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The Effects of Bypass Diodes on Partially Shaded Solar Panels

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ABSTRACT

This study seeks to determine the effects of partial shading on the power output of solar panels and to test the effectiveness of bypass diodes in minimizing these effects. The first part of the study focuses on determining the effect of partial shade on the energy output of a solar panel. The second part of this study is aimed at establishing the effect that partial shade has on solar panel power output. In this study, partial shade was found to reduce the amount of energy generated by solar panels when compared to the solar panel in fully exposed conditions. After conducting experiments and reviewing scholarly works, this study concludes that partial shading does decrease the power produced by the solar panels, thus reducing the amounts of energy produced. Moreover, this research establishes that bypass devices are effective in mitigating these effects, which can improve the performance of the solar panel arrays, increasing the overall efficiency of solar panel systems. This research may offer support for the creation of new solar panel technologies that are more effective and efficient and can better endure the effects of partial shading, ultimately resulting in a global adoption of solar energy as a workable and sustainable energy source.

Introduction

Global warming is perhaps one of the most prevalent concerns in the modern world. Humans are constantly impelling the increase of Earth's temperature mainly by burning fossil fuels and destroying ecosystems. Energy is essential for the modern way of life. The industrialization of the world and technological developments brought a higher energy need for the entire world (Demirtas, 2013). It is the utmost necessity for everything in a society. Energy is produced to power workplaces, heat and cool homes, transport individuals, manufacture products, and more. To produce this energy, fossil fuels, such as coal and oil, are burnt. By burning fossil fuels, humans are releasing greenhouse gasses, that contribute to global warming, into the atmosphere. Contrived greenhouse gasses join Earth's atmosphere and absorb heat, increasing Earth's temperature. Earth's increasing temperature, recalled by scientists as 'global climate change,' can cause numerous hassles including more frequent severe weather, higher sea levels, and increasing mortality rates. In order to live in a healthier, sustainable world, greenhouse gas emissions must be decreased. Since the production of energy by burning fossil fuels produces great amounts of greenhouse gasses, alternate forms of energy generation must be implemented into our society. Renewable energy technologies offer the promise of clean, abundant energy gathered from self-renewing resources such as the sun, wind, earth, and plants (Bull, 2021).

Solar Energy

Solar energy, among other renewable sources of energy, is a promising and freely available energy source for managing long term issues in energy crisis (Kannan & Vakeesan 2016). Solar energy is of great value to our modern world due to its many benefits. Amongst all of the benefits that come with solar energy, it being a renewable resource is one of the most important. Solar energy, being an interminable source, can be harnessed from any place with access to sunlight, every day of the year. The ability to never run out of this resource is perhaps the most important aspect in terms of sustainability and addressing present generational demands without jeopardizing future generational demands with regards to ecologic, environmental, and economic balance. Additionally, there is very little maintenance to be carried out on solar electric systems (Boxwell, 2021). Solar energy does not require heavy maintenance when compared to the maintenance required for other renewable energy sources such as wind, water, or nuclear energies. Fully incorporating solar energy into our society also comes with economic benefits. Adopting solar energy as a society will help create jobs dealing with the installation, manufacturing, and maintenance of solar energy systems. Furthermore, rising energy costs have allowed for solar power to become relatively cost effective over the years. Correspondingly, solar power is economically beneficial, as federal governments and global corporations are incentivizing the use of solar energy through grants, tax incentives and rebate programs. The solar industry would definitely be a superlative option for future energy demand since it is superior in terms of availability, cost effectiveness, accessibility, capacity, and efficiency compared to other renewable energy sources (Kannan & Vakeesan, 2016).

Solar Panels

Photovoltaic (PV) solar modules, commonly known as solar panels, generate electricity from the sun (Boxwell, 2021). Groups of PV cells are configured into modules and arrays, which can be used to power any number of electrical loads (Resch, 2007). Solar panels are configured in series circuits, where all components are connected end-to-end, establishing a single path for current to flow through. In a parallel circuit, conversely, all modules are linked across from each other, forming precisely two sets of electrically common points. In a series circuit, if one component is faulty, the rest of the circuit would be cut off since all the components in a series circuit are connected through a single path. This wouldn't be the case in a parallel circuit.

In a solar array with solar cells linked in series, you may determine the maximum amount of power and voltage the array will produce by adding the voltages and wattages of each cell individually. The greatest amount of electricity that a solar array will produce is determined by adding the average voltage of all the solar cells in a parallel configuration and the average wattage of each cell.

All countries have placed a high priority on emissions and the effects of electricity generation on the environment. Since the COP21 World Climate Summit, which took place in Paris in December 2015, nations have vowed to meet ambitious goals. A general consensus emerged what such an agreement needed to address: (a) long-term vision and direction for avoiding global warming over 2 C° or less, (b) equity and differentiation among countries, and (c) a binding process to periodically reviewing pledges and for transparent monitoring and reporting of national emissions (Clémençon, 2016). The energy sector reacted. The United Kingdom closed its coal-fired power plants years ahead of schedule, China is constructing and installing two grid-scale wind turbines each hour, and numerous businesses have committed to eliminating fossil fuels from their power mix over the next years. No method of generating electricity is completely eco-friendly, however. Waterways and surrounding fauna are impacted by hydroelectric power plants. Each year, a significant number of bird fatalities are caused by wind turbines. The carbon impact of building hydro, wind, or solar equipment must also be considered. Solar electric systems, the most optimal solution, are a low-carbon energy generator after they are established. Both sunlight and system maintenance are completely free. Solar panel production however has a carbon footprint, and historically this footprint has been fairly significant. This is mostly because of the low volume of panels produced and the chemicals needed to "dope" the silicon in the panels. Yet in the last few years, the carbon footprint of solar panels, appreciably, has been decreased as a result of better production methods and bigger quantities. The global photovoltaic sector has been growing at an average of over 40% in the last eight years, manufacturing over 2,200 megawatts in 2006 (Resch, 2007). Solar energy is proving to hold great potential for meeting the ambitious goals of reducing carbon emissions and combating climate change.

