyses of climates globally and how those climates can be harnessed to provide sustainable energy.

1.2 Description of Qatar’s Solar Power potential

Solar Energy is also one of the fastest growing energy industries in the world, showing a growth of 0.1 gigaWatts (gW) in 1992 to a staggering 36 gW in 2010 (Varnas et al., 2012, p. 17). With the Middle East’s arid and sunny climate, it is reasonable for this to be the best alternative to fossil fuels in the region and why it matters in this study that Solar energy should be looked at as the primary alternative. Qatar’s interest in this form of energy is becoming

[1] GDP: A measure of the value of the total goods and services produced by a state in a year

increasingly known as “Qatar currently has 44 MW of installed renewable capacity, comprising 6 MV of solar [power] and 38 MV of biomass/biogas” (Seznec, 2018, p. 8). This is again expressed in how Guo et al. (2015), professors and researchers at Texas A&M University Qatar, Qatar Environment and Energy Research Institute, and GreenGulf Inc., have expressed that “Qatar General Electricity & Water Corporation (Kahramaa) will complete a 200-MW solar power plant by 2020” (p. 1). To help Qatar expand their Solar power potential, it is necessary to find ways to use existing solar technologies so that costs spent can be used in a manner that allows maximum electrical output. One of the more prominent forms of this technology is known as Solar Photovoltaics.

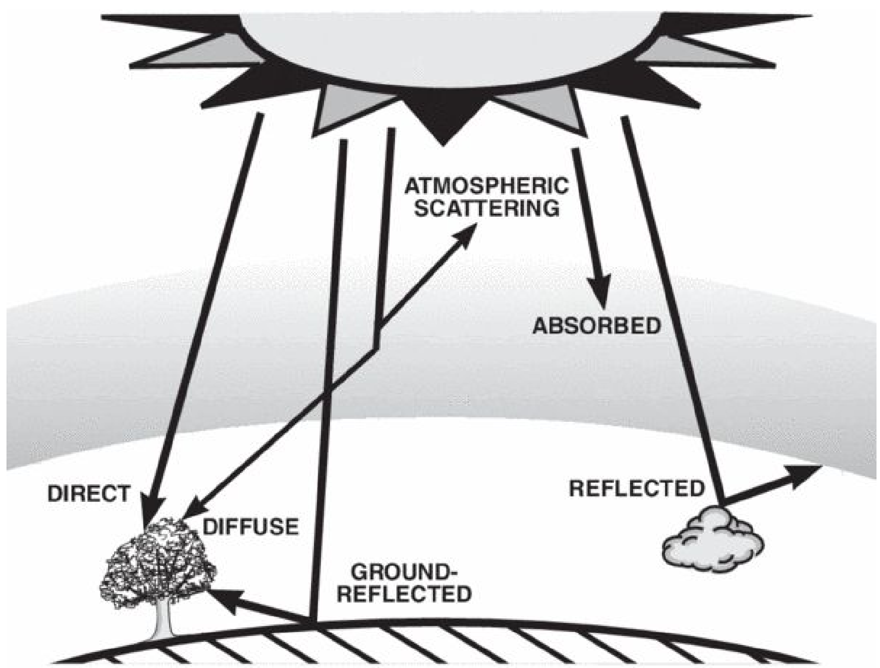
1.3 Photovoltaics and their definitions

First, Solar Photovoltaics can be defined as a system that converts sunlight into electricity via capturing photons[2] with semiconductors, which causes the semiconductor to release electrons that can be harnessed as electricity as mentioned by Varnas et al. (2012, p. 18). This definition can be expanded as Solar Photovoltaics are a subset of Solar Energy that uses solar panels to capture photons through semiconductors (Varnas et al., 2012, p. 18,). Another form of this is Solar Thermal Technology that uses heat from sunlight to heat places (Varnas et al., 2012, p. 18). Furthermore, Semiconductors are substances that are not fully conductive but not fully insulative either. They are essential to most circuits and give out an electron that is when interacted with a photon (Varnas et al., 2012, p. 18). Since the purpose of this study is to maximize electrical output, looking primarily on the analysis of Solar Photovoltaics and how they can be optimized is the best way to do so.

[2] Photons: Particles of light at the atomic level

1.4 Measures of Photovoltaic efficiency

Measures of 'electrical output' must also be expanded upon so that it is clear how they can be used for this study. Experts in the field use Solar radiation as a primary indicator to observe the energy potential of a PV at different tilt angles. According to Kaddoura et al. (2016), researchers at King Abdulaziz University Department of Electrical and Computer Engineering in Saudi Arabia, Solar radiation can be defined as "The amount of potential radiation harvested by a PV panel is primarily affected by its orientation with respect to its horizon (azimuth and tilt angles) and local climate conditions" (p. 627). Its units are described in W/m^2 or Watts per meter square, where Watt is a measure of electrical power potential (Kaddoura et al., 2016, p. 627). Furthermore, Solar radiation is a calculation of three of its subsets as sunlight entering the atmosphere is scattered in three ways (Kaddoura et al., p. 627). These three subsets are Direct, Diffuse and Reflected radiation (Kaddoura et al., 2016, p. 627). According to Santos et al. (2018), Direct Radiation is defined as "the radiation that has not



