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How important of the effect of temperature on the efficiency of solar photovoltaic cells?

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Abstract. The most direct effect on the efficiency is the temperature of solar modules. I discussed the reasons why the temperature of modules can affect the efficiency of solar cells and the explanation of how can we improve the solar system to decrease the influence of high cell temperature. The scarcity of traditional energy increases, so the scale of use of renewable energy increases. The efficiency of the energy-generating system is the most important factor that users consider. The extent of change in the temperature of solar modules is the highest, so the temperature of solar modules can cause an influential decrease in the efficiency of energy generation. I have used the data based on experiments set by other authors to illustrate the extent of influences of four main variables on the efficiency of the solar cells. I used of the properties of air and water to design two schemes to minimize the effects of high temperatures of solar cells. I compared the change in efficiency under one unit increase in variables. All of the data used in calculating or referring are from different experiments done by different authors. I connected the results with real conditions to determine the most influential variables-temperature of modules. Based on the theoretical result, the shading effect has the largest value of decrease in efficiency, so the effects of shading are considered by manufacturers a lot. Based on real-life situations, the scale of change in the temperature of modules and the actual temperature of modules are always higher than the standard operating temperature, 25℃, so the temperature of modules is the most influential variable. Monocrystalline silicon solar cells have different extents of influence of variables to polycrystalline silicon solar cells, these two types of solar cells are suitable to be installed in regions with low humidity. However polycrystalline solar cells are more sensitive to increases in the temperature of modules, so they need to pay more attention and avoid the effects of high temperature of modules.

Keywords: temperature, solar photovoltaic cells, efficiency

1. Introduction

This project illustrates the value of change in efficiency under the change in four different variables and explains the reasons why these four variables can affect the efficiency of solar cells by stating the academic explanations. Global warming is now the most serious and most concerned environmental problem. The temperature of air continues to rise every year. One of the most significant measures is to convert the main energy supplied from traditional convenient energy resources to renewable energy resources. The typical traditional convenient energy is fossil fuels and the commonest renewable energy resource is solar energy. So, the research on how to keep the high efficiency of solar photovoltaic systems is very important. Particularly, the prices for unrenewable resources and some renewable resources are too high to pay for electricity generation in the poor areas, and so the governments of poor countries set their sights on solar photovoltaic systems. Solar energy solves many problems of household electrification for poor families.

Otherwise, there are still several issues with the efficiency of solar power systems. One of the main components of a solar photovoltaic system is a solar cell, the main influence factor on the performance of a solar cell is temperature. Avoidance of this problem is beneficial to many households around the world and can improve the efficiency of electricity generation. The temperature of air has a directly proportional link to the temperature of modules, due to the effects of global warming, the temperature of modules increases generally. According to existing articles, the high temperature of modules has negative effects on the efficiency of solar cells. Hence, I want to study the effects on the efficiency of solar cells. The main photovoltaic technology is the crystalline silicon solar cells, as stated by a report published on May 7, 2022 [1]. Crystalline silicon solar cells are currently the most mature and hottest materials in the production of solar cells. So, in this project, the research object is a crystalline silicon solar cell. The discussion in this project includes two main sections, the analysis section and the discussion section. The conclusions given in the analysis are used to be the evidence of arguments existing in the discussion section. There are some introductions of each device of a typical solar system in the technology review. There may be some effects that can affect two or more influences of solar cells. For example, weather conditions affect both shading effects and humidity effects and the relationship between temperature and solar irradiation. The exact values of the change in efficiency with an increase in different effects are very convenient for users or learners to identify whether current environmental conditions are suitable for the installation of such solar cells, especially for crystalline silicon solar cells. The improvements in solar systems are very important since we already know the temperature of modules is the most influential effect and the other three influences also had a relatively high value of impact on the efficiency. The reasons for these arguments and the explanations of these research directions are discussed in this project.

2. Research review

2.1. Technology review

2.1.1. Introduction

Solar panel efficiency is a measurement of how much of the energy produced from the sun in a certain panel can be converted into usable electricity. This is completed by capturing the electrical current generated when sunshine reacts with silicon or the thin film cells inside a panel. [17]

A solar cell or photovoltaic cell is an electrical device that can use the photovoltaic effect to transfer light energy into electricity. [2] Solar panels absorb energy from the sun and transfer it to electricity. The light energy from the sun is called photons, which are the form of packets with different wavelength levels. Photons can be found on the silicon plate of the pane. Some photons with short wavelengths are controlled by the surface of the panel and the panel abstracts the energy from photons depending on their efficiency. [3]

Whether a grid-connected photovoltaic system includes the batteries is acceptable. [4]

2.1.2. Operation and components of solar photovoltaic system

-Solar cell

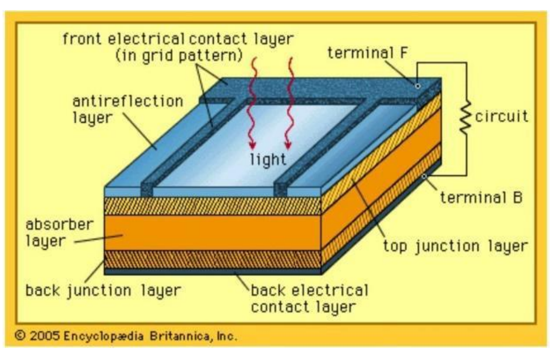

Figure 1. 2005 Encyclopaedia Britannica, Inc

The solar cell is the central power station of a solar photovoltaic system. Firstly, light enters the solar cell the first process place is an antireflection layer which can let the loss of light by reflection reach its minimum level. Typical antireflection layers are made of oxide of silicon, tantalum, or titanium that form on the cell surface. Usually, the electrical contact layer is made of light metal blocks and patterns in thin and wide grid lines, thus it cannot influence the collection of the current produced by the cell. The operating principle of the energy layers is to improve their transmission to the energy conversion layers to trap the light arriving on the solar cell effectively. The top and absorber layers are the additional layers that construct a complete electric circuit by transferring the electric current to an external load and back to the cell. The back electrical contact layer is an electrical contact as a cover of the back surface of the cell structure, always made of a very good electrical conductor, like metal. [5]

-Solar photovoltaic modules

The main part of a photovoltaic system is the solar module. The combination of the photovoltaic cells by producers is a solar photovoltaic system. The size of a solar photovoltaic system can be described in the order of site, strings, and array, from small size to big size. The most common way to construct photovoltaic modules is rigid flat modules and most of these modules are made from three types of silicon which are single-crystalline, poly-crystalline, and amorphous. Those crystalline silicon cells can produce a maximum open-circuit voltage of about 0.5 to 0.6 volts.