Output Measurements

Voltage, current, and power are essential concepts that play a critical role in the design and function of electrical circuits. A multimeter is a multipurpose tool that can be used to measure these properties.

The potential difference between two places is referred to as voltage. It is a measure of the energy required to move an electric charge between two points in a circuit. It is a key factor in determining the behavior and performance of electrical components. In simple terms, Voltage is a measurement of the potential energy of a circuit to cause an electric current or to give off power. A good example of this is an AA battery: the voltage is the difference between the positive tip and the negative end of the battery. Voltage is measured in volts and has the symbol 'V' (Boxwell, 2021). The flow of electric charge is essential for the operation of a wide range of electrical devices. In a circuit, current is a measure of the rate at which electric charges flow past a point in a circuit. This flow of electric charge is caused by a difference in electric potential, or voltage, between two points in a circuit. The sign for current is 'I', and its unit of measurement is amps. In solar panels, there occurs a constant current; a type of direct current (DC) that does not change in intensity with time. It occurs in series circuits according to Kirchhoff's current rule, which states that the total current entering a point in a circuit must be equal to the total current leaving that point. This is based on the conservation of energy principle, which states that energy cannot be created or destroyed, only transferred. Therefore, the current flowing into a circuit must be equal to the current flowing out of it, resulting in a constant current. Power is a measure of the rate at which electric energy is transferred. The greater the energy being transferred, the greater the power. It is denoted by the letter 'P' and is measured in watts. Energy is typically measured in joules (J), where one joule equals one watt-second.

Joule's law relates power, voltage, and current in an electrical circuit. This law is based on the principle of energy conservation. It states that the power (P) dissipated in an electrical circuit is equal to the product of the voltage (V) and the current (I), $P = V\ x\ I$. By applying this law in conjunction with measurements taken using a multimeter, researchers can examine circuits effectively.

Partial Shading

Numerous distinct solar cells make up a crystalline solar panel. Each of these cells typically produces a voltage of half a volt. To generate a high enough voltage in PV systems, several solar cells must be connected in series (Gallardo-Saaverrda & Kaslsson, 2018). One or more strings of these series-circuit arrays of solar cells make up each individual solar panel. The cell that gives the lowest current limits the string's current when the cells are joined in series (Gallardo-Saaverrda & Kaslsson, 2018). So, it can be said that solar panel's performance depends on the strength of its weakest cell because these strings of cells are interconnected in series-circuit arrays. All the cells in a string are compromised if one cell in the string provides a weak output. This implies that the output of the entire string of solar panels may be compromised if there is a "soft shadow" present, such as a faraway tree limb casting a gentle shade across only one or two cells. This is known as the partial shading of a solar panel.

Even if only a very small amount of the solar array is in shade, the impact on the performance of the whole system can have a very big effect. In contrast to solar thermal (hot water) systems, shading results in a significantly larger loss of power than the quantity of the panel that is shaded. Depending on the exact circumstances, even if only 5% of a photovoltaic solar panel is in shade, it is possible to lose 50–80% of power production from your entire solar array (Boxwell, 2021).

The increasing adoption of solar panel arrays as a renewable energy source has led to a growing concern regarding the partial shading of these panels. This topic is highly relevant and important in today's society, as more people are investing in solar panel systems to power their homes, businesses, and other buildings. According to studies, researchers believe that solar energy users could be losing about 40% of the potential energy of the solar array due to partial shading.

Bypass Diodes

Bypass diodes are electric devices that connect, in parallel, to each solar cell, and they provide a low-resistance path for the current to bypass the shaded cell. In other words, they connect arrays of solar cells in order to form a parallel circuit between the arrays. They are made of a semiconductor material, usually silicon, and they have a low forward voltage drop. When a shaded cell reduces its output voltage, the bypass diode turns on and diverts the current around the cell, allowing the other cells in the series to, in theory, continue producing electricity at their maximum output.

Moreover, when a solar cell is shaded, its output voltage drops, and it can no longer contribute to the overall power output of the module. This can cause a "hot spot" to form on the shaded cell, which can lead to thermal stress and ultimately damage the cell. The diversion of current caused by a bypass diode can help prevent a "hot spot" and protect the rest of the module from thermal stress.

The number of bypass diodes that can be used in a PV module depends on the design of the module and the shading conditions it will be exposed to. In general, modules that are more susceptible to shading can have more bypass diodes installed.

After thorough examination of scholarly works, it can be said that a proposed solution for the inefficiency of solar panels due to partial shading is installing bypass diodes, as it provides an alternate path for the current to flow when a solar cell is shaded.