experienced scattering in the atmosphere, so that it is directionally fixed, coming from the disk of the Sun". Adefarati & Bansal (2019), define Diffuse radiation as "the solar radiation that is absorbed, scattered, or reflected by water vapor, dust particles or pollution when passing through the atmosphere". Lastly, Li & P.E. (2016) define Reflected radiation as "the amount of solar energy reflected from a surface, based on the solar reflectance or albedo of the surface material." These three quantities are directly measurable, unlike Solar radiation and the sum of all three gives the Solar radiation (Kaddoura et al., 2016, p. 627). As Kaddoura et al. (2016) suggest, "In application of solar energy such as photovoltaic (PV), solar radiation potential is essential" (p. 627). In this application, Solar radiation can be used to estimate when the greatest electrical output can be produced from whatever specified tilt angle of a Photovoltaic Panel, on whatever day during the year.

1.5 Types of Photovoltaics

The two most common forms of Solar PV today are Crystalline-Silicon panels and Concentrated PV (Varnas et al., 2012, pp. 18-19). While Concentrated PV uses a parabolic mirror to focus sunlight to a particular panel in order to create concentrated energy, and actually produce a significantly greater energy output than Crystalline-Silicon panels, Crystalline-Silicon panels remain more efficient as they operate at a cheaper cost, and therefore the energy return for the money spend on Crystalline-Silicon panels actually tends to be greater, as stated by Varnas et al. (2012, pp. 18-19). To create them requires Silicon ingots that are cut into thin wafers that are then used to make the solar cells that constitute the panel (Varnas et al., 2012, pp. 18-19). The silicon wafers act as the semiconductors that allow photons to hit them and emit an electron (Varnas et al., 2012, pp. 18-19). They exist in two forms: Mono-crystalline panels and Poly-crystalline panels, with the main difference being that Mono-crystalline panels are cheaper as they are constituted of one crystal of Silicon to create wafers and Poly-crystalline being constituted of multiple crystals of Silicon to create wafers (Varnas et al., 2012, p. 18-19). Subsequently, because Mono-crystalline is more uniform as it consists of one crystal, it is far more efficient since the more rugged design of Poly-crystalline panels prevent photons from hitting them at a specific uniform angle and emitting electrons (Varnas et al., 2012, pp. 18-19). Therefore, for the purpose of this study, Mono-crystalline panels will be used.

1.6 Literature Review

Despite being a relatively new alternative source of energy in Qatar, a variety of research exists that outlines ways to improve Photovoltaic potential as well as how it can be optimized in Qatar. Part of this research includes unique, new ways to implement Photovoltaics in areas that do not have flat planes present to set up large arrays of panels. One such study described by Abu-Rub and Iqbal, professors at the Texas A&M University in Qatar and Qatar University respectively, showed how Qatar has implemented Solar Photovoltaics on top of high-rise towers, especially in areas such as the Qatar Financial Centre which are dense with high-rise towers (2009). This directly corresponds with the growing interest Qatar has to expand the use of Photovoltaics to meet the renewable energy quota stated in the Qatar National Vision 2030 plan (Weber, 2013). Specifically in terms of large scale arrays of panels and experimentations to optimize them in Qatar, research in that area exists in all types of forms.

One study published by Touati et al., researchers at the department of Electrical Engineering at Qatar University, that in a stationary setting, a 120W Mono-crystalline panel produces the greatest electrical output from 9:24 to 11:48 a.m (2013, p. 263). This is proved as the greatest solar radiation (based on Watt/m^2) in Qatar typically occurs from 11:00 to 14:00, as experimentally determined, and verified by a MATLAB simulation (Touati et al., 2013, p. 264). This is because these times indicate high noon, and therefore a panel stationed to face the sun at that angle will be able to harness the greatest amount of Solar radiation as it would hit it directly (Touati et al., 2013, p. 264). For mono-crystalline panels, greatest efficiency based on temperature and relative humidity occurs at 15:45 with a panel efficiency of 80 percent, with the second highest being 78 percent at 12:45 (Touati et al., 2013, p. 264). Since this difference is not significant, the researchers attributed this increase in efficiency as a result of slight temperature increases and humidity decrease (Touati et al., 2013, p. 265). Furthermore, it was shown that an increase in temperature has negative impacts on the efficiency of the panel as there is a -0.015 percent decrease in efficiency for every 1 percent increase in PV temperature, a -0.06 percent decrease in efficiency for every 1 degree celsius increase in Relative Humidity, and a -0.095 percent decrease in efficiency for every 1 g/m^2 of dust (Touati et al., 2013, p. 266). This shows that dust accumulation has the most impact in an elongated period as a decrease in efficiency due to dust accumulation increases per day, for ex. In a 100 days, there would be a 9.5% decrease in efficiency (Touati et al., 2013, p. 266). Therefore, a study that finds the optimum tilt angle would need to be around a time from 11:00 to 14:00 and not be placed in long durations to avoid the impact of dust accumulation on a solar panel.