There are also some other materials used in solar modules, cadmium telluride, and copper indium telluride. It is also a good way to add these materials together. [4] [6] [7]

-Grounding Equipment

Grounding equipment offers a clear, low-resistance path from your photovoltaic system to the ground to avoid any hazard from lightning strikes or equipment malfunctions to the system from current surges. [4]

-Combiner Box

Wires from individual photovoltaic modules or strings flow to the combiner box. A combiner box typically has a good-quality fuse or breaker for each string, and even includes a surge protector, which can protect the system from power surges. [4]

-Meter and Instrumentation

Meters help the solar user to monitor their system. A batteries meter can measure the energy getting and energy lost in the battery bank. [8] Two kinds of meters are used in photovoltaic systems, Utility Kilowatt-hour Meter and System Meter. Utility Kilowatt-hour Meter measures energy transport to or delivered from the grid. [4]

-Inverters

Energy from an array modules or battery bank is direct current, despite DC having serval uses, if there is anywhere is used based on alternating current (AC), the direct current needs to be converted into alternative current by inverters. [8]

-AC disconnects

The role of AC connects disconnect is to separate the on-grid power converter. It is simply like a circuit breaker. The output of the inverters can be separated because of the consideration of the size of AC disconnects. [9]

-DC isolator

The function of installing a DC isolator switch is to disconnect direct current power sources and enhance the system's safety. Basically, there are two parts to form a DC isolator, the conductive contract section and the operating mechanism. Additionally, the DC isolator is used to ensure the operators safely check and repair the system. [22]

-Battery bank

The energy which is used in the future is stored in the battery bank. There are two types of battery lead-acid batteries and alkaline batteries, lead-acid batteries used for grid-connected systems are commoner than other ones. The conditions for using alkaline batteries are very complex, with extremely cold temperatures. However, the conditions of operating are easier for alkaline batteries, because, any type of alkaline battery is always in a full state of charge and some types of lead-acid batteries need to add water to work. [4]

-Charge controller

The goal of the charge controller work is to prevent reserve currents and avoid them from overcharging. They ensure the batteries are properly working for the system for a long period. Solar photovoltaic panels work to keep the current in one direction when they through in the battery, but sometimes especially at night the currents may be slightly discharged, hence the charge controller can solve this problem [10]

-Solar fuse

It is a device that preserves solar circuits that are affected by overcurrent. An overcurrent is caused by three factors, short circuits, faulty equipment, and lighting strikes. The fuse uses a conductor that can be melted when the circuit is exposed to too much current. This action causes the broken of the circuit and the interruption of the flow of electricity, therefore, further damage or fire can be prevented. [21]

2.2. Literature review

The effects of efficiency of solar photovoltaic cells

2.2.1. Temperature of modules

In the first experiment set by K.V Vidyanandan [11], he gave a conclusion that in general, up to about 0.5% loss of efficiency per degree Celsius rise in temperature of modules is typical in silicon cells. The author used line graphs and tables to illustrate the data and trends. When the temperature increased approximately 0.4% to 0.5%. An increase in current but a decrease in voltage, however, the extent of the decrease was greater than the increase, so the efficiency of the solar panel was decreased. The author did not say the invariants in this temperature and the interval for data in the x-axis and y-axis is not small enough to make the experiment more accurate. There were many types of solar cells so the author only showed crystalline silicon cell and he did not think about the magnitude of the impact on temperature by other types of solar cells. The author also stated that this conclusion is suitable for silicon solar cell, so the reliability of this conclusion for other types of solar cells is low. (10)

The second statement made by Valentine, Chigozie, and Godwill [12] is that when the current increases over a certain value then stop increasing and start to decrease. This statement was proved by an experiment. When the temperature was about 43 °C, the current is increasing. Then the temperature increased over 43 ˚C, and the current started to decrease. Therefore, this phenomenon indicated that 43 ˚C is the maximum operating temperature of this photovoltaic module.

Meanwhile, the temperature has a significant effect on voltage output. According to the experiment, when the temperature remains between 25 ˚C and 35 ˚C the voltage increases, but when the temperature is 44 ˚C the voltage drops. This also indicates the maximum operating of the photovoltaic module and expresses that the high temperature does not like to have high performance of the photovoltaic module. [12] Low current and low voltage, lower efficiency of solar panels.

In comparison, in these two articles and experiments, authors K.V.Vidyanandan [11] did not mention the invariants and he did not realize the result made by authors Valentie Benjamin Omubo, Chigozie Israel, and Godswill Alminokuma [12], which current is increasing when the temperature do not beyond the maximum operating temperature. Authors [12] did not mention the controlled variants in detail, so the process of the experiment is not very clear, additionally, the reliability of the result decreased.

Author Hannah Glenn stated that solar panels cooled by 1 ˚C, increasing by 0.05% on the efficiency of solar panels, but he did not show any experiment to prove that statement. The source is referenced from a standard website. The precondition for this statement is that increased wind speed lets the solar panels cool down. [18] The result of the change in the efficiency of solar panels by cooling the solar panels is ten times smaller than the result proved by authors K.V.Vidyanandan [11]. The experiment set up by K.V. Vidyanandan [11] is controlling variables, especially for environmental conditions. The authors, Leow, Irwan, Iwanto, Amelis, and Safwati, stated that PV panels with wind speed can produce a higher output power than PV panels without wind speed due to the larger heat extraction. [19] The indoor experiment set by K.V.Vidyanandan has the small influence on wind speed. [11] So the change in efficiency with wind speed is smaller than the change in efficiency without wind speed.

In summary, the conditions for the experiment are also very important and they can influence the consequence of the experiment. So, the results for author Hannah Glenn [18] and author K.V.Vidyanandan [11] are different due to the wind speed. For actual conditions, citizens or firms will prefer to reference the result from author Hannah Glenn [18], for this article, the reliability is higher than that of K.V.Vidyanandan [11] in real life.