Research Goals and Gaps

PV solar arrays are becoming an increasingly popular source of renewable energy. Additionally, the use of solar energy as a sustainable and environmentally friendly substitute for conventional energy sources is growing quickly. To maximize the potential of solar energy and implement solar arrays efficiently into our society, we must understand thoroughly what solar panels are and how they work. Numerous studies on the workings of solar panels have been conducted over the years. Scientists and researchers have run experiments, examined data, and produced a large number of publications and articles on solar panels' fundamental operating concepts, which entails the transformation of solar energy into electrical energy. More importantly, however, to sustainably implement the use of solar energy in our society, we must understand how to maximize PV solar modules' efficiency. Thus, there is a growing need for research to better understand the specific factors that impact their efficiency and performance.

Partial shading is one of these factors that has been proven to affect a solar panel's efficiency. While minor studies have been done on how shade affects solar panel performance, the majority have concentrated on full shading rather than partial shading. This creates a sizable research gap in our knowledge of the precise effects of partial shading on the performance of solar panels. There is an urgent need for further research to determine how partial shading affects the efficiency and output of solar panel arrays. Apart from being crucial for decision-makers and experts in the field to have a better understanding of the effects of partial shading on solar panel performance, this necessary research can help advise the design and installation of solar panel arrays, which can lead to more efficient and cost-effective use of solar energy.

In addition to this research gap, there is also a lack of understanding on the functionality of bypass diodes in reducing the negative effects of partial shade on the output of solar panels. Additional research is required to ascertain the precise efficiency of bypass diodes in reducing the detrimental effects of partial shade on solar panel output. Necessary research on this focus can help determine if bypass diodes are a viable solution to the concern of partial shading.

Goals

After carefully reviewing academic journals, and identifying a specific research gap, the goals for this study were established. This study seeks to first, test the effects of partial shading on the power output of solar panels and then, to test the effectiveness of bypass diodes in minimizing these effects.

Thoroughly testing the effects of partial shading on the power output of solar panels, enables us to understand how partial shading affects the overall efficiency of a PV solar system, and may allow us to design solar panel systems that are more resistant to shading. Power is the rate at which electrical energy is transferred; the greater the power produced by a solar panel, the more energy is transferred into the home or business. Therefore, understanding the effects of partial shade on the power output can also help to optimize the operation of existing PV solar systems, helping to improve the performance and efficiency of solar panels in the field.

In addition, this study also focuses on testing the effectiveness of bypass diodes in minimizing the effects of partial shade. Bypass diodes may be a viable solution to the problem of shading in PV solar systems. By testing the effectiveness of bypass diodes, this study will seek to understand the extent to which they can mitigate the effects of partial shading on power output and identify the conditions under which they are most effective.

This study will provide comprehensive insight that may have applications for enhancing the performance of solar panels in partially shaded conditions. Additionally, this research may offer support for the creation of solar panel technologies that are more effective and efficient and can better endure the effects of shading, ultimately resulting in a global adoption of solar energy as a workable and sustainable energy source.

Methodology

Part 1: Effects of Partial Shading

The first part of this study seeks to determine the effects of partial shading on the power output of solar panels. In order to test this, a quantitative experimental research design was used. This approach allowed for the accurate measurement and quantification of the effects of partial shading on the power output of a solar panel. The measurements taken and data gathered are used in a comparative analysis in which the power output of the solar panel in partially shaded conditions and in fully exposed conditions are compared.

The experiment consisted of a solar panel set up in a controlled environment. Data from the solar panel was collected using a multimeter, an instrument used to measure electrical properties. Measurements from the solar panel were taken in two different scenarios. The first being whilst the solar panel was in fully exposed conditions, meaning that all PV cells were fully exposed to sunlight. The second scenario being whilst the solar panel was in partially shaded conditions, in which about 10% of the solar array was deliberately shaded.

Data gathered from this experiment was unconditionally quantitative. The voltage and current of the solar panel were measured in volts and amperage, respectively. These measurements were taken in both scenarios using a multimeter.

Even though the solar panel was in a controlled environment, the weather and sunlight conditions may have had an effect on the output of the solar panel. Thus, measurements were taken repeatedly, throughout 5 different days, in order to reduce experimental error. Additionally, these measurements were taken at the same time each day (1:00 p.m.) in order to reduce the volatility to sunlight exposure.

After the data was obtained, Joule's law, which states that the power (P) is equal to the voltage (V) multiplied by the current (I), was used to calculate the power of the solar panel in watts.

$$P = VI$$

This allowed for the determination of the power output of the solar panel in both the shaded and fully exposed scenarios. By comparing the power output in these two scenarios, the effect that partial shade had on the power output of the solar panel is quantified.

Hypothesis 1

For the first part of the study, which seeks to determine the effects of partial shade on the power output of the solar panel, a solar panel with bypass diodes installed was used. Therefore, after scholarly works were read, the hypothesis proposed was that the power output of the solar panel would decrease in partially shaded conditions.

However, it was also proposed that this decrease in power output would be slight, so the solar panel would still be considered of valuable use. This is due to the fact that this part of the experiment considered the solar panel with bypass diodes installed. Moreover, the fact that this experiment deliberately shaded only 10% of the solar array contributed to this hypothesis.

Data 1

Table 1. Solar Panel Output in Fully Exposed Conditions.

	Voltage (V)	**Current (A)**	**Power (W)**
Day 1	166.2	1.45	240.99
Day 2	182.5	1.42	259.15
Day 3	172.9	1.4	242.06
Day 4	154.9	1.62	250.938
Day 5	167.3	1.43	239.239
Average	**168.8**	**1.46**	**246.48**

Note: Measurements of the voltage and current were taken using a multimeter, and Joule's Law was used to calculate power.

