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Does Arranging Solar Panels Vertically Mitigate Effects of Expansive Land Use?

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

When it comes to solving the ever more pressing problem of global warming, solar panels have a major flaw in the large land cost. As such, renewables such as solar panels must become more efficient in terms of land use. To evaluate a possible solution to this issue, namely, stacking solar panels vertically, we connected 4 solar panels to a trolling motor (load). Initially, all 4 panels were laid side-by-side, and voltage data of the load was collected. An extra solar panel was used to play the role of absolute standard for comparison. Then we stacked 4 panels on a wooden tower, the last panel serving as control, with 0, 3, 6, … and 18 inches of separation. Analysis of the initial side-by-side with temperature, humidity, and atmospheric pressure all confirmed that our system behaved as intended. We found that 18 inches of separation generated around 40% of the power of side-by-side while 15 inches generated around 65% across similar weather conditions. Naturally, 18 inches of separation should have generated more power than 15 inches. This discrepancy could be explained by the experiment being conducted later in the winter. As a result, we can conclude

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that vertical configurations could produce the same amount of energy as side-by-side with just 38% of the land and 50% extra cost. However, the true benefits could be even higher, considering multiple facets of the solar system.

Keywords: Land use reduction; solar energy; solar panel arrangement; vertical panel stacking.

1. INTRODUCTION

In Florida, the future of the youth who experience those same emotions under many unpredictable climate changes seems to become more dismal. In fact, for many around the world, problems caused by climate change have already begun to drastically endanger their lives. Tsunamis, hurricanes, and wildfires all become more and more severe every year. One crazy and unfortunate statistic on climate change is that 9 out of the last 10 years are within the 10 hottest years on record [1,2].

One of the leading approaches to the issue is renewable energy sources. However, renewables come with their own cornucopia of issues, specifically land use [3]. Even if society could solve all the global warming issues with renewables, what use would that be if the States would have to use “twice the landmass of Massachusetts” to achieve that goal [4]. Land is important. Natural beauty, like Yellowstone, Yosemite, and Glacier National Park are some of my favorite places in the world. But the everyday forests around me are just as important. It is not worth it to sacrifice these places for renewables [5]. Because then there will be nowhere for the children to enjoy fallen leaves and snowy days.

There are concerns that solar energy may take up a significant amount of land and cause land degradation or habitat loss for wildlife [6]. While solar PV systems can be fixed to already existing structures, larger utility-scale PV systems may require up to 3.5 to 10 acres per megawatt and CSP facilities require anywhere from 4 to 16.5 acres per megawatt [7]. However, the impact can be reduced by placing facilities in low-quality areas or along existing transportation and transmission corridors.

Specifically, land use required for solar is at least $10x$ as much as that for coal and oil, including the land used to transport, harvest and finally consume the latter [8]. What more is, coal plants are generally constructed in areas with little political power, meaning most of the public never feels their effect. Solar panels and other renewable sources, however, are installed in nearly every corner of the country. This brings about the problem of local opposition due to risk to local species, noise and impact on views [9]. On the number’s side: average coal/oil power plants range from $200\ Wm^{-2}$ to $1000\ Wm^{-2}$. This means powering the average household requires $2500\ W$ or $2.5\ m^2$ to $12.5\ m^2$ of area (average bathroom size to average bedroom size). Solar, on the other hand, has a density of $10\ Wm^{-2}$ in sunny areas. This requires $250\ m^2$ to power the average house, which is the size of a house. Plus, renewables are not consistent, as they must rely on the sun being out, which is not always the case [10].

Even when renewables such as solar energy are used in areas not occupied by humans (ie mountains, oceans, etc) there are many logistical issues and these projects often create environmental concerns for endangered species [11]. As such, it is absolutely critical that renewables such as solar panels become more efficient in terms of land use.

In this research paper, we seek to determine the validity of one proposed way to do so, that is to place solar panels vertically instead of side by side. In our stacked configuration, 4 solar panels will be placed horizontally in a wooden tower with 0 through 18 inches of separation between the panels.

This study partially builds off the work done by MIT in 2012. MIT created towers that had as much as 20 times the power output of standard configurations [12,13]. However, due to the high cost of their configuration, their towers were never commercially viable. In this paper, we attempt to examine a lower-density stacked configuration to reduce the increase in cost while still producing more energy.

By stacking solar panels instead of placing them in the horizontal configuration, they could use as little as ⅓ the land typically used by solar panels to generate the same amount of energy.