2.2.2. Humidity

According to Panjwani and Dr. Ghous' article [13], humidity has a dramatic effect on the efficiency of performance of the solar panels and their proven out a result that if the solar panels are placed in an environment that high humidity level can cause a decrease in power producing from the solar panels up to 15 percents to 30 percents by the experiment. Depending on the experiment, same in the type and maximum power of the solar panels. the intensity can the distance to the illuminant are all the same value during the whole experiment. The most important effect of the experiment is the environment temperature, however, the temperature for the whole experiment is kept at 305K. As the humidity levels increased from 23 to 55, the DC voltage dropped from 17.1V to 16.32V, the current decreased from 2.78 A to 1.88 A, and power declined from 47.538 W to 30.681W. Finally, authors Manoj and Dr. Ghous Bukshsh Narejo, calculate the Percent Reduction in Power, about increased every 5% in humidity, decreased by approximately 6% of power. [13]

Valentine, Chigozie, and Godswill articles, [12] they took another experiment to prove that lower humidity higher efficiency of solar panels. One solar panel was placed in a fixed position, and the solar temperature and solar flux changed as the humidity levels changed. The data for current, voltage, power, and changes in variables are recorded accordingly. Both increases in current by high solar flux and voltage can cause a decrease in humidity, however, when the humidity levels are low, the efficiency is high. [12] This article was bad in controlling variables and research on all influences is not separate and is not specific. The data for change in humidity is not accurate because, the data can be disrupted by many other impacts, such as time and solar flux.

The experiment made by Panjwani [13] is more accurate and the report is more detailed because they realized the gap existed in the experiment and wrote it in the report, for example, they mention the distance between the illuminant and solar panel, however, the authors of the second experient [12] were not mentioned it.

2.2.3. Shading

The first experiment made by Monadhil, K. Sopian, Salameh, Zhang, and Alghoul [14], expressed that different numbers of bypass diodes have different extents of influences by shading. A diode is an electrical component that lets the flow of current in only one direction. [16] The electrical characteristic of the PV panel used in testing is fixed and the author chooses two panels with 2 or 4 bypass diodes. The testing experimented under actual temperature, irradiance, and real operating conditions, so the value for those environmental factors did not fully conform to Standard Test Conditions, therefore the performance of the panel deviated slightly from the rated value. Authors tested for two bypass diodes, when only one cell was fully shaded, the amount of decreased voltage and power was less than about 50% of the unshaded output. If two cells with the same bypass diode were fully shaded, the panel output would decrease to 50 percent similar to one cell shaded case. If two shaded cells have different diodes, the power output will decrease to an almost negligible level. Hence, if there are more cells shaded, but only with two bypass diodes, the output levels would always be low. The authors test for 4 numbers of diodes. When there is only one cell shaded, the panel voltage is kept at 69.6%. The voltage and power drop each time was merely 25% as with the shading of every subsequent cell under different diodes. Therefore, a high number of diodes is less sensitive to shading effects. [14]

The next experiment by author Nick Seghers [20] expressed one conclusion that the efficiency is influenced by connection, either it is connected in series or connected in parallel. The author used three PV panels with the same voltage and maximum power of 100W. The same area of shading. The shaded point will reduce the current from 5amps to 3amps at 52.5 Volts. In series, the addition of voltages equals the total voltage and the current stays the same.

In parallel, the voltage stays the same but the total current exists as an addition. The solar irradiance only influences the current on the same voltage. So, the total current for series is 3amps but for parallel is 14.6amps. the total voltage for the series is 52.5V and for the in parallel is 17.5V. therefore, the power dissipated by panels in series is 157W and the power provided by panels in parallel is 255.5W. The power for solar panel installs in parallel is better than installs in series. The efficiency is larger in solar panels connected in parallel than in solar panels connected in series. The author Nick Seghers [20] does not mention the actual area of shading in this article, so if readers want to calculate the change in efficiency as increasing the area of shading, readers will use the inaccuracy unit ‘points ‘. So, it is a concern for the reader to reference these results in their articles.

2.2.4. Solar radiation

The experiment taken by Mann, Ali, and Kadhem [15] controlled the variables. The humidity is not more than 40% and the limited airspeed. The authors used the only solar system for experiments with current and voltage, thus finding out the impact on the efficiency of solar modules when the solar radiation was changed. The authors used the temperature changing with the advance of time to indicate the radiation intensity of the lights was increased at the same time. The temperature both increased and decreased to restore the real sun radiation. When the solar radiation increased, the current(amp.) increased. The voltage increased as the solar radiation increased. The power increased as the increase in solar radiation, because of the increase in current. However, the standard stated that the maximum power reached 1000W/m2, but in this experiment, the power reached its maximum value at 800W/m2. That is because the temperature of the cell is higher than the standard temperature 25℃. Solar radiation not only affects the power but also affects the efficiency of the Photovoltaic Panel. The increase in solar radiation intensity both increased temperature and decreased the power and thus reduced the efficiency. [15]

In conclusion, the graph given by the author Mann, and Kadhem [15] is all-sided, they are very helpful for readers to analyze and they are arranged in order to let readers understand the conclusion more easily. Although the number of diagrams is enough, the detail of the diagrams is not very clear. The information of on x-axes and y-axes is stated greatly and the scale of x-axes is very detailed.

However, the range of scale of y-axes is too large, so every data should be estimated by the readers themselves. It is very hard to collect the data for the next part.

The experiment set by Md. Nazrul Islam, Mohammad Ziaur Rahman, Sharif Mohammad Mominuzzaman. The experiment introduction is explained clearly. The authors want to explore the extent of the influence of solar irradiation on the efficiency of the solar cells. According to the experimental result, the efficiency increases with the increase in solar irradiation. The temperature of the solar cell is controlled at 25℃, so the operating temperature is the best. The temperature of solar cells has minimum impact on solar irradiation.

3. Discussion / Development

3.1. Analysis

3.1.1. Module temperature

-Crystalline silicon solar cell

The experiment was set by EL-Shaer, Tsdros, and Khalifa [23] Experiment introduction:

One mono-crystalline silicon module and one poly-crystalline module silicon are used in this experiment.