Table 1 shows the voltage and current of the solar panel that were measured using a multimeter while fully exposed to sunlight. These values were repeatedly measured throughout five different days in order to reduce experimental error. Additionally, the measurements were taken at the same time each day (1:00 p.m.) in order to reduce the volatility to sunlight exposure. The results were recorded and Joule's law, which states that power is equal to the voltage multiplied by the current, was used to calculate the power output of the solar panel in watts. The average measurement was found by adding all the individual measurements and dividing by the number of measurements, in this case 5. Thus, it was determined that the average power output of the solar panel in fully exposed conditions was 246.48 W. This data is used as a benchmark for comparison to power output in scenarios where shading was present.

The data in *Table 2* pertains to the solar panel in partially shaded conditions, in which about 10% of the solar array was shaded. Measurements of voltage and current were taken on five different days, at the same time each day (1:00 p.m.) in order to reduce experimental error by obtaining the measurements consistently. The results were recorded, and the average measurements were found. The power output of the solar panel was calculated using Joule's law. Thus, it was determined that the average power output of the solar panel in partially shaded conditions was 164.783 W. When this data is compared to the data collected on the solar panel under fully exposed conditions, the effect of shading on power output is understood.

Table 2. Solar Panel Output in Partially Shaded Conditions.

	Voltage (V)	Current (A)	Power (W)
Day 1	113.6	1.48	168.128
Day 2	119.6	1.31	156.676
Day 3	108.9	1.63	177.507
Day 4	116.1	1.38	160.218
Day 5	117.8	1.37	161.386
Average	**115.2**	**1.434**	**164.783**

Note: Measurements of the voltage and current were taken using a multimeter, and Joule's Law was used to calculate power.

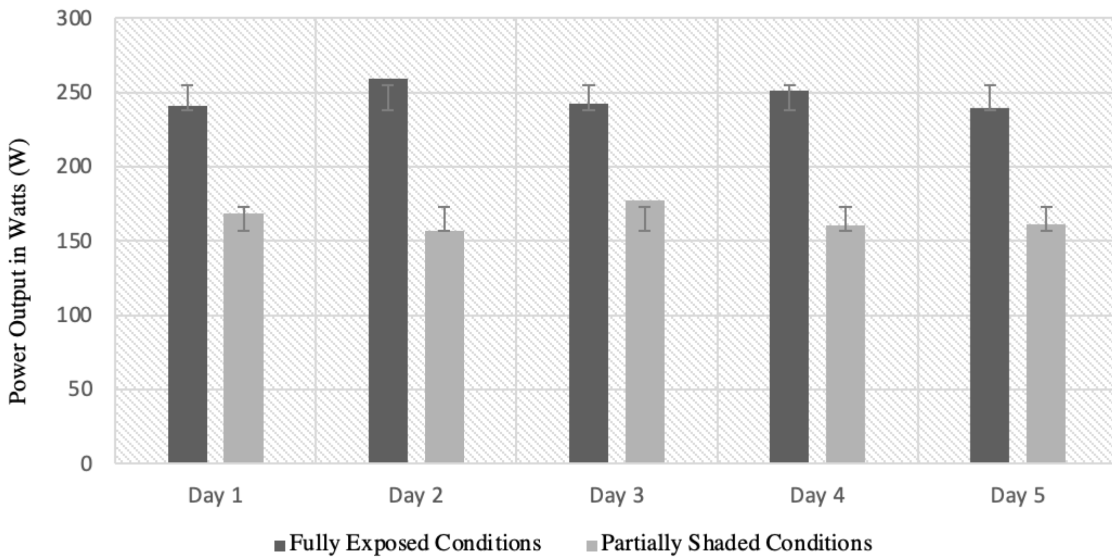

Figure 1. Power Output, in Watts, of Solar Panel in 2 Scenarios.

Figure 1 presents the power output in watts (W) of the solar panel in both scenarios. One being whilst the solar panel is fully exposed to sunlight, and the other whilst the solar panel is partially shaded. As seen from the figure, throughout all five trials, the power output of the solar panel expressively decreased in partially shaded conditions, when compared to the power output of the solar panel in fully exposed conditions. *Figure 1* also presents standard deviation error bars which quantifies the variation among the values. These SD error bars present an idea of how accurate the measurements are. As seen in the figure, the error bars present a very low margin of error. This minimal margin of error may be due to the volatility to sunlight exposure, or the accuracy of the multimeter used. Nonetheless, the fact that the power output of a solar panel is decreased in partial shade, is becoming realized.

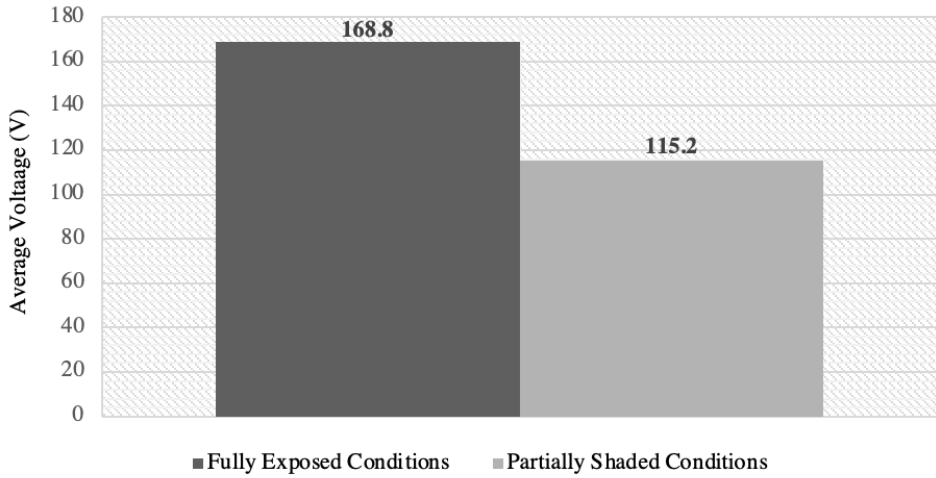

Figure 2. Average Voltage, in Volts, of Solar Panel in 2 Scenarios.