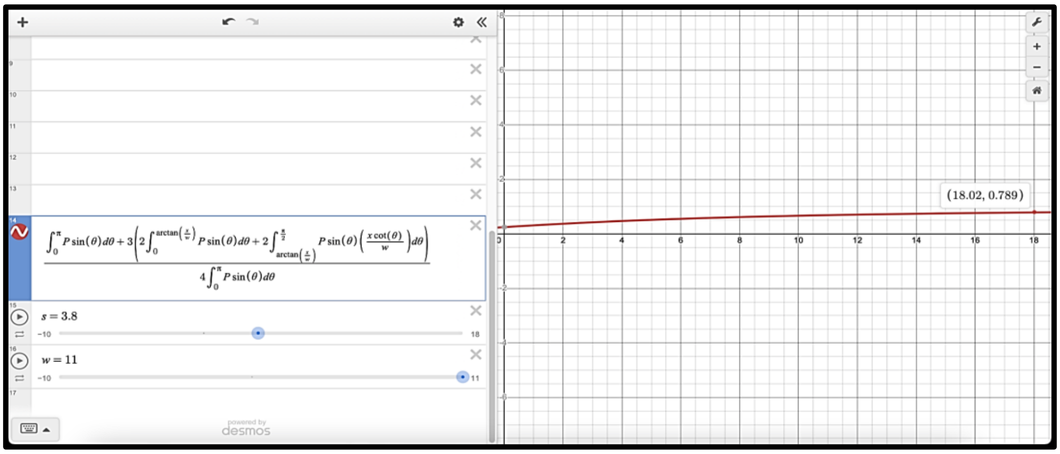

Fig. 1. Desmos graph showing an approximate function for efficiency of stacked apparatus with x inches of separation

Based on a simplified model of the sun's path, that is that the sun follows the highest arc in the sky, we can use mathematical models to predict the efficiency of the stacked model. Specifically, we can find the energy output of each individual solar panel by integrating the power from the sun with respect to angle. We also know power from the sun will be close to some constant P multiplied by sin(θ). Then, making the assumption that a shaded area does not produce any sunlight, we can also calculate the energy output from a solar panel that has another panel s inches above it.

To do this, we first integrate P*sin(θ) from the angle 0 to arctan(s/w) where w is the width of the panel (in our case 11 inches). This represents the frame in which the panel has no shade over it. Next, we integrate from arctan(s/w) to pi/2, the frame in which the panel is shaded. In this integral, we multiply P*sin(θ) by an additional s*cot(θ)/w, which represents the portion not shaded by the solar panel above. The above two calculations only calculate the energy output for half the day. Luckily, the other half is symmetrical, so we multiply all of that by 2 to find the full day. Finally, since we have 4 panels, we can sum one non-shaded panel's energy output with three shaded panel's energy output to find the total energy output of the stacked apparatus, and then divide that by the sum of four non-shaded panel's energy output to find the efficiency of the stacked apparatus.

Doing these calculations shows that 78.9% efficiency for a separation distance of 18 inches as shown below in Fig.1, 75.4% for a distance of 15 inches, 70.8% for a distance of 12 inches, 64.4% for 9 inches, 55.5% for 6 inches, 42.7% for 3 inches, and 25% for 0 inches.

That means at 15 inches approximately one third the amount of land would be needed in comparison to the typical side by side mode.

We actually contend the real system might be even more efficient than this mathematical model. For one, our assumption that the sun follows the highest arc in the sky is not always true. For lower arcs, our system would be more efficient as the effect of shading would be less. Additionally, shaded solar panels are not completely doing nothing, in fact a general rule of thumb is that shaded panels are still operating at 50% efficiency [14]. All of this could mean that stacked arrangement of panels could significantly improve on the land use of current solar panel arrangements.

2. EXPERIMENTAL METHODS

2.1 Detailed Material Descriptions

5 solar polycrystalline solar panels were purchased from Mighty Max (MFG, Part# MLS-2-WP, SKU 3829283). They were rated for maximal energy output of 20 watts, optimal operating voltage of 17.5V, optimal operating current of 1.14A, open-circuit voltage of 21.88V, and short-circuit current of 1.24A. Mighty Max Solar panels are typically used for RV solar energy, trolley motors, and other on and off-grid applications. 4 such panels were prepared with MC4 connections in parallel.