A solar simulator was used to operate the experiments under any constant light intensity and temperature.

The module temperature is from 10℃ to 50℃ with light intensity 1 Sun. Result explanation:

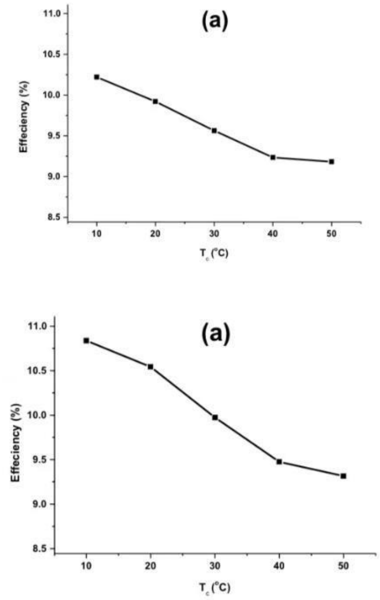

Fig. 10: Module temperature dependency for efficiency of: (a) Mono C-Si and (b) Poly C-Si

Figure 1. module temperature dependency for efficiency of monocrystalline silicon solar cell and polycrystalline silicon solar cell EL- Shaer, Tsdros and Khalifa [23]

The x-axis is ascending, from small numbers to large numbers.
-mono-crystalline module
When the module temperature is increased from 10℃ to 50℃, the efficiency is decreased from 10.25% to 9.25%.
The change in efficiency is 1%
The average change in efficiency per degree is 0.025%
-poly-crystalline module
When the module temperature is increased from 10℃ to 50℃, the efficiency decreases from 10.77% to 9.26%.
The change in efficiency is 1.51%
The average change in efficiency per degree is 0.03775%

3.1.2. Humidity

-Crystalline silicon solar cell
The experiment was set by Ali Sohani, Mohammad Hassan Shahverdian, Hoseyn Sayyaadi, and Davide Astiaso Garcia. [24]
Experiment Introduction:
Type of solar cells:

Specifications of the investigated photovoltaic modules.

Parameter	Value	
Model	YL50C-18b	YL050P-17b
Reference for data	Solar (2019)	Sentra Energi (2019)
Cell type	Monocrystalline Si	Polycrystalline Si
Rated power	50 W	50 W
The operating voltage at the maximum power point (*Vmp*)	18.18 V	18.50 V
The operating current at the maximum power point (*Imp*)	2.75 A	2.71 A
Open-circuit voltage (*Voc*)	22.64 V	22.90 V
Short-circuit current (*Isc*)	2.94 A	2.87 A
Cells efficiency	18.0%	14.0%

Figure 2. specification of investigated photovoltaic modules [24]

The prediction of voltage and current are introduced by ANN models for investigated modules. According to the working principle of modeling by ANN, changing one parameter and keeping others constant is not necessary.

The ranges of variation of the effective parameters for the data which is used to develop ANN models.

Parameter	Range	Unit
Ambient temperature	-2.0–43.2	°C
(Ambient) relative humidity	4.0–93.7	%
Wind velocity	0.0–8.7	$m.s^{-1}$
Solar radiation	10–1215	$W.m^{-2}$

Figure 3. the ranges of variation [24]

Result explanation:

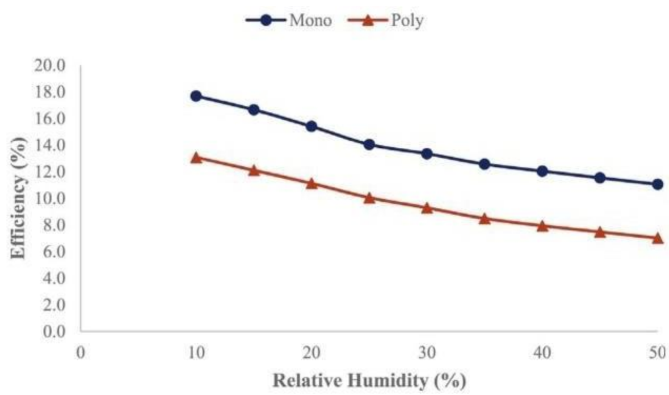

Figure 4. the impacts of relative humidity on the efficiency of the investigated solar modules [24] The x-axis is ascending.

-mono-crystalline silicon solar cell

In the relative humidity of 50%, the efficiency of the mono-crystalline solar cell is 11.1%. [24]

In the relative humidity of 10%, the efficiency of the mono-crystalline solar cell is 18%. The total decrease in efficiency is 6.9%. The efficiency decreased by 0.1725% per 1% increase in humidity.

-Polycrystalline silicon solar cell

In the relative humidity of 50%, the efficiency of the poly-crystalline solar cell is 7.0%.

In the relative humidity of 10%, the efficiency of the poly-crystalline solar cell is 13.1%. The total decrease in efficiency is 6.1%. The efficiency decreased by 0.1525% per 1% increase in humidity.

3.1.3. Shading

-Crystalline silicon solar cell

The experiment was set by Abhishek Kumar Tripathi, M.Aruna and Ch.S.N.Murthy. [25] Experiment Introduction:

An indoor laboratory study with constant solar irradiation $1190W/^2$. Under the same shading conditions

The total power input of Monocrystalline is $1190W/^2 \times 0.03565^2$=42.4235W The total power input of Polycrystalline is $1190W/^2 \times 0.035011^2$=41.66309W Solar cell:

Specification	Mono crystalline	Polycrystalline
Maximum power	5W	5W
Maximum voltage	9.64V	8.8V
Maximum current	0.52A	0.57A
Short circuit current	0.57A	0.65A
Open circuit voltage	11.57V	10.8V
Tol	(0 to ±3)%	0 to ±3)%
Dimension	23cm×15.5cm	22.3cm×15.7

Figure 5. technical specification of 5W PV panels [25]

Result explanation:

	Mono crystalline			Polycrystalline		
Shading strength	Reduction in I_{SC}	Reduction in V_{OC}	Reduction in P_{MAX}	Reduction in I_{SC}	Reduction in V_{OC}	Reduction in P_{MAX}
1.56	4.53	1.05	3.75	6.52	2.18	10.07
6.25	15.90	2.15	13.28	30.43	3.26	35.63
12.5	29.54	3.68	21.80	54.34	4.89	53.20
25	47.72	5.26	41.40	60.86	6.52	61.80