Figure 2 displays the average voltage, in volts, of the solar panel in fully exposed conditions and in partially shaded conditions. Voltage is a measurement of the potential energy of a circuit to produce power. As seen in the figure, the voltage in the partially shaded scenario is significantly less, meaning that the solar panel is less capable of producing power in partially shaded scenarios.

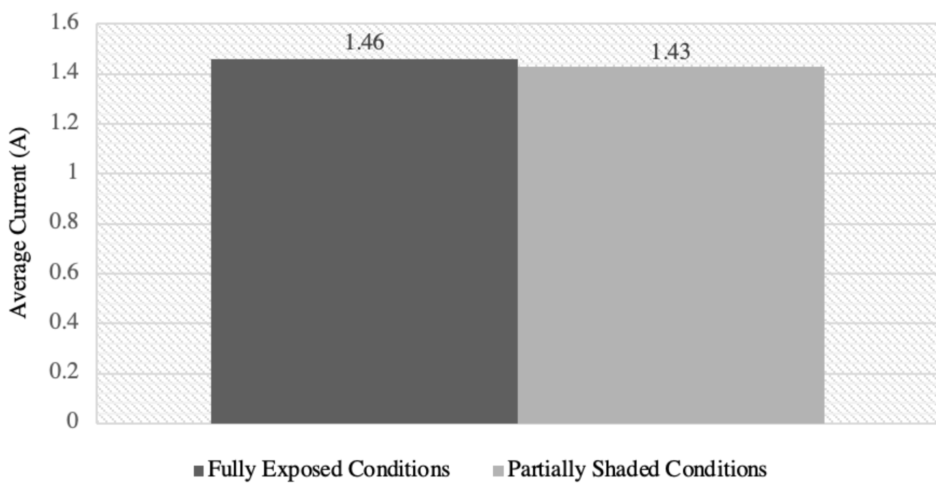

Figure 3. Average Current, in Amps, of Solar Panel in 2 Scenarios.

Figure 3 shows the average current, in amps, of the solar panel measured in fully exposed conditions and in partially shaded conditions. Current is a measure of the rate at which electrons flow past a point in an electrical circuit. As seen on the graph, the current is almost the same in both scenarios. This is because the current of the solar panel is constant. A constant current is a type of direct current (DC) that does not change its intensity with time, and it occurs in series circuits according to Kirchhoff's current rule and the conservation of energy principle.

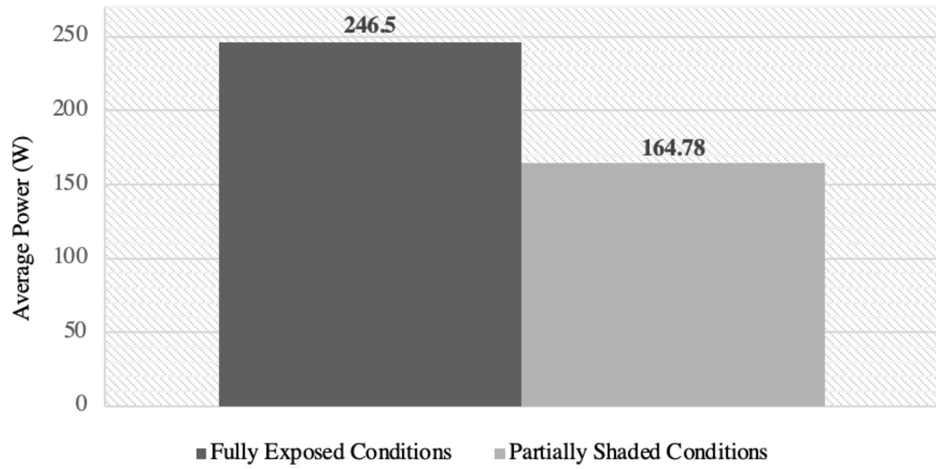

Figure 4. Average Power, in Watts, of Solar Panel in 2 Scenarios.

Figure 4 presents the average power output, in watts, of the solar panel in fully exposed conditions and in partially shaded conditions. Power is a measure of the rate at which electric energy is transferred. The larger the power generated by a solar panel, the greater the electrical energy transmitted into the home/business. As seen in *Figure 4*, the power produced by the solar panel in the partially shaded scenario is remarkably less. This means that a solar panel in partially shaded conditions will yield less energy when compared to a solar panel in fully exposed conditions.

Conclusions 1

After conducting research pertaining to the first part of this study, conclusions were drawn on the effects of partial shading on the power output of a solar panel. The data shows that even a small amount of shading can lead to a significant reduction in power output. The average decrease in power output under partially shaded conditions was determined to be approximately 32%, when compared to the power output in fully exposed conditions.