A similar study was published in Qatar by Martinez-Plaza et al., all of whom are researchers in the Qatar Environment and Energy Research Institute, pertaining to the use of zero, one or two axial programmed tilts on solar panels and what system tended to have the greatest electrical output (2015). This study found that when comparing an array of solar panels that was completely stationary, an array of solar panels that had a one-axis tracking system and an array of solar panels that had a two-axis tracking system, that the one-axis tracking system barely improved efficiency as only 10% more electrical power was produced than the stationary, and the two-axis system while improving efficiency by more than 50% of that of the stationary, it was a far more expensive implementation that allotted fewer panels for testing as well as further implementation (395). What this also shows about the optimization of PV in Qatar is that by choosing a stationary system to test for optimal tilt angles, prices not only for testing but for further implementation would be lowered and increase efficiency of the panels itself.

1.7 Gap in Research

While the study conducted by Martinez-Plaza, Abdallah, Figgis & Mirza was the closest into actually finding an optimal tilt angle since they looked at various systems that they could be observed, the study specifically mentions: "The stationary system may be an option of interest, still pending study of the optimal angle of inclination for Doha climate conditions" (2015, p. 394). This clearly indicates a gap in research as it shows a lack of information regarding optimal tilt angle of inclination for PV in Qatar. The specific gap in research, as the study mentions, is Qatar and how no optimal tilt angle has been determined to suit all solar panels in Qatar to maximize electrical output. Therefore this study can be assumed to be relevant and exploring new knowledge in the field of Photovoltaics as it illustrates a study that has not been pursued before. However, assumptions on this study can still be made. Another study done in Ras Al Khaimah, UAE by Omar Akash, a researcher at the University of North Dakota has conducted a similar experiment and identified that "the peak power increases with raising the tilt angle from 15 to 25 degrees due to the fact that the system is located in Ras Al Khaimah, UAE with Latitude of 25.7 [degrees]" (2016, p. 2). Lastly, one study published by Nadim et al., Bangladeshi researchers from the University of Texas at San Antonio as well as the Bangladesh University of Engineering and Technology theorized a function where given certain parameters, such as the time of day, latitudinal coordinates, days since the beginning of the year and solar radiation were taken into account to depict what would be optimal tilt angle for Mono-crystalline PV for maximum electrical output. The theoretical optimal tilt angle in Bangladesh yearlong developed from the study was shown to support what actual experimentation suggested in Bangladesh yearlong, being 21.4 degrees (2017, p. 271). Such a function has yet to be derived for the purposes and cases for Qatar, and furthermore, this modified function, if shown to support experimental findings, could pave the way of finding optimal stationary tilt angles for Qatar, but also also algorithms that can be used to optimize a one-axis tracking system for Mono-crystalline PV. This brings about the question, **to what extent can a function modelling maximum Solar PV output based on tilt angle in Qatar be accurate for predicting the optimal tilt angle for a stationary PV during a specific time and date?**

I hypothesize that since Qatar shares a similar latitudinal coordinate of 25.3548 degrees north (Martinez-Plaza et al., p. 387), and the UAE has very similar climate conditions to Qatar, therefore a tilt angle at a similar range should be considered optimum for PV in Qatar, and therefore, with this modified function, I should be able to attain a theoretical tilt angle within the same range.

Methodology

2.1 Research Method

Since this study looks at finding an optimal tilt angle for stationary Mono-Crystalline Photovoltaic panels in Qatar within a certain time range through computation and then comparing it with experimental data, an experimental design must be used in order to assess the validity of the theoretical optimal tilt angle. In this scenario, experimental design is mandatory for two reasons. One, a detailed procedure would be outlined that shows how the Solar Panel would be used and tilted in such a manner that it actually is able to assess different electrical outputs at different angles and compare it to theoretical ones. Secondly, any confounding variables that are currently known or assumable can be removed with the implementation of control parameters which is discussed in Sections 2.3 and 2.4. From there, a 1-sample *t* test for mean differences[3] to assess whether or not there are external factors that cause expected power outputs at given angles at given times to be different from that of the actual. Given the nature of my testing conditions to be limited to one day, this remains the best option on finding and assessing the optimal tilt angle at that given time and date as by using this modified function, it allows me to predict what the predicted optimal tilt angle for Qatar should be at that given time, and compare it with the experimental data, and assess whether or not based on that point, the function is good enough to be generalized continuously throughout a year for Qatar.

2.2 Theoretical Framework

First, to be able to predict what the solar radiation would be at a given time of the day and at a specific tilt angle, their formulas must be established. The process described by Nadim et al., shows that initially, the Air Mass[4] (AM) must be calculated using $1/cos\theta$, where θ is the angular height of the sun in the sky calculated from the vertical (2016, p. 271). θ, also referred

[3] 1-sample *t* test for mean differences: A statistical test which analyzes the differences between two samples of data to see if there is a significant difference.