Figure 6. reduction in PV panel output parameters [25]

-mono-crystalline silicon solar cell

Table 1. efficiency of monocrystalline solar cell under the different useful power

Useful power	Efficiency%
4.8125W	11.34%
4.336W	10.22%
3.91W	9.22%
2.93W	6.91%

Total shades are 23.44%
Total decrease in efficiency is 4.43%
The efficiency decreased by 0.189% per 1% increase in shade.
-Polycrystalline silicon solar cell

Table 2. efficiency of polycrystalline solar cell under the different useful power

Useful power	Efficiency%
4.4965W	10.79%
3.2185W	7.73%
2.34W	5.62%
1.91W	4.58%

Total shades are 23.44%
Total decrease in efficiency is 6.21%
The efficiency decreased 0.26% per 1% increase in shade.

3.1.4. -Solar irradiation

-crystalline silicon solar cell

-monocrystalline silicon solar cell

The experiment set by Md. Nazrul Islam, Mohammad Ziaur Rahman, Sharif Mohammad Mominuzzaman. [26]

Experiment introduction:

Solar cell:

Shinew XH SERIES,Model:XH-36M-5	
Maximum power(Vmp)	5w
Open circuitVoltage(Voc)	21.47V
Short circuit current(Isc)	310m A
Voltage at Pmax	17.40 V
Current at Pmax	290 mA
Module dimensions	342×160×25mm
Module weight	0.8kg
Cell type	Mono crystalline
No.of cells	36 in series
Data measured in standard condition(STC):Irradiation 1000 W/m2,AM1.5,cell temperature 25^0C,Tested according to:IEC 61215 and IEC 61730	

Figure 7. major specification for the experimental module [26]

A pyranometer used to measure the solar radiation.

Result explanation:

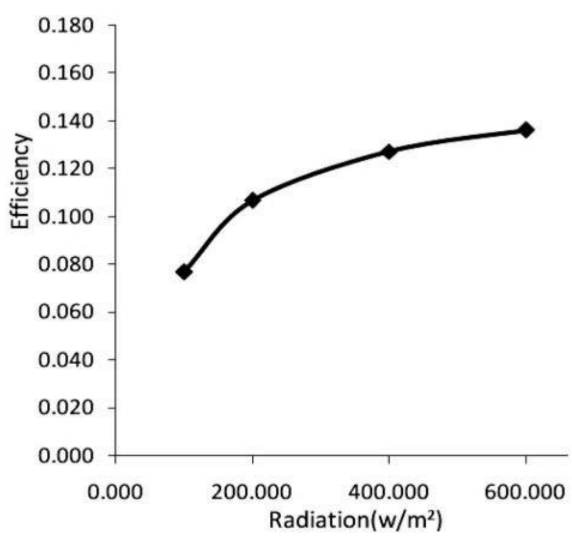

Figure 8. the radiation versus efficiency characteristics [26]

The x-axis is ascending

The maximum efficiency at radiation, $602W/^2$ is 13.6%. [26]

The minimum efficiency at radiation, $105W/^2$ is 7.7% (estimated from the graph)

The total increase in efficiency is 5.9% and the total increase in solar radiation is $497W/^2$. The efficiency increased 0.0119% per 1 increase in solar radiation.

-Polycrystalline silicon solar cell

The experiment set by Chengquan Xiao, Xuegong Yu, Deren Yang, and Duanlin Que [27] Experiment introduction:

Solar cell:

Sample	Resistivity (Ω cm)	B concentration (cm^{-3})	P concentration (cm^{-3})	O concentration (cm^{-3})
Reference	2.20	6.3×10^{15}	NA	1.0×10^{18}
C1	0.64	4.1×10^{16}	1.2×10^{16}	1.0×10^{18}
C2	2.84	1.1×10^{17}	9.1×10^{16}	1.0×10^{18}

Figure 9. detailed parameters of reference and compensated silicon wafers [27]

C1 and C2 are compensated silicon crystals with electronic grade silicon with B and P. These two solar cells can be determined as polycrystalline solar cells.

Therefore, I decided to use C1 as my object of study.

The irradiation range is from 100-1000 $W/^2$. The temperature was kept at 25℃ during the period of the measurement process.

Result explanation:

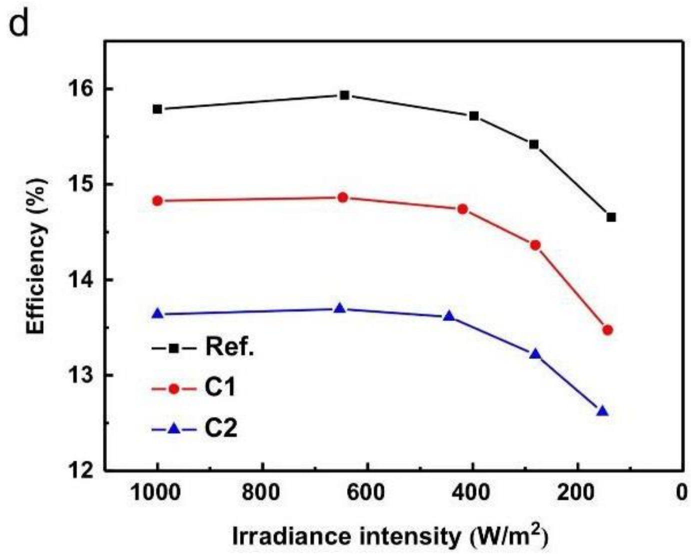

Figure 10. module irradiance intensity dependency for efficiency [27] x-axis is descending, from high numbers to small numbers.

The maximum efficiency at radiation, $1000W/^2$ is 14.8% The maximum efficiency at radiation, $100W/^2$ is 13.6% The total increase in efficiency is 1.2%.

The total increase in solar radiation is 900 $W/^2$.

The efficiency increased by 0.0013% per 1 increase in solar radiation.