In addition, the solar charge controller 20A solar panel battery controller used in this study was a 12V/24V PWM solar controller intelligent regulator adjustable LCD with dual USB load timer setting on/off hours (Bienen Brand), solar-powered. And its operation voltage was 24 volts, connected to each part through a USB connector. The 20A Solar Charge controller was purchased from the Bienen solar charger company, which had UL 1741 certified. The solar charger controller is compatible with 12 and 24V systems. It operated with the discharge current of 10A, a built-in industrial microcontroller, and stand-alone controlled the function of solar panels and batteries in the solar energy system. Fully 3-stage PWM charge management maximized the system efficiency and enhanced the battery's lifespan. The charge regulator was solely manufactured for lead-acid batteries such as OPEN, AGM, and GEL. The nickel hydride, lithium, Li-ions, or other batteries should not be used with this unit. The solar controller was automatically powered off when the battery's voltage was recorded below 8V.

The DI-245 data acquisition system was purchased with a six-foot USB cable, a screwdriver for signal connections, an NIST-traceable calibration certificate, and appropriate software. It is internally wired with four differential and isolated analog input channels with programmable voltage and thermocouple measurements for each channel. And its voltage range was from 10 mV to 50 V with programmable support for type J, K, T, B, R, S, E, N thermocouples for individual channels. The sampling rate could be adjusted to 2000 Hz for a single channel and 200 Hz for more than two channels. Practically any measurement was enabled for a difference in ground potential between the instruments of the signal source and even among signal sources. Defined as common-mode voltages, these potential differences generated noisy backgrounds even in the best case, or worse damage to the electrical unit for some serious spikes when it was not specifically protected to overcome them. Each analog input of the DI-245 was electrically isolated from other channels and ground for safe and accurate measurements in the presence of common-mode voltages.

2.2 Materials Setup

2.2.1 Battery connection of solar panels

Four solar panels were connected in parallel to a rechargeable battery. Their voltage was maintained constantly, while the current should be accordingly added up and wired to charge the rechargeable battery via the solar charger controller. For the vertical arrangement of the four solar panels, a wooden tower assembly was created and placed in the backyard of a residential building in New City, New York, where the international latitude and longitude coordinates were 41.147594, -73.989304.

2.2.2 Structural tower for solar panel holder

A rectangular wooden structure of 200 cm in height was built with four chemically treated kinds of wood (3”x2”x86”) in which 24 holes were drilled for each of them and inserted with 5.0 cm long screws and nuts reinforced with washers. The screws were aligned inside each wood, as seen in Fig. 2a, and used to manage the gap distances and angles between the solar panels. Fig. 2a presents the view of our structure with a 15 inch gap vertically stacked.

Fig. 2a. Presents the vertical placement of four solar panels with 15 inches of separation

Fig. 2b. Presents the connections of the four solar panels side-by-side with the stacking tower on the side

As seen in Fig.2b, the four solar panels (#1, #2, #3, #4) were connected in parallel, while the standard solar panel (STD, #5) was not connected with the four solar panels but independently wired to the DI-245 for being used as a source of reference point. This setup was similarly used for both stacked and side-by-side configuration.

2.2.3 Diagrammatic presentation of electrical system

Our system was built, as illustrated in Fig. 2c. The solar panel controller and data acquisition matrix were connected to the system's three main parts for solar panel combinations, rechargeable battery and heater. The solar energy controller managed the distribution of electricity among the components. Meanwhile, the data acquisition analog/digital and multiplexer box DI-245 measured the electrical potentials as the voltage at the input and output point of the solar panel combination, rechargeable battery, and the electric load acquired while recording and displaying in a real-time mode on the monitor. The voltage levels were stored on a hard disk. The data was retrieved and analyzed with built-in statistical functions in the waveform browser (Dataq Instrument, Inc, Akron, Ohio).