[4] Defined as the "the direct optical path length through Earth's atmosphere" (Nadim, M., Rashed, M. R. H., Muhury, A., & Mominuzzaman, S. M. , 2016, p. 271).

to as the zenith angle[5] is equated as $90 - elevation\ angle$[6] (Nadim et al., 2016, p. 271). The elevation angle (α) can be put as a function of the declination angle[7] and the latitude angle[8] such that $\alpha = 90 - (latitude\ angle + declination\ angle)$ (Nadim et al., 2016, p. 272). In this particular scenario, the latitude angle of Qatar is known as 25.286106º N (Martinez-Plaza et al., 2015, p. 367) and the declination angle (δ) is defined using the function:

$\delta = 23.45° * sin(\frac{360}{365} *(d - 81))$ where d is "the number of a day in a year that starts with January 1 as d = 1" (Nadim et al., 2016, p. 272). From there, the Solar intensity (I), or "the intensity of the sunray on a perpendicular plane and calculated in units of kW/m2" (p. 271) is calculated using the formula: $I = 1.353 * 0.7^{AM^{0.678}}$ (Nadim et al., 2016). This computation is necessary as then, the Solar radiation can be calculated as $Solar\ Radiation = I * sin(\alpha + \beta)$, where β is the specific tilt angle the Solar Panel is positioned at (Nadim, M., Rashed, M. R. H., Muhury, A., & Mominuzzaman, S. M. , 2016, p. 272). This Solar radiation function would represent the amount of Solar radiation would be present on the panel at a specific day and can be graphed to show what tilt angle would produce the highest Solar radiation on the day of the experiment.

2.3 Materials Used

- An open unobstructed field that provides uninterrupted sunlight from sun to panel
    - This can be done by ensuring that no obstructions portude vertically and the plane that the Panel lies on is completely flat

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[5] Defined as the angle between the sun and the vertical axis (Nadim, M., Rashed, M. R. H., Muhury, A., & Mominuzzaman, S. M. , 2016, p. 271).
[6] Defined as the angle between the sun and horizontal axis (Nadim, M., Rashed, M. R. H., Muhury, A., & Mominuzzaman, S. M. , 2016, p. 271).
[7] Defined as the angle of the Earth in respect to the days that pass by in comparison to its axis (Nadim, M., Rashed, M. R. H., Muhury, A., & Mominuzzaman, S. M. , 2016, p. 272).
[8] Defined as the geographical coordinate of a particular area in comparison to the rest of the world, measured in degrees North from the South Pole Defined as the angle of the Earth in respect to the days that pass by in comparison to its axis (Nadim, M., Rashed, M. R. H., Muhury, A., & Mominuzzaman, S. M. , 2016, p. 272).

- 1 Mono-Crystalline Photovoltaic panel with terminals that can link it to circuitry[9]
- A flat wall, perpendicular to the flat plane that the panel
- Electrical gloves suited to protect experimenter of over 0.1 Amperes[10] (A) of current
    - This is for safety measures, as the experimental design will most likely generate current over 0.1 A, which can be lethal if in contact with the circuitry, unless gloves are used
- Measuring tape that measures the distance from the end of the wall to the end of the panel
- Graphing calculator (specifically a TI-nSpire for its sheer computational power)
- Weights to hold the panel at a specific inclination
- A 50 ohm resistor[11] to use as load to measure voltage[12] of circuit from (circuit consisting of PV cell and load)
- Multimeter[13] capable of reading voltage of circuit through load
    - Can be found in any Science Classroom
- An ammeter[14] to measure current in Amperes (A)
- Insulated cables[15] that connect the positive Photovoltaic terminal to the ammeter, load[16] and back to the negative Photovoltaic terminal

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[9] Defined as the actual electrical circuit where electricity produced travels through and is consumed for a certain load

[10] Measure of electric current, which is the flow of electricity throughout a circuit. This is measured in Amperes (A)

[11] Defined as a load in the circuit that current passes through, and limits the current so that the circuit doesn't overheat. The resistance, or the amount of current that is limited through the use of resistors, is measured in Ohms (Ω)

[12] Measure of electric potential throughout a circuit, which is further elaborated as how much current a Photovoltaic can produced. This is called Voltage and is measured in Volts (V)

[13] Tool capable of measuring Voltage

[14] Tool capable of measuring Current

[15] Metallic cables which electricity passes through which are protected with plastic, so that the individual does not come in contact with them and be at risk of their safety

[16] Something the current passes throughout the circuit; a broader description of a resistor

- Allocated time to conduct the experiment, which in this case is January 21st 2020 at 2 pm
- Laptop to record data

2.4 Procedure

First, wear electrical gloves on hands to ensure maximum safety when conducting an experiment. Ensure that there is chaperone supervision to keep your safety in check and get you medical attention if you somehow come into contact with open circuitry. Attach cables such that they connect to the resistor, then the ammeter and back to the cable. Then, connect both ends of the cable to each terminal of the Panel. Next, measure the distance needed to place the panel in the angle you based on the equation provided earlier. Place the panel such that the edge of it is at the distance you desire. Then to ensure the panel stays in place, put the weights adjacent to it to stop it from falling down. After, record voltage using multimeter and current using Ammeter. Change the distance from the wall to panel to achieve a new tilt angle and repeat the processes outlined in the first seven sentences of this Section. Record all data of current and voltage on the computer corresponding to the tilt angle and distance used.