3.2. Discussion

3.2.1. The most influential factor

Four influential variables have been discussed in the analysis part, for monocrystalline silicon solar cells and polycrystalline silicon solar cells have different extents of influence by those four variables. For temperature, when temperature increases by one Celsius degree, the efficiency of polycrystalline silicon solar cells decreases by 0.03775% and the efficiency of monocrystalline silicon solar cells decreases by 0.025%. In contrast, polycrystalline silicon solar cell has a more serious extent of influence of temperature change, by approximately 0.01275%. [28]. For humidity, when humidity increases by one percent, the efficiency of the monocrystalline silicon solar cells decreases by 0.1725% and the efficiency of the polycrystalline silicon solar cells decreases by 0.1525%. By contrast, monocrystalline silicon solar cell has a more significant extent of influence of humidity, by approximately 0.02%. [29] For shading, when shade increases by one percent, the efficiency of polycrystalline silicon solar cells decreases by 0.26% and the efficiency of monocrystalline silicon solar cells decreases by 0.189%. By contrast, polycrystalline silicon solar cell has a more significant extent of influence of shading, by approximately 0.071%. [30] For solar irradiation, when solar irradiation increases by one percent, the efficiency of monocrystalline silicon solar cells increases by 0.0119% , and the efficiency of polycrystalline silicon solar cells increases by 0.0013%. By contrast, monocrystalline silicon solar cell has a more significant extent of influence of solar irradiation, by approximately 0.0106%. [31] [32]

Table 3. Impact of Environmental Factors on Solar Cell Efficiency by Type of Material

Type of variable:	The most influential material:
Temperature	Polycrystalline silicon solar cell
Humidity	Monocrystalline silicon solar cell
Shading	Polycrystalline silicon solar cell
Solar irradiation	Monocrystalline silicon solar cell

3.2.2. The explanation for those effects is that the most important and physical basis of dependency

The explanation of the effect of **temperature** on solar cells. Temperature effects are the consequence of the connatural identity of crystalline silicon cell-based modules. A higher amount of voltage is produced by solar cells as the temperature decreases. In contrast, a lower amount of voltage is produced by solar cells as the temperature increases. [40]When the temperature increases, the band gap of the semiconductor is smaller, and the open circuit voltage drops due to the p-n junction voltage temperature dependency of open circuit voltage in the diode factor q/kT decreased. Furthermore, temperature has a negative coefficient of open circuit voltage. As the temperature rises, the charge carriers are released with a lower potential, so output power can be lower with the same amount of photocurrent. [33] [34] As the further increase in temperature, the band gap of the intrinsic semiconductor becomes small again, which means more incident energy is absorbed because more and more charge carriers are raised from the valence band to the conduction band by the increasing percentage of the energetic incident light. A larger photocurrent is the result of a further increase in temperature. Hence, the amount of short circuit current that is used for a given insulation increases. This effect can increase the theoretical maximum power according to the relationship, $_m$= short circuit current×open circuit voltage. [35]

A statement made by Valentine, Chigozie, and Godwill [36] is that both current and voltage have their maximum level for increasing. If the solar panel temperature increases over the level, current and voltage will decrease. Therefore, the power output decreases and efficiency decreases. When the current increases over a certain value then stops increasing and starts to decrease. This statement was proved by an experiment. When the solar panel temperature was about 43 ˚C, the current was increasing. Then the solar panel temperature increased over 43 ˚C, and the current started to decrease. Therefore, this phenomenon indicated that 43 ˚C is the maximum operating temperature of this photovoltaic module. Meanwhile, the temperature has a significant effect on voltage output. According to the experiment, when the temperature remains between 25 ˚C and 35 ˚C the voltage increases, but when the temperature is 44 ˚C the voltage drops. This also indicates the maximum operating of the photovoltaic module and expresses that the high temperature does not like to have high performance of the photovoltaic module. [36]

The surrounding temperature has a large difference to the temperature of solar cells. In summer, the average temperature is 40℃, the surface temperature can reach up to 70℃ after a period of time.

The effect on the cell temperature is very large with a long time of operating. Based on the theoretical knowledge, high temperature causes a high amount of output of current, the resistance will decrease, and the potential difference increases. The power will increase and then efficiency will increase. However, if the temperature is too high the performance of cells decreases, and the risk of short circuits increases. The performance of solar cells includes the abilities of the export currents and voltages to the whole PV system and the ability to convert solar energy to electricity. As a decrease in the performance of solar cells, the efficiency of solar cells must be decreased.

The explanation of the effect of **humidity** on solar cells. Two aspects that should be considered when the effect of humidity is analyzed. The first one is the extent of influence of solar irradiation level of sunlight experienced because of the water vapor particles, this influence is short-term. The second one is humidity invasion of the solar cells and this influence is long-term.

Three phenomena that will happen when the light hits the water droplets, which are refraction, reflection, and diffraction. These effects let the reception level of the direct component of solar irradiation decrease. Humidity changes the irradiation non-linearly. Open circuit voltage variances a litter within a non-linear manner and short circuit current variances a lot within a linear manner due to the irradiation. The significant effect of humidity on short circuit current causes a decrease in power output and efficiency. [37]

When PV cells are installed and exposed to humidity for a long period, there will be some reduction in performance. The encapsulant delamination appeared because of the high content of water vapor in the air. Generally, there are two main failure mechanisms, one is failure at cell interconnection cracked cells happens in crystalline silicon, and another happens in thin film modules. Humid weather can accelerate these deterioration processes. [38] Passivated PV cells' surface causes a degradation in short circuit current. Therefore, the following degradation of performance of the PV module. [39]

If a country has heavy clouds and haze all year round, the humidity will always be high. In the common condition, the density of water molecules existing in the air is smaller than the density of air. When the weather is heavy clouds or haze, the density of water molecules must be increased, hence, the density of air is decreased. The result is the atmospheric pressure is decreased. When the pressure is decreased, the water molecules cannot go up to the sky. The water molecules remain in the air. therefore, the percentage of water molecules in the air is getting higher. The relative humidity is increased. If the country has many rainy days all year around. There are many plashes in the roads, and the water levels of rivers or lakes increase. The sunlight time during the rainy period is short, so the original water molecules in the air cannot be evaporated, additionally, the evaporation of water cannot stop. The percentage of water molecules in the air remains high. So atmospheric pressure decreases, and the relative humidity is high. However, whatever the weather is cloudy or rainy, the temperature of modules can be lower and the increasing range of temperature would not be too large, in this way, the efficiency of the solar cell will not be reduced much because there is not enough light time. The dust also can be removed by rain, and the efficiency of PV modules will not be impacted.