While this decrease in power output is significant, it is believed that the solar panel can still be of valuable use in day-to-day needs. To further this point, the average refrigerator typically requires between 100-250 watts of power to run. The average power output of the solar panel in fully exposed conditions and in partially shaded conditions was found to be 246.48 W and 164.783 W respectively. Thus, in both scenarios, the power output of the solar panel would be sufficient to power the refrigerator.

Additionally, it must be noted that this conclusion aligns with the hypothesis proposed at the beginning of the study, which expected a decrease in power output due to partial shading but establishing that the panel would still be of valuable use.

It also is important to note that this experiment was done on one type of solar panel and with specific shading conditions, therefore the results can be different for other types of solar panels or different shading conditions.

Nonetheless, this first part of the study provides a quantitative understanding of the effects of shading on solar panel performance and provided insights on the impact of shading on solar panel power output, which can inform future designs of solar panel systems and help to improve their performance and efficiency in the field.

Part 2: Effectiveness of Bypass Diodes

For the second part of the research, the effectiveness of bypass diodes in minimizing the effects of partial shading on solar panel power output was tested. A quantitative experimental research design was used, similar to the first part of this study. However, this time, the bypass diodes in the solar panel were removed in order to quantify their effectiveness. Measurements of voltage and current were taken on five different days in order to reduce experimental error and power was calculated using Joule's Law. These measurements were then compared to the results of the past experiment, which considered the solar panel with bypass diodes. This would make it possible to evaluate the extent to which the bypass diodes perform to reduce the impact of shading on the solar panel's power output.

Hypothesis 2

The second part of this study aimed to determine the effectiveness of bypass diodes in minimizing the effects of partial shading. Therefore, after scholarly works were read, the hypothesis proposed was that the power output of the solar panel without bypass diodes would decrease significantly in partially shaded conditions as compared to a solar panel with bypass diodes, under the same shading conditions, proving the effectiveness of the bypass diode. It was hypothesized that the presence of bypass diodes would greatly mitigate the effects of shading on the power output of solar panels.

Data 2

Table 3. Solar Panel, with No Bypass Diode, Output in Partially Shaded Conditions.

	Voltage (V)	Current (A)	Power (W)
Day 1	81.4	0.53	43.14
Day 2	86.9	0.40	34.76
Day 3	91.5	0.32	29.28
Day 4	87.8	0.38	33.36
Day 5	85.6	0.40	34.24
Average	**86.64**	**0.41**	**34.96**

Note: Measurements of the voltage and current were taken using a multimeter, and Joule's Law was used to calculate power.

Table 3 shows the output of the solar panel, with no bypass diodes, in partially shaded conditions. A result of measuring the voltage and current of the solar panel, with no bypass diodes, in partially shaded conditions, and calculating the power output using Joule's law, it was determined that the average power output of the solar panel, without bypass diodes, in partially shaded conditions was 34.96 W. These values are compared to values from the past experiment in order to quantify the effectiveness of the bypass diode.

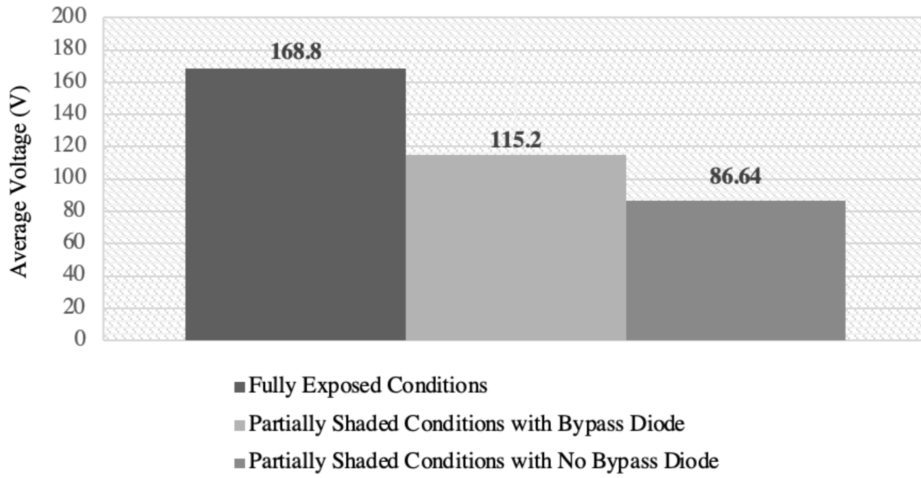

Figure 5. Comparative Analysis: Voltage (V).

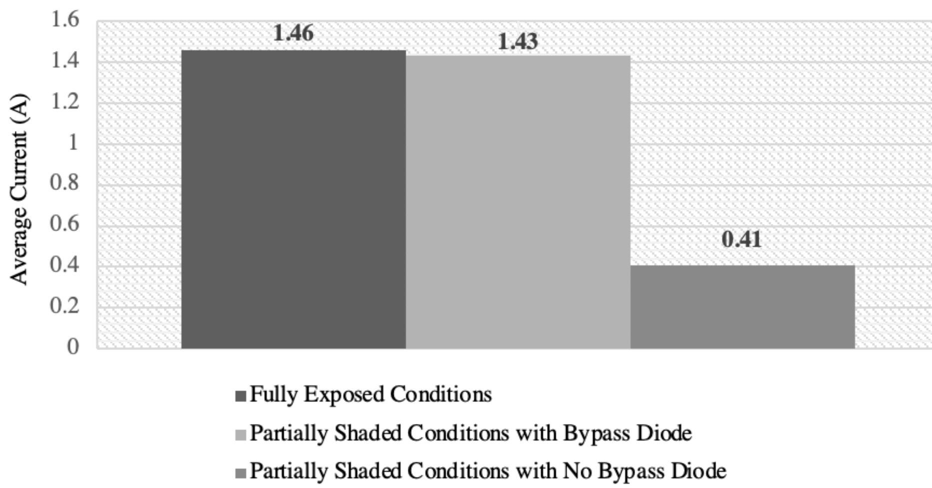

Figure 6. Comparative Analysis: Current (A).