Results and Findings

3.1 Theoretical understanding

The experiment took place on January 21st, 2020, at 2:01-2:15 PM, in Doha, Qatar. This means that the theoretical optimal tilt angle based on the equation described in the previous section has to reflect these specific conditions so that the tilt angle provided is the optimal tilt angle of January 21st, 2020.

The Solar Zenith angle will then be calculated as a mean of $90 - \textit{elevation angle}$ from the different elevation angles from the times of 2:01 PM and 2:15 PM in Doha. This data, as shown in Figures 1 and 2, is provided by TimeandDate.com, a website that specializes in providing accurate meteorological[17] as well as solar and lunar data.

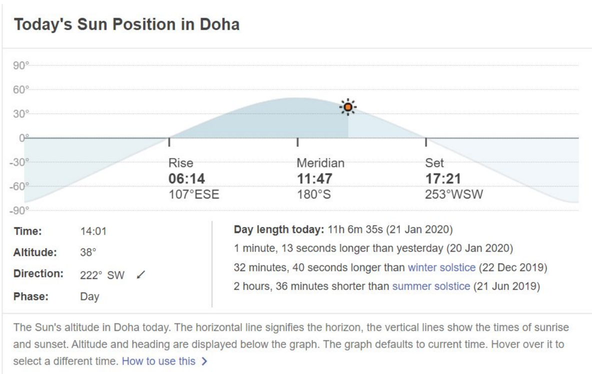

Figure 1

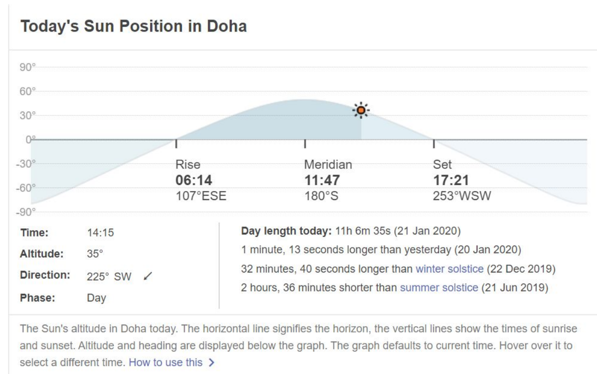

Figure 2

Both of these charts indicate that on January 21st 2020, the 'Altitude'[18], or the elevation angle drops from 38º to 35º from 2:01 PM to 2:15 PM. To portray a graph of an optimal tilt angle at this time frame, the mean angle between these two intervals shall be used, being 36.5º. Therefore the Solar Zenith angle for this purpose shall be 53.5º. Air Mass is thus calculated to be 1.68, with the Solar Intensity (I) therefore being 0.896 between the times of 2:01 to 2:15 PM.

The declination angle (δ) can also be calculated as d in this sense is 21, representing 21 days since the start of 2020. Therefore, the declination angle is -20.18º. From this, α is calculated to be 44.54º.

The function for Solar Radiation is thus represented as the following:

$Solar\ Radiation = 0.896 * sin(44.54 + \beta)$ where β is the tilt angle.[19]

[17] Meteorological data is data pertaining to the weather
[18] Assumed to be elevation angle as it describes the angle of the sun from the horizontal plane, which is what the elevation angle is
[19] Graph below represents Solar Radiation as a function, f(x) with x being the tilt angle

Table 1 shows the expected Solar Radiation values at the 10 degree angle increments.

Angle (in degrees)	Solar Radiation (W/m^2)
0	0.683
10	0.730
20	0.809
30	0.864
40	0.892
50	0.893
60	0.867
70	0.815
80	0.738
90	0.639

Table 1

Figure 3 shows a graphical representation, with Solar Radiation represented in the Y-axis and tilt angle represented in the X-axis.