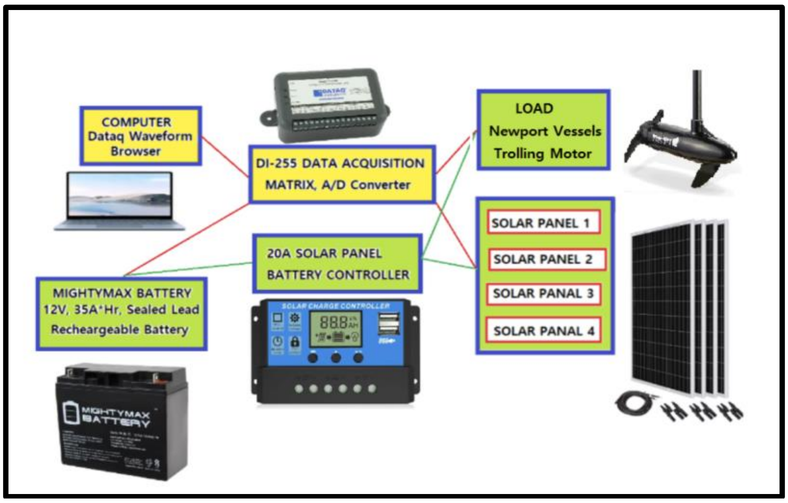

Fig. 2c. Illustrates the diagrammatic presentation of our electrical system

2.3 Baseline Study

In principle, the data was reported here with mean, standard deviation, and variance. As an example, observe Fig. 2d. The two show 24-hour waveforms. One statistic that is derived from these waveforms is the Voltage Output Area (VOA), which is calculated by integrating voltage with respect to time or summing the recorded voltages at one-second increments during the observation period, the observation period being one day.

Specifically, Fig. 2d presents the four channels of (1) voltage from four solar panels, (2) voltage from the single STD panel, (3) voltage from the battery, and (4) voltage from the trolling motor as the load on a sunny day. As seen, there can be large variations in voltage.

Therefore, it is important to confirm that our system works as intended. For this purpose, we perform a baseline study to compare VOA to various weather conditions. The quantitative measure of weather is made through the following measurements: humidity, atmospheric pressure, temperature, and weather index score. The weather index score was defined as adding scores of 5 when sunny, 4 when partly cloudy, 3 when partly sunny, 2 when cloudy, 1 when rainy or snowy from two sections of the day: midnight to noon and noon to midnight.

In order to conduct this baseline study, we place the four solar panels side by side, as shown in Fig. 2b. As shown, the STD panel is placed on the side. This should be similar to layouts in prior studies (see analysis). By comparing this baseline study to various study sets, we can confirm that our system works and proceed with further study. T-tests were carried out when necessary.

2.4 Novel Study

In our novel study, the four panels will be placed in the structural tower, as shown in Fig. 2a. All other conditions, including but not limited to electrical connections, will remain the same as the side-by-side construct. Panels will initially have a 9" gap between them and, by the end of the study, will have had 0", 6", 9", 12", 15" and 18" gaps. Each gap will maintain the same for around 2 weeks. In order to compare these studies to the side-by-side study, we will consider the voltage of the Trolling Motor Load and average the Voltage Output Area across the studies.

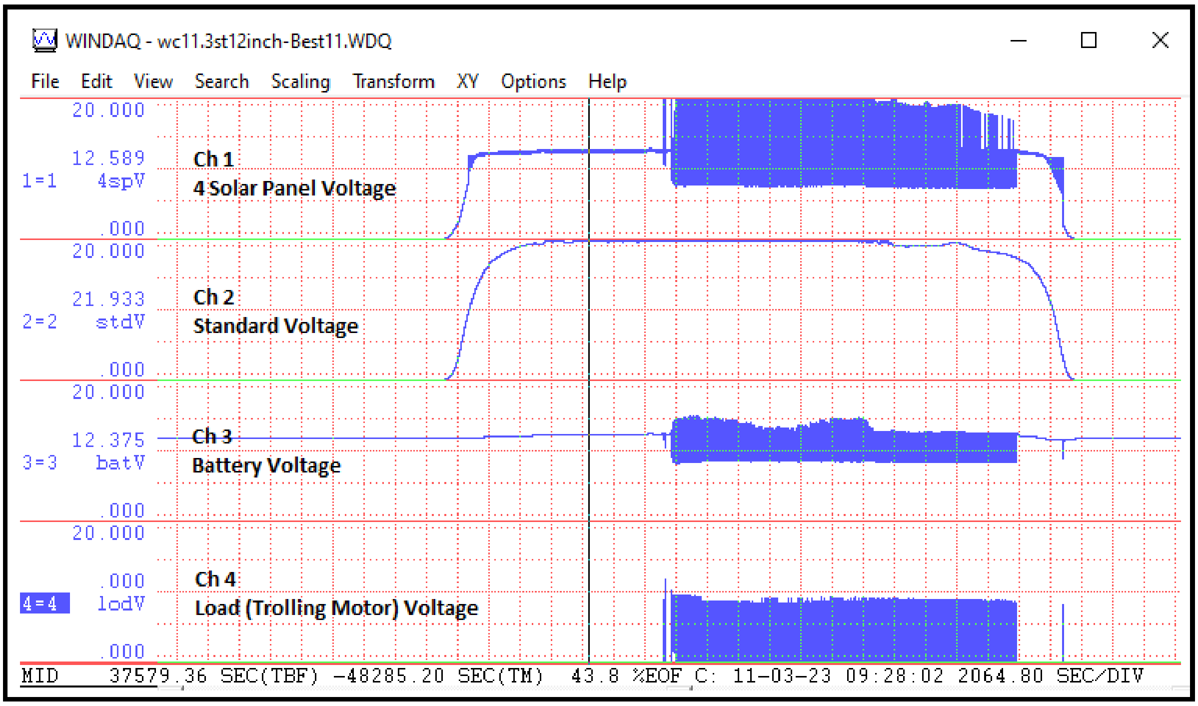

Fig. 2d. Compressed waveforms from a four-channel data acquisition system acquired on a sunny day