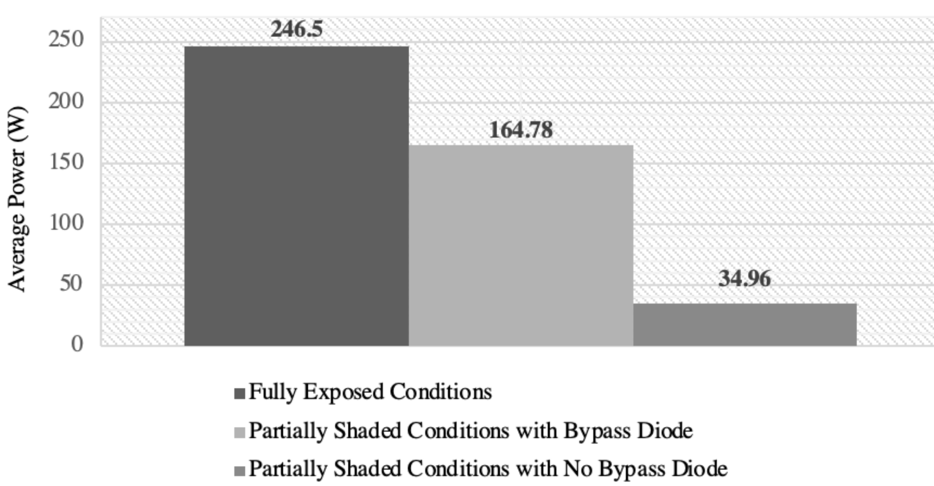

Figure 7. Comparative Analysis: Power (W).

Figure 5, Figure 6 and Figure 7 show the output of the solar panel in 3 different situations, one being in fully exposed conditions, another being in partially shaded conditions with bypass diodes present and the other being in partially shaded conditions without bypass diodes present. As seen in *Figure 5*, there was a significant decrease in the voltage of the solar panel in both partially shaded scenarios. When comparing the solar panel with and without bypass diodes in the same partially shaded conditions, it is seen from the figure that the voltage extensively decreases when no diodes are present. This means that the solar panel without bypass diodes is much less capable of producing power in a partially shaded scenario, when compared to a solar panel with diodes under the same shading conditions. As can be observed from *Figure 6,* the current remained constant whilst the solar panel was in fully exposed conditions and when the solar panel with bypass diodes was partially shaded. This is due to Kirchhoff's current rule which explains that in a DC circuit, there is a constant current that doesn't change its intensity with time. However, the current of the partially shaded solar panel with no bypass diodes decreased by about a third when compared to the current in the other two scenarios. This is because the shaded cells, arranged as a series circuit, prevented the electrons from flowing in the circuit, thus decreasing the current. As seen in *Figure 7,* the power produced by the solar panel with bypass diodes in the partially shaded scenario is about 30% less than the power produced in fully exposed conditions. Moreover, the power produced by the solar panel in partially shaded conditions without bypass diodes is about 85% less than the power produced in fully exposed conditions. This significant difference in power output, between the solar panel with and without bypass diodes in the same partially shaded conditions, proves the effectiveness of bypass diodes.

Conclusions 2

This conclusion regards the effectiveness of bypass diodes. After conducting extensive research, it is concluded that bypass diodes are effective in minimizing the effects of partial shading on the power output of a solar panel.

Table 4. Percentage Decrease in Power Output.

	Power Output (Watts)	**Decrease in Power (%)**
Fully Exposed Conditions	246.5	0%
Partially Shaded Conditions with Bypass Diode	164.78	34%
Partially Shaded Conditions with No Bypass Diode	34.96	86%

Note: The power output of the solar panel in fully exposed conditions was used as a benchmark. All decreases in power are compared to 246.5 W.