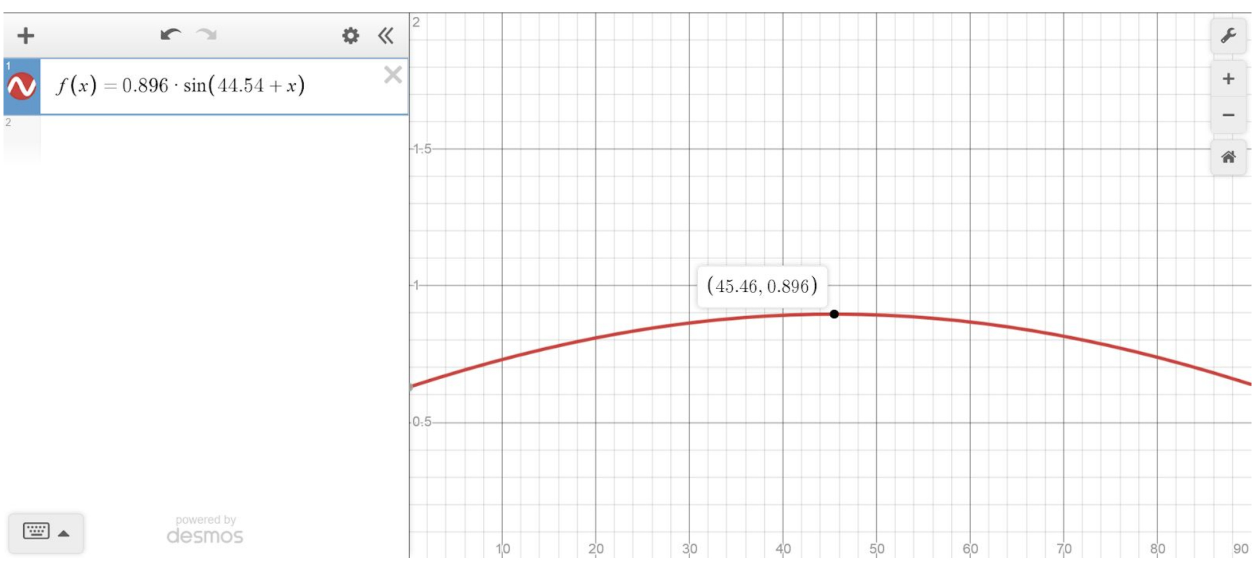

Figure 3

This model indicates that the theoretical optimal tilt angle on January 21st 2020, in Doha, Qatar from the times of 2:01 PM to 2:15 PM is 45.46°, with the Solar Radiation being 0.896 W/m^2 in that particular angle.

Calculating the square of the average rate of change for the Solar Radiation[20] per increase in degree for the 9 10 degree intervals, Table 2 is obtained.

Angle Interval (in degrees)	Square of average rate of change of Solar Radiation (W/m^2 per degree)^2
0-10	2.304×10^{-5}
10-20	6.241×10^{-5}
20-30	3.025×10^{-5}
30-40	7.840×10^{-6}
40-50	1.000×10^{-8}
50-60	6.760×10^{-6}
60-70	3.721×10^{-5}
70-80	5.929×10^{-5}
80-90	9.801×10^{-5}

Table 2

[20] Maintains differentiability of this variable while making it positive so it can be used in analysis

3.2 Experimental Proceedings

Table 3 shows the experimental data collected.

Temperature (in Celsius)	Time	Angle	Ground distance	Voltage	Current	Power	Humidity
24	2:01 PM	0	Length needed: 119.85 cm	18.5 V	0.6215 A	11.50 W	60%
	2:02 PM	10	Length needed: 118.03 cm	18.6 V	0.6215 A	11.56 W	
	2:03 PM	20	Length needed: 112.62 cm	18.7 V	0.6215 A	11.62 W	
	2:04 PM	30	Length needed: 103.79 cm	18.7 V	0.6215 A	11.68 W	
	2:06 PM	40	Length needed: 91.81 cm	18.8 V	0.6215 A	11.68 W	
	2:08 PM	50	Length needed: 77.04 cm	18.8 V	0.6215 A	11.68 W	
	2:10 PM	60	Length needed: 59.93 cm	18.8 V	0.6215 A	11.68 W	
	2:12 PM	70	Length needed: 40.91 cm	18.8 V	0.6215 A	11.68 W	
	2:13 PM	80	Length needed: 20.81 cm	18.7 V	0.6215 A	11.62 W	
	2:15 PM	90	Length needed: 0 cm	18.6 V	0.6215 A	11.56 W	

Table 3

A graphical representation data with a curve fit is shown in Figure 5.