3. RESULTS AND DISCUSSION

3.1 Baseline Study

3.1.1 Voltage output area with temperature

It must be intriguing to know the relation of solar energy generation with temperature. As expected, the potential output area from the four solar panels in a side-by-side arrangement should be correlated to the temperature each day [15], as shown in Fig. 3a. Specifically, temperature and VOA should be linearly correlated.

3.1.2 Voltage output area with atmospheric pressure

In Dr. Amajama's 2016 study [16], he finds that both voltage and current in solar panels should be positively and linearly correlated to Atmospheric Pressure. Since our load can be approximated as a resistor, we should find that the square of the load voltage is proportional to the current times voltage of the solar panels. In other words, the voltage output area of the load should be positively and linearly correlated to atmospheric pressure as well. This result is confirmed by our study, as shown in Fig.3b.

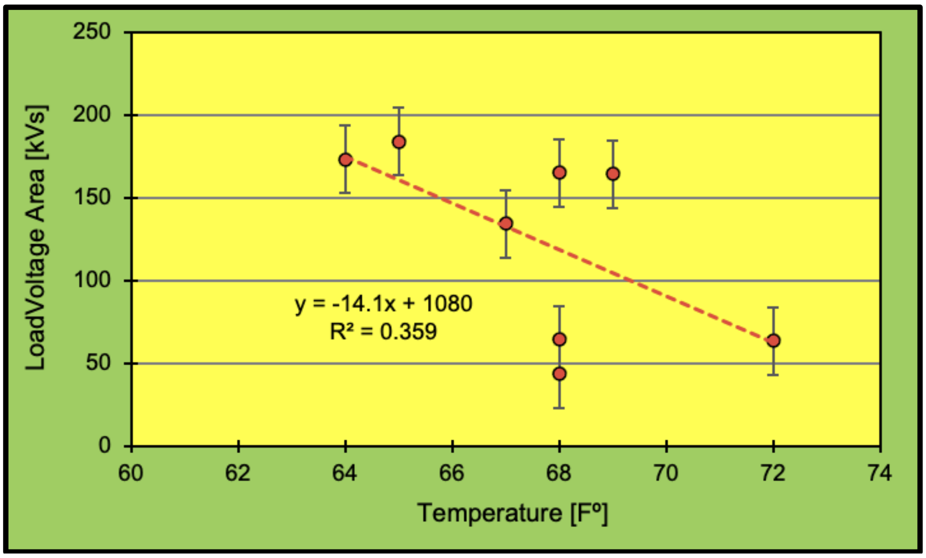

Fig. 3a. shows the load voltage area drawn for daily low-temperature

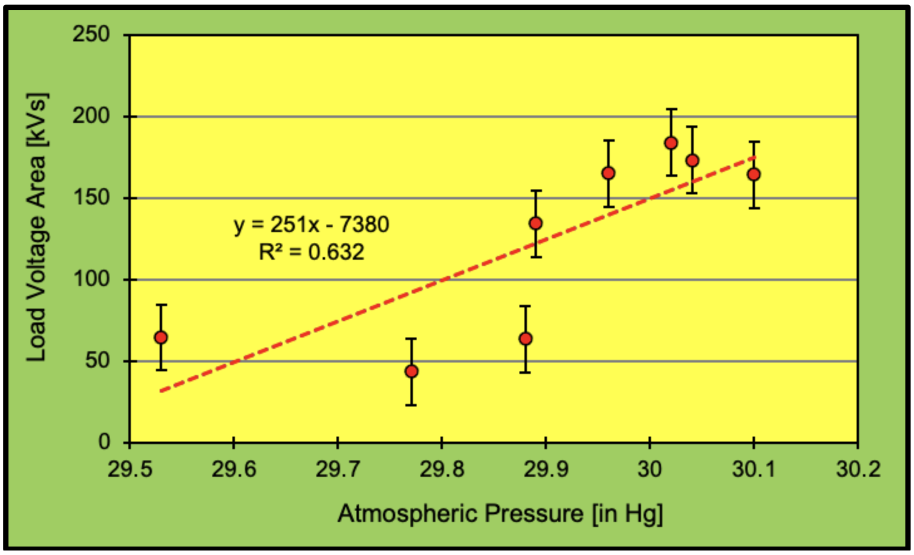

Fig. 3b. Shows the Load Voltage Area drawn for daily atmospheric pressure

3.1.3 Voltage output area with humidity

In Dr. Panjwani's 2014 study [17] on the relationship between humidity, voltage, and current. A very complicated relationship was found for voltage. However, this relationship can be approximated as negative and linear for a normal range of