The explanation of **shading** on solar cells. There are two main types of shading: subjective and objective shadings. Subjective shading is caused by shading objects due to the angle of the sun and objects that make the surface solar module dirty. Objective shading is caused by weather, like heavy clouds and haze. The sizes of the shaded cells can be different, it can partly and completely cover a single or several a cell, modules, arrays, and strings. [41] The strength of reception of irradiation controlled the amount of output power a PV system. The one of factors that can reduce the solar intensity of solar irradiation is a shade that appears on the surface of the panel. [42] For an array that is connected in parallel, a small shaded area leads to the total output drops to a fraction of rated power which causes the failure of the system. For an array that is connected in series, a small shade area lets the module lose the ability to produce the normal output power because of the inability of voltage production. In the series case, the unshaded modules will need to compensate for the voltage losses of entire the system, therefore this phenomenon makes less current and more reductions of power. Hence the efficiency of the PV module decreases. [43] [44] [45]

The explanation of **solar irradiation** on solar cells. In the experiment of the analysis I have quoted, the ambient temperature is controlled at 25℃. So, the result expressed that higher solar irradiation, higher efficiency. However, does solar irradiation have any influence on the ambient temperature? According to the result expressed by Maan J B Buni, Ali A. K. Al-Walie, and Kadhem A. N. Al- Asadi, solar irradiation has a direct effect on the temperature of the cell. As an increase in solar irradiation, the temperature of solar cells will increase. [46] Increase in solar irradiation does not mean the temperature increases. There are many effects that can cause an increase in temperature. However, in the real world, the variables cannot be controlled as well as in the lab. So, the temperature is increased as an increase in solar irradiation, but the extent of the increase in temperature depends on the locations and the climate type of the area. If the solar radiation is higher than the average level, and the temperature of this area is not very high, the efficiency of the solar PV modules is very high, for example, Xinjiang Tianshan, China. There are many areas like this nature, especially in some high-altitude areas, the temperature of this area is not high but the solar irradiation is very high. From this perspective, these areas are suitable for installing solar PV systems. On the other hand, the rise of solar irradiation increases the output current within a suitable range of cell temperature, because if the cell temperature is too high, it is too high to produce more current, therefore there is a decline in output current. The resulting voltage is not affected by the increase in output current significantly, but voltage gets larger with higher cell temperature. Lower currents and higher voltages cause a decline in the resulting power and efficiency. [46]

3.2.3. The best location for installation

One of the facts is that the shading effect is the most important variable. However, the shading effect is the most influential effect for all types of solar cells. The reason for this statement is the main function of solar panels that absorb light energy from the sun and convert the energy into electricity, but the direct acceptor which is the solar cell is shaded which means those shaded solar cells are operating nonnormally because there is none of the light radiation and light energy illuminate on the solar cell. Therefore, no electricity is converted to the bank battery on the shaded solar cells. So, the shading effect is the main effect for all solar cells need to be ignored.

Additionally, the dust effect can be classified as a shading effect. After a period of working time, the dust in the air and the dust are absorbed on the ground and other objects can be carried by air or blown to the solar panels by winds, and the intensity of light energy absorbed by solar cells decreases. If the extent of cover of dust is too deep, the solar panel cannot operate normally, it has the same result in shading effects. It is unsuitable to install solar panels in the desert areas. Users should clean the surface of solar panels termly if they do not install any cleaning system. After that, manufacturers should consider the second influential effect which is humidity. The humidity affects the solar by encapsulant delamination, that is disconnection between solar cells. The phenomenon of disconnection between cells disrupts current flows and then the following decrease in efficiency appears to be a common relationship between current and efficiency.

According to the effects of humidity, solar cells should be used in areas that have low levels of relative humidity. For Europe, Spain is a country with a low-humidity Mediterranean climate. When it is in summer the weather is hot and dry, while it is in winter the weather is mild. Cordaba is famous as the hottest and driest city in Europe. [47] As the reasons explained above, if the humidity is low, the temperature would like to be high, so the efficiency can be reduced by the high temperature. However, for only the aspects of humidity, solar cells are suitable to be used in Spain, where the weather conditions are relatively dry whatever is in which season.

According to the data above, humidity is one of the important effects, so countries that have a lower level of humidity are more suitable to install silicon solar panels. The daily temperatures in summer are always higher than 35℃.The operating temperature of modules has less amount of decrease in efficiency, but the value of the temperature of the module is usually higher than 40℃ after full-day operation, especially for the tropical zone. The PV module temperature may reach 60-65℃ when it is operated in summer noon time with high irradiation. [49] The best operating temperature of a solar system is 25℃, the actual operating temperature is much higher than the standard level. The flow of current causes the heating effects on the solar cell, and the temperature of the solar cell will increase by itself. So even it is operating in the winter, the effect of the high temperature of solar cells also influences the efficiency of solar cells. The additional increase in temperature enhances the influence of cell temperature on efficiency. Therefore, the increasing scale of the temperature of the module is always larger than any other changing scales of the other three variables. The total decrease in the efficiency of the temperature effect may be greater than the total decrease in the efficiency of other effects. Countries with high temperature are likely to install the solar PV systems. They have the high intensity of light and the illumination time is longer than other countries. The influences of effects of high temperature of modules on the efficiency of solar modules are more serious in these high-temperature countries. So, the temperature of the module is also an influential effect.

3.3. Improvement

3.3.1. Temperature of module

Almost every solar panel system has their own cooling system. Thermoelectric cooling system and floating tracking concentrating cooling (FTCC) are all the recent methods to cooling the system. [48]

- Floating tracking concentrating cooling (FTCC)

The artificial basins for installing PV floating plants are used for the achievement of optimal output power. There are three main components in the floating plants, PV modules, a set of reflectors and a solar tracking system. The goal of cooling of system can be achieved by water sprinklers. The floating plant contains a tracking system in order to positioning reflectors and also raise the radiation of solar panels. These plants are called FTCC. [48]

-Thermoelectric cooling system

This system is an additional part of the PV system. A heat sink is combined with a thermoelectric module. When the PV system is operated for a long period, the temperature increases. The heat dissipation of the PV module is done completely by the heat sink. The heat sink cooled down the surface of the PV module. [48]

However, the cooling system is operating normally, and the temperature of modules still is going to increase. So, I want to discuss about the direct and crude methods to decrease the temperature of modules.

