

# Photovoltaic Integration in Vertical Hydroponic Systems: Performance, Optimization, and Feasibility

Neil Anand, Alaina Wenitsky, Kai Haavik, Alaina Welser

## Abstract

The project investigates the integration of solar energy with hydroponic units to optimize energy efficiency and sustainability in modern agriculture. By measuring the energy consumption of 2 hydroponic units under varying light, pump, and nutrient delivery cycles, the research quantifies baseline energy demands. An educational solar unit was deployed and tested, incorporating a very small photovoltaic (PV) panel with dielectric lighting, enabling partial to full autonomy from grid electricity. Analysis based on power output revealed that residential solar panels have true feasibility for integration with small-scale hydroponic systems. By combining real-time energy monitoring with plant growth metrics, the study provides a quantitative framework for designing scalable, solar-powered hydroponic systems that are both cost efficient and more sustainable than traditional agricultural techniques. Strategies for PV integration in local and international hydroponic farms are discussed, as well as theoretical optimizations for solar power output. This research demonstrates a pathway toward fully sustainable vertical agriculture solutions and establishes a baseline for an energy-efficient system design, with potential applications in urban farming and modern agriculture.

## Introduction

By 2050, the United Nations projects a world population of more than 9 billion people (Velazquez-Gonzalez 2022), with about 66% of that population residing in urban areas (Treftz and Omaye 2016). As the population grows and cities increase in density, global food production must increase to meet demands, further stressing arable land. Agriculture currently accounts for about 70% of global freshwater use and 30% of energy consumption (Haryanto 2024), putting stress on freshwater systems and power grids. These resources are required in the production and storage of traditional agriculture, creating significant need for more modernized farming systems. In addition, Arable land continues to become unusable considering climate change, pesticide contamination, and diseases in soils (Treftz and Omaye 2016) while global need for fresh food continues to grow. Sustainable solutions to this scarcity must reduce energy use and emissions while providing easily accessible food for an increasingly urban global population, all of which are addressed in hydroponically grown produce.

Hydroponics is a form of agriculture that provides plants with nutrients through water as opposed to soil (Treftz and Omaye 2016). These systems essentially remove the use of soil entirely, submerging plants in nutrient dense water as a substitute. Through a series of water reservoirs, pumps, and automated growth controls, hydroponically grown plants access their necessities while saving soil, land, and avoiding lethal plant diseases. This lack of need for soil allows for crops to be grown in deserts and cities, expanding access to produce. Additionally, vertical hydroponic systems have reduced land-use, making them viable for densely packed communities.

In terms of production, hydroponic systems can control the variables of temperature, humidity, light, and root environments (Treftz and Omaye 2016), allowing for optimal growth conditions. Controlled conditions reduce the concern of soil-borne diseases and pests, thereby limiting the needs for pesticides. Types of crops are not limited by nutrient availability in the soil, eliminating the traditional agriculture consideration of crop rotation. Therefore, communities can grow the kinds of plants they need without the concern of strain on the land.

Hydroponics also addresses the issue of agriculture's contributions to climate change, specifically regarding water use and greenhouse gas emissions. Hydroponic lettuce in particular uses 10% of the water compared to traditionally grown lettuce (Treftz and Omaye 2016), mostly due to the system's inherent lack of waste in recirculating water. Evaporation is also minimized in this closed system, reducing the strain on viable drinking water. Additionally, traditionally grown crops from large farms can travel between 1500 and 3000 miles before reaching consumers (Treftz and Omaye 2016), leading to high costs of travel, transportation emissions, and a lack of fresh food for most of the population. Transportation accounts for 16% of all food production energy use (Treftz and Omaye 2016), further contributing to the positive feedback loop of climate change and its impact on food production systems. Growing produce locally through hydroponics reduces travel time and supports the economies of the communities producing the food, allowing for fresh, less energy-intensive food at reduced costs.

Despite these benefits, for hydroponics to be implemented on a larger scale, limitations in energy intensiveness and high upfront costs must be addressed. Heating, ventilation, water pumps, lights, and all aspects of creating a controlled environment require constant energy use and a high initial investment in

materials. Energy efficiency is therefore the next step in improving sustainable food production systems, a process that can be approached through the use of solar panels.

Close to 90% of costs associated with hydroponic lettuce are energy and labor (Treftz and Omaye 2016), meaning that alternative sources of energy could have significant influence on improving agricultural sustainability. In a study conducted between April and October of 2024, researchers at Muhammadiyah University of Jakarta partnered with the Independent Agricultural and Rural Training Center in Indonesia to apply solar panels to a vertical hydroponic system of spinach plants (Haryanto 2024). With an unreliable energy source due to frequent power outages and a loss of profit due to the cost of energy (Haryanto 2024), the group applied four 200-watt monocrystalline solar panels alongside batteries and a solar charge controller to the hydroponic system. The group ultimately determined that solar panels could reduce 66% of their electric power use, contributing to a 15% increase in the farm's profit.

Additionally, a study at Ain Shams University in Egypt compared two hydroponic systems on crop production, greenhouse gas emissions, and energy efficiency. System-I sourced energy from a grid-powered system while System-II utilized solar energy and greywater. The group found that System-II was able to reduce CO<sub>2</sub> emissions by over 94% compared to System-I (Abdelhamid 2025). System-II entirely offset System-I's energy consumption using photovoltaic cells, with both systems still producing similar yields in terms of water and chlorophyll content of the lettuce (Abdelhamid 2025).

Clearly, integrating solar technology is a promising direction for the development of hydroponic systems. However, many hydroponic systems reside in small personal and community gardens, as well as family farms, where owners typically have hyper-limited budget and space. The present study aims to determine the feasibility of solar cell integration at this "human scale."

## Procedure

The present study examines the power and energy balances between Gardyn Hydroponic units and a Dr. Fuel Photovoltaic Cell (Left of Figure 1). Our objective stood at quantifying the energy requirement of a fully functional hydroponic tower, and cross comparing the energy production of a solar cell to test the feasibility of solar integration in hydroponics.



Figure 1.

We initially tested the Gardyn system (Right of Figure 1), a commercial vertical hydroponic system, growing lettuce under standard operating conditions to determine its average daily energy consumption. Cumulative Power readings were recorded at the end of a full growing week using a Poniiic PN2000 Watt Meter connected between the unit and a 120 V AC outlet. Measurements accounted for both lighting and pumping cycles to ensure the total operational load was captured over a continuous 7-day period. The reading from the Watt Meter showed 90.53 W, which was then extrapolated to weekly energy consumption, 10.63kWh, required by the hydroponic system.

In parallel, the photovoltaic (solar) cell was positioned in a controlled environment under a white light to measure its electrical output. The cell’s instantaneous voltage and current were recorded in two different experiments, one changing radius from the cell to the light source, and the other changing the angle that the light source interacted with the panel. The multimeter readings were converted to power, and graphed/regressed, showing exponential and sinusoidal relationships against distance and angle, respectively (Figure 2). The angle was adjusted in 15° increments (with 0° and 180° indicating the light and cell are parallel, and 90° indicating the light is perpendicular to, and directly facing the light source), while maintaining constant distance. Following this, the panel was placed at 1cm incremental distances from the light source, ranging from 25 cm to 45 cm, while keeping the optimal angle (90°) fixed.