humidity, although the relationship initially appears to be quadratic. Since the current was negatively and linearly correlated. As before, with atmospheric pressure, we should expect the load voltage area to be negatively and linearly correlated. This is confirmed by our study as in Fig.3c on the subsequent page.

3.1.4 Voltage output area with weather index

The Weather Index was defined as the sum of the score given to the weather from midnight to noon and the score given to the weather from noon to midnight. Sunny was given a score of 5, mostly sunny was given a score of 4, mostly cloudy was given a score of 3, cloudy was given a score of 2, and any precipitation was given a score of 1. Although there could be large variations due to weather before sunrise and after sunset and the score being non-analog, we should still expect the load voltage area to generally rise with the weather index. This result is confirmed, as shown in Fig.3d on the subsequent page.

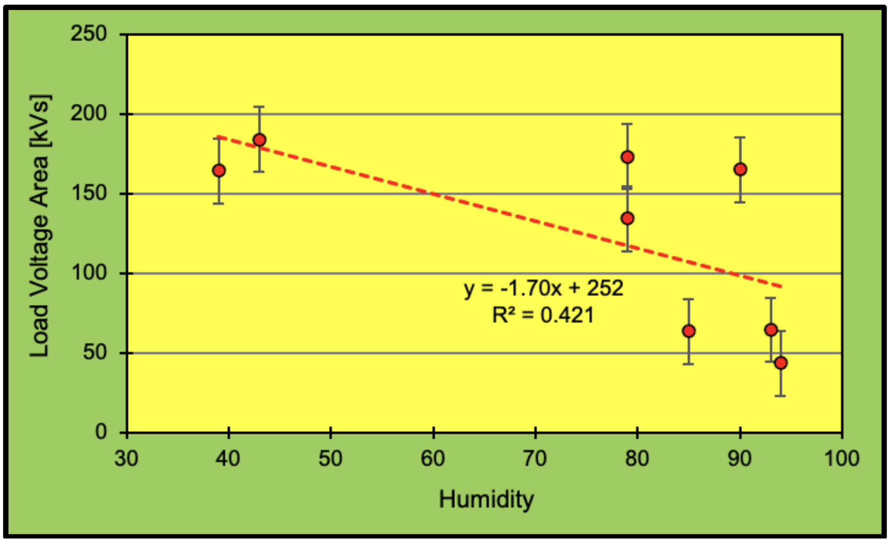

Fig. 3c. Shows the Load Voltage Area drawn for daily humidity

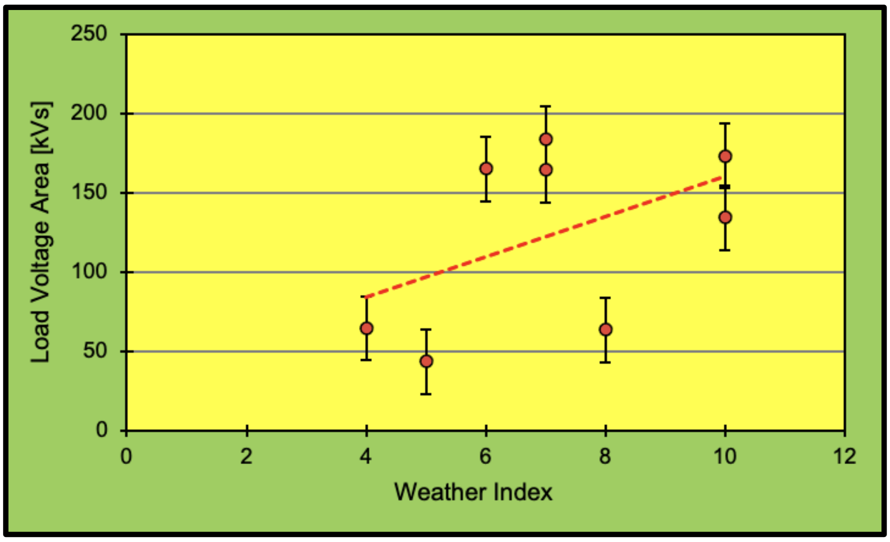

Fig. 3d. Shows the load voltage area drawn for daily humidity

3.1.5 Concluding discussion of baseline study

One particularly strange occurrence during the baseline study was a week-long period where the load did no work, and the ratio of 4-panel voltage to control panel voltage was significantly higher. These phenomena are shown in Fig. 3e and Fig. 3f, respectively.