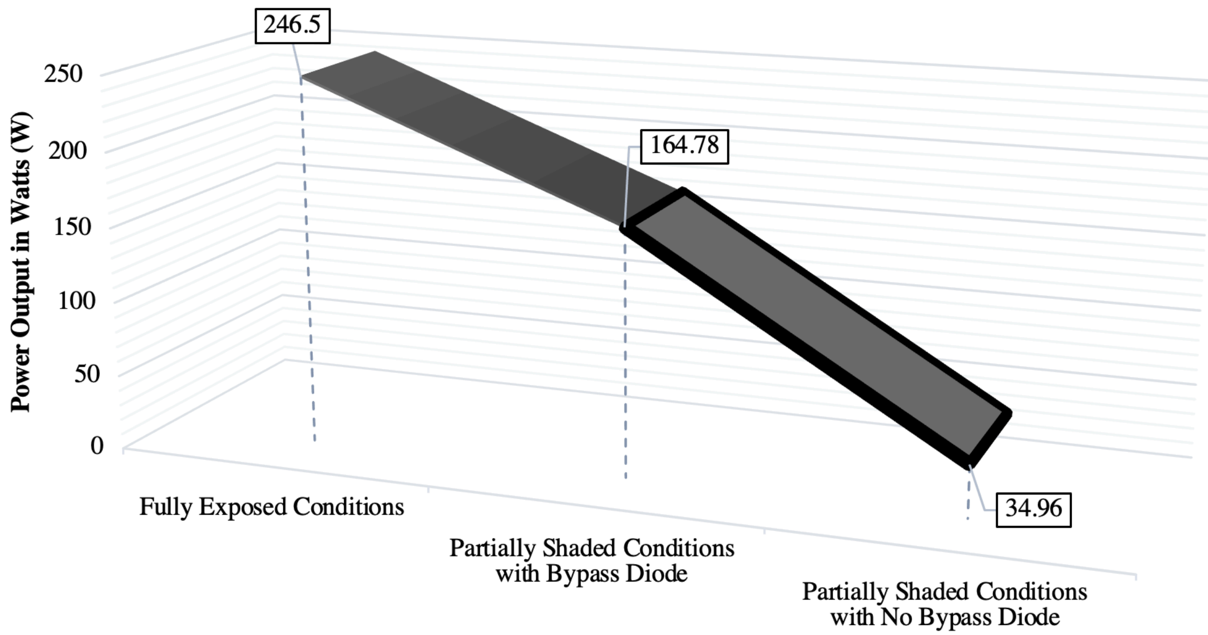

Figure 8. Decrease in Power Output. The outlined region represents the effectiveness of the bypass diode.

Table 4 demonstrates the differences in the decrease in power output of the solar panel concerning the three different scenarios. When compared to the solar panel in fully exposed conditions, it was found that the decrease in power output of the partially shaded solar panel with bypass diodes was 34% while that of the partially shaded solar panel without bypass diodes was 86%. This 52% difference represents the effectiveness of bypass diodes. In other words, bypass diodes were found to mitigate the effects of partial shading by 52%. Furthermore, the 52% difference in decrease in power output, between the solar panels with and without bypass diodes in partially shaded conditions, proves the effectiveness of bypass diodes in diminishing the effects of partial shading. This becomes relevant when solar array users rely on solar energy to power their homes/businesses. Solar panels with bypass diodes are much more reliable in partially shaded conditions. As seen in *Figure 8*, the 52% difference in decrease in power output, between the solar panel with and without bypass diodes in partially shaded conditions, is represented by the outlined region. It was found that a solar panel with bypass diodes in partially shaded conditions allows for 52% more electricity to be transferred into the home/business than a solar panel without bypass diodes in similar conditions. Solar panels with bypass diodes were found to be much more reliable in partially shaded conditions, as they produce more power, thus allowing for more electricity to be transferred. Lastly, this conclusion aligns with the hypothesis that bypass diodes efficiently decrease the effects of partial shading on the power output of PV solar arrays.

Discussion

New Understanding

After conducting experiments and reviewing scholarly works from credible sources, this study concludes that partial shade does decrease the power output of solar panels. Moreover, this study establishes that bypass diodes are effective in mitigating the effects of partial shading on the power output of solar panels. Thus, bypass diodes may be a viable solution that can improve solar modules' efficiency.

These conclusions recommend homeowners and business owners to adopt the use of bypass diodes into their solar array systems for more energy to be generated efficiently.

Limitations

As with all conclusions, there come limitations. The solar panels used to conduct this study were not of the highest quality, nor were they of the newest technology available. Additionally, the data obtained through this study may have been skewed due to the accuracy of the multimeter used. However, when comparing the data gathered, the conclusions drawn must be accurate since the same multimeter was used throughout the experiment. Lastly, the volatility of the exposure to sunlight of the solar panels may have led to defected data. In order to reduce this error, the experiment was repeated throughout 5 different days and the results were averaged. Additionally, measurements were taken at the same time (1:00 p.m.) each day in order to try and reduce the volatility of the exposure to sunlight.

Implications

This study recommends users of solar arrays to adopt the use of bypass diodes into their solar array systems for more energy to be generated efficiently. However, bypass diodes are susceptible to overheating, and this may cause them to explode, possibly resulting in a fire, damaging the solar array. It's also important to note that adding bypass diodes will increase the cost of the solar panel system, making it a rather expensive solution. Nonetheless, it is certainly a viable solution especially for systems where the solar arrays are expected to receive shade on a regular basis, such as systems near tall buildings or trees.

Extensions and Further Studies

Further research may be conducted on various factors regarding this topic, one of these being the economic factor. Researchers could study the cost-effectiveness of solar technologies and compare other technologies to the costs of bypass diodes. Additional, research could be done to determine the optimal placement of bypass diodes in a solar panel to minimize the impact of shading. Lastly, studies could be done to examine the performance of different types of solar panels, such as monocrystalline or polycrystalline, in partially shaded conditions.

Closing

Partial shading is a significant problem in today's society. More and more people are adopting the use of solar energy to power their homes and businesses. This study establishes the fact that partial shade reduces the power output of solar panels, thus reducing the amount of energy generated by solar arrays. This study goes on to prove that bypass diodes can significantly improve the performance of the solar panel arrays and increase the amount of energy produced in partially shaded conditions. Therefore, it can be concluded that bypass diodes are a viable solution that can mitigate the effects of partial shade on the power output of solar arrays, increasing the overall efficiency of solar panels.

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