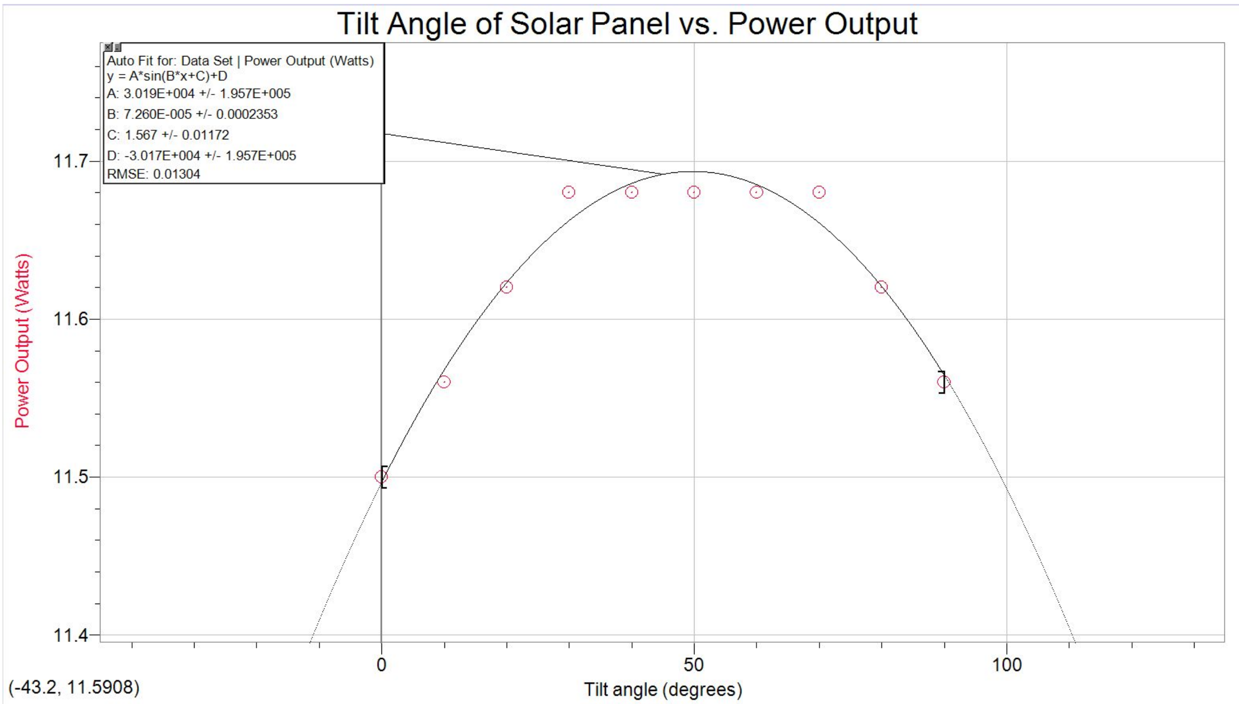

Figure 5

Using the derivative of this curve to find the relative maximum[21], this curve indicates the greatest power output for the Mono-crystalline panel on January 21st 2020, from 2:01 to 2:15 PM will tend to be 50.3 degrees with a predicted power output of 11.6937 W. This does not support the initial hypothesis from Section 1.7 that the optimal tilt angle would be similar or within the range to that of the study collected in Ras Al Khaimah by Omar Akash, being 15 to 25 degrees (2016, p. 2).

Converting the experimental power output into Solar Radiation units, based on the panel area (0.6389 m^2) and computed with the panel dimensions provided in Appendix B, and power output given in Table 3, Table 4 is obtained.

[21] The relative maximum is the highest point in the graph

Angle (°)	Power per area (W/m^2)
0	18.00
10	18.09
20	18.19
30	18.28
40	18.28
50	18.28
60	18.28
70	18.28
80	18.19
90	18.09

Table 4

Calculating the square of the average rate of change for the Power per area per increase in degree for the nine 10 degree intervals, Table 5 is obtained.

Angle Interval (in degrees)	Square of average rate of change of Power per area (W/m^2 per degree)^2
0-10	$8.1x10^{-5}$
10-20	$1.0x10^{-4}$
20-30	$8.1x10^{-5}$
30-40	0.0
40-50	0.0
50-60	0.0
60-70	0.0
70-80	$8.1x10^{-5}$
80-90	$1.0x10^{-4}$

Table 5

Discussion

In order to see if the pattern for the change in Solar Radiation due to angle from the theoretical model matches the pattern for the change in Power per area due to angle from the experimental data, a 1-sample *t* test for mean differences will be used.

The null hypothesis (H_0) is such: $\mu_{\text{Solar Radiation-Power per area}} = 0$

The alternate hypothesis (H_A) is such: $\mu_{\text{Solar Radiation-Power per area}} \neq 0$

$\mu_{\text{Solar Radiation-Power per area}}$ is the mean difference between the squares of the rates of change of Solar Radiation and the squares of the rates of change of Power per area, where each difference is calculated by matching the two values based on their respective angle interval. Table 6 shows the differences between both values for their respective angle interval.

Angle interval (in degrees)	Square of rate of change of Solar Radiation (W/m^2 per degrees) minus square of rate of change of Power per area (W/m^2 per degrees)
0-10	-5.796×10^{-5}
10-20	-3.759×10^{-5}
20-30	-5.075×10^{-5}
30-40	7.840×10^{-6}
40-50	1.000×10^{-8}
50-60	6.760×10^{-6}
60-70	3.721×10^{-5}
70-80	-2.171×10^{-5}
80-90	-1.99×10^{-6}

Table 6

Checking for conditions to run a 1-sample *t* test for mean differences, Randomization is not used as the values in the sample pertain specifically to the time and date of the study. Normality is assumed as the only possible effect of comparing the squares of the average rate of change for the power per area to the squares of the average rate of change for the Solar Radiation would be through measurement error from the equipment. It is reasonable to assume that measurement error is approximately normal at zero, as it is reasonable to assume that the equipment do not have any measurement issues as they automatically calibrate. Independence of observations is evident due to the short time frame of data collection that caused the elevation angle to only drop down 3 degrees.

Calculating $\bar{x}$ (sample mean) gives -1.313×10^{-5} (W/m^2 per degree)^2. Calculating $s_{\bar{x}}$ (sample standard deviation) gives 3.115×10^{-5} (W/m^2 per degree)^2. Since the sample size is n = 9, the df (degrees of freedom[22]) is 8 and thus, $t = -1.26459$. Since t is two-tailed[23] by nature of the alternate hypothesis suggesting that there is a difference independent of sign, therefore the p-value[24] is 0.241613.

Therefore, I fail to reject the null hypothesis as there is insufficient evidence that there is a difference between the squares of the rates of change of Power per area and the squares of the rates of change of Solar Radiation. With a t of -1.26459, and a p-value of 0.241613, as the p-value is higher than any reasonable significance level[25] ($\alpha = 0.01, 0.05, 0.10$).

Conclusion

The data gathered supports the idea that the theoretical model is the best model that can be used to predict the optimal tilt angle for Qatar. With a lack of convincing evidence that suggests that the squares of the average rates of change of Solar Radiation within different angle intervals differs from the squares of the average rates of change of Power per area within the respective angle interval to that of the Solar Radiation interval, it is clear that the model is appropriate to measure the relationship between the tilt angle and power output for the time and date of January 21st 2020, from 2:01 PM to 2:15 PM. This means that the optimal tilt angle

[22] Degrees of Freedom: Number of sample entries minus 1.
[23] Two-tailed: Null hypothesis can either be rejected from a negative t or a positive t with two-tailed statistics, hence why the use of not-equals alternate hypotheses are two-tailed in nature; they can be positive or negative, but they require a value that is not 0.
[24] P-value: The probability that a certain value/proportion can be achieved based on the distribution of the value/proportion of the null hypothesis.
[25] Significance level: A level of which the p-value must be under for the null hypothesis to be rejected.

attained by the theoretical model for this time and date can predict the actual optimal tilt angle for the specified time and date.

This answers the question, **to what extent can a function modelling maximum Solar PV output based on tilt angle in Qatar be accurate for predicting the optimal tilt angle for a stationary PV during a specific time and date?** While these results and analysis do support the understanding that a function modelling maximum Solar PV output based on tilt angle in Qatar is accurate for predicting the optimal tilt angle for a stationary PV for the specific date January 21st 2020 from 2:01 PM to 2:15 PM, further research needs to be conducted that shows that the model established by Nadim et al. can be used extensively for any day and any time throughout a year in Qatar. This is because the data obtained is not randomized, and therefore the conclusion made cannot be generalized to all days and times throughout a year in Qatar, and instead only specifically to the study.

Certain limitations of this study included the fact that the allotted research was within a very fixed time frame, and therefore with the resources available, January 21st 2020 was the only day where data could be collected. This is because the Solar Panel was rented for a week as it was too expensive to pay for more time, and a month was allotted in total to do the data collection. The voltmeter also had incredibly limited precision which limited my ability to see small changes between voltage and tilt angle. This experiment could thus be improved by having a more precise voltmeter as well as more data collection points throughout the span of a year.

Qatar's massive amounts of air pollution also may play a role in impacting the tilt angle through prolonged periods of Photovoltaic use as soiling is a factor previously mentioned in Section 1.6 according to Touati et al., that can inhibit the maximum potential of the panel. It may also explain why the actual data for the date and time used in this experiment had differed, but not to a significant level, from the theoretical values obtained from the model, and why from the angles of 30 to 70 degrees, there was no change in power in the panel. Therefore, further research could also look at how soiling might impact the tilt angle function for Qatar over time, and how it can be rectified so that Qatar’s photovoltaic potential is truly harnessed.

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Appendix A

Justification of Materials used

The use of the Mono-crystalline Photovoltaic panel is justified as it is the most readily available type of panel as well as the most efficient for widespread use in Qatar (Varnas et al., 2012, p. 19). An open unobstructed field will ensure that the solar radiation that is present on the panel is consisted mainly of direct radiation and not diffuse or reflected as those can prove to be hindrances for the purpose of conducting this experiment (Kaddoura, Anwari & Al-Turki, 2016, p. 627). Positioning the panel on a perpendicular war is also necessary to incline at certain angles, and to keep them at those positions, weights are necessary to hold them in place. Through a use of cosine function, the tilt angle can be calculated by using $arccos = (desired\ angle) = \frac{Distance\ from\ wall\ to\ edge\ of\ panel\ (horizontally)}{Length\ of\ panel}$. This is the easiest and most efficient way to position the panel at the described angles, and the distance from wall to edge of panel can furthermore be found using the graphing calculator. The cables themselves connect to the 2 ports on the panel, which then continue to connect to the resistor as well as the ammeter, as current can only be measured by an ammeter if the ammeter is part of the circuit. Since the only load the current will pass through is the 50 ohm resistor, the multimeter must be used so that the two probes are placed at either end of the resistor as all of the electric potential provided by the panel passes through those 2 points.

Appendix B

Experimental Design

In the actual experiment, a Mono-crystalline solar panel with a length of 1.199 meters and a width of 0.5329 meters, and the ability to produce a maximum of 5 amperes of current with potential difference of 18 Volts was used. The panel was placed in a specific manner based on calculations of tilt angles as mentioned in the previous section. Figure 6 shows a visual representation, where weights are kept in place to hold the panel in place, and a tape measure is used to measure out the distance from the ground to the edge of the panel.

Figure 6