Although it is plausible that the load does not work, the ratio between the 4 panels and the control panel should remain constant regardless of weather conditions. However, interestingly, when comparing these days of higher 4-panel voltage to control panel voltage ratio, they tend to be cloudy and/or rainy days. This leads us to believe that there is a minimum requirement of sunlight input for the load to operate. As a result, we decided to only consider days when this minimum is met because the 2 to 3 weeks that this experiment was conducted under was insufficient to normalize the weather conditions. Initially, we attempted to remove days based on weather. However, we quickly found that no one weather condition was a good indicator of whether the minimum would be met. As a result, we found a better way to determine this: to remove all days with an abnormal side-by-side ratio to control. We performed this removal for all subsequent stacked studies as well.

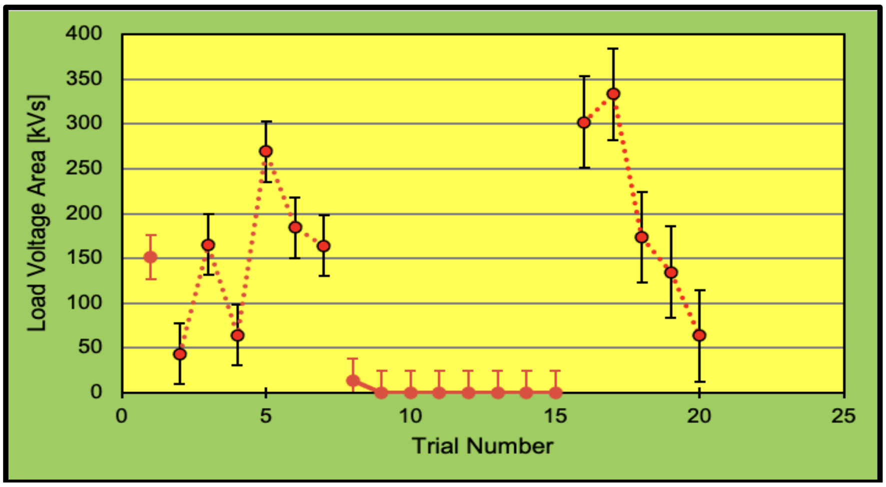

Fig. 3e. Shows the Load Voltage Area dropping to 0 for a week-long period during the side-by-side trial

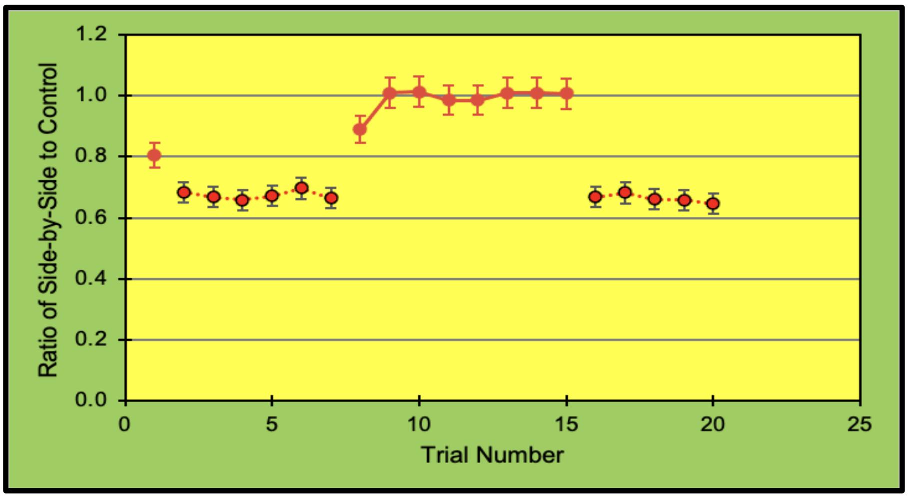

Fig. 3f. Shows the ratio between the 4-panel voltage and control voltage rising significantly for the same period