-Ideal devices

To decrease or control the operating temperature, the direct method is to apply wind or cold air. In the real world, the range of applications is commercial and domestic. So, it is impossible to add a hundred air conditioners to cool the solar cells. So, the better method is the use of nature. Users can use the wind to let the temperature decrease. It is unpractical that there is enough amount of time for cooling by winds every day, especially for some areas that low wind velocity and if the area is summer now, the wind application is not enough. So, for some typical low-wind velocity countries, they can install some large-scale electric fans. By contrast, countries with high wind speeds are unlikely to install large-scale electric fans. A question is the following, where are the electric fans installed? If the electric fans are just installed standing on the rooftop or ground as usual, the shading areas must be increased. So, the electric fans should be installed in ingenious ways. The electric fans should be installed on one side of the rooftop. But this method is confined, it is effective for houses that have half of a rooftop. The energy supplied by the electric fans could be from a new solar photovoltaic system. However, users may want to use the energy supplied by the original solar system. A question occurs, the energy used to run the electric fans will be worth the efficiency increase due to the temperature reduction? The answer probably be yes. These electric fans are installed on one side of the rooftop, so there is no effect of shading on the efficiency of solar module. If users install other equipment, the shading effects will appear. The total amount of efficiency growth is greater than energy supplied to the electric fans. These electrical fans must be energy-efficient.

The second direct method is the use the water spraying. One water pipe was installed on the top of the each of PV modules. The water pipe can release many water droplets on the solar module. The water droplets flow on the PV module and the water usually is cold. The cooling water droplets can decrease the temperature of the PV module directly. The cooling component is the same as the heat sink, the surface area of the PV module. The release time should be regular. For example, in a tropical area, the gap in releasing time should be short. The time-lapse system is more convenient for users. Users do not need to look for the temperature condition of PV modules. Water is a limited natural resource, so the system should reduce the waste of water. Therefore, a water cycle system should be installed in the PV system. Another direct way to solve this problem is to use the rainwater. Users do not need to add water to the water cycle at some critical time. if the operating condition is very dry, the water droplets will evaporate rapidly. The water droplets cannot flow in the water cycle system. Hence, users can use rainwater for storage. Then the water can be used again and again. The diameter of the water pipe is small. If the diameter is too large the pipe may cause more shading areas on the solar modules, and the efficiency of the PV module will decrease. So, the suitable water pipe does not produce any shading area for the PV module. Users may be concerned about the water pipes are too small to the achieve the requirement of water. This question can be solved by increasing the number of watering holes. For some large-scale of installation of PV modules, the cost of adding water pipes to each single module are too high, so we can use sprinklers. The shape of the sprinklers is a cylindrical column. The installation of this column may cause some shading area for the PV modules. the efficiency is decreased following. So, we should minimize the shading area by reducing the diameter of the columns. The larger amount of water is used by cylindrical columns than used by water pipes. So, the time of spraying should be precise.

We can use a thermometer to measure the temperature of modules, if it is over than the operating temperature which can produce maximum efficiency, the working time of cylindrical sprinklers starts now. Users cannot measure the operating temperature every day, so we need to install a system that can test temperature timely and if the temperature is too high it can activate the sprinklers automatically. The whole system is called an automatic spraying column.

Some devices or operating systems are used to decrease the operating temperature of modules. The electricity for working all comes from PV modules. the small amount of useful energy and electricity produced by PV modules are transferred to households or commercial uses. The efficiency of PV modules will decrease. A question occurred, where does the electricity for sprayers come from? The electricity used for that spraying system could not be so large, the working time and working period is fixed or relatively short. For winter and autumn, the frequency of using those spraying systems is decreased. So, users or manufacturers prefer to add a separate PV module for the power supply of those sprayers. The scale of PV modules can be smaller. However, if the season is summer, a shortage of electrical supply to spraying system, users can use the electricity produced by the other modules. The sunshine duration of most countries is longer than in other seasons, so the demand for electricity declines.

4. Conclusion

The temperature of modules can be increased by itself or by the surrounding temperature, the extent of influences of temperature of modules has a reasonable increase. The effects of shading of solar cells always be the main reason for the decrease in the efficiency of solar cells due to the unoperated areas of solar cells and the decrease in the total output of energy. There are some influence factors that can affect more than one effects of solar cells, so there is a further decrease in the efficiency of solar cells due to the double effects on the solar cells. There are many influences factors that can increase the temperature of modules, so the temperature of modules is the most important effect of solar cells. Now, more and more countries choose to use solar photovoltaic systems be their major generator of energy due to the common development goal that environmental-friendly processes of energy production. The height of efficiency of one piece of equipment or a system is one of the major concern problems. In this article, it was already talked about the change in efficiency per increase in one unit of variables. These results are very useful to users and managers to consider about whether they are now in the right position to install such solar cells and help them decide whether monocrystalline silicon solar cells or polycrystalline solar cells can help them achieve maximum productivity. The government always subsidy some industries with environmental-friendly technologies. If the efficiency of the solar system increases, higher the possibility of reception of the subsidies by the government. Hence, the financial pressure of development of solar system is decreased and more and more firms want to produce the devices of solar system and use the energy generated by the solar system. Users can decide if they install some additional system to ignore the effects of the high temperature of solar cells. Based on my articles, users can know which factors can affect the efficiency of solar cells and how can they reduce the impact of these factors. There are many influential factors that can affect the temperature of module, humidity, shading area, and solar irradiation, so each factor can be discussed separately.

Furthermore, the influence principles of each of those influential factors are very meaningful to be researched. So, researchers can argue for different influential factors to create different improvement methods. I have already listed each component in the solar cells and solar system, researchers can analyze how those influential factors affect each component based on my technology literature. I have designed three schemes that can cope with the common effects of the temperature of solar cells, so researchers can ameliorate my schemes to match different situations.

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