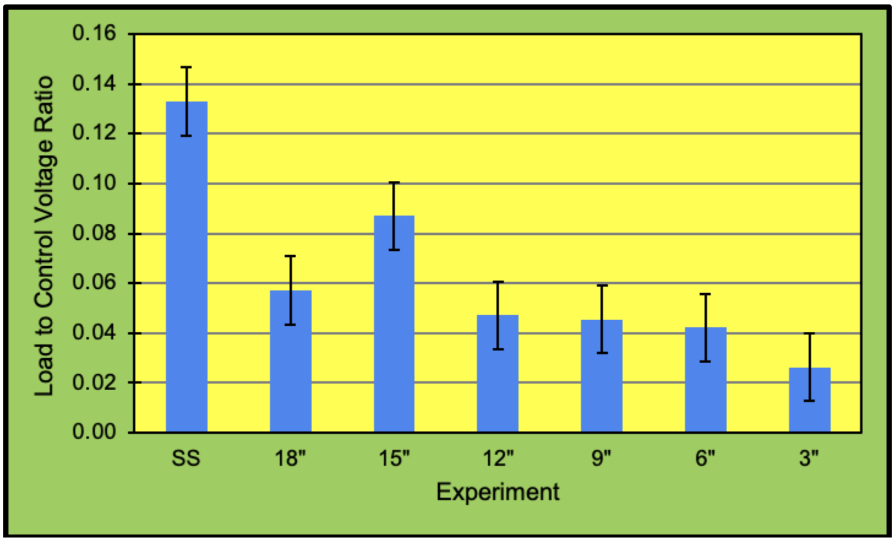

Fig. 4. presents the relation of load to control voltage ratio to the experiment type

3.2 Potential Output Area between Side-by-Side and Stacking Arrangements

In order to best balance the Load Voltage Area for weather conditions, we took the Load Voltage Area's ratio to the voltage of the control solar panel. This should help stabilize the load voltage area despite weather conditions. We then averaged this ratio across the duration of each side-by-side or stacked study in order to create a comparative index for each study. This resulted in an index of 0.133 for the side-by-side study, an index of 0.0572 for the 18" stacked, an index of 0.0869 for the 15" stacked, an index of 0.0471 for the 12" stacked, an index of 0.0455 for the 9" stacked, an index of 0.0422 for the 6" stacked, an index of 0.0264 for the 3" stacked. These indexes are graphed in Fig.4 below. Also note that the 0" stacked index was 0.0186 for 0" stacked, not shown on the graph below.

4. CONCLUSION

Purely quantitatively, the 15-inch experiment, which was the most efficient out of all the stacked configurations, achieved a ratio between load voltage and control voltage of 0.0869. Comparatively, the side-by-side had a ratio of 0.133. This means that the most efficient stacked configuration was 65% as efficient as the side-by-side configuration. Assuming two adjacent stacked towers would not interfere with each other, placing stacked towers would result in 260% of the power output of side-by-side panels. Another way to say this is that stacked towers could use just 38% of the land use of typical solar panels and produce the same amount of energy. Additionally, saving this 62% of the land would only come at a 50% cost increase!

The study contends that the savings due to stacking solar panels could be even higher. Our results found that the 15" stacked configuration results in greater power output than the 18" configuration. This is partly due to better weather but mostly because of the angle of the sun in the sky. Since the side-by-side study was conducted first, it would have the greatest angle in the sky and a large increase compared to the other studies, as power is a function of the sunlight's angle to the panel. This is especially evident in the discrepancy between the side-by-side study and the 0" study. The side-by-side study was conducted when the sun was near its highest angle in the sky at the location of the study. The 0" in meanwhile was conducted when the sun was near its lowest angle in the sky. Typically, we should find that the output of the single solar panel would be ⅖ that of the side-by-side (considering the output of the control as well). However, the ratio of 0.0186 to 0.133 is clearly much less than the expected ⅖.

Despite this 15" still reached a whopping 65% efficiency. Had the 18" study been conducted at the same time, it likely could have reached a 70% efficiency. If it had been conducted at the same time as the side-by-side, perhaps as much as 75% could have been possible. These numbers are not as great as first hypothesized, but are still significant and could be useful in new solar systems. In addition, the full extent of benefit given by stacking solar panels is not on display here. For example, stacked panels offer additional protection against precipitation as only the top panel is affected.

Ultimately, this study shows that stacking solar panels is feasible. This new technology could be used to reduce the size of solar farms or increase the efficiency per unit of land of ones that are constrained in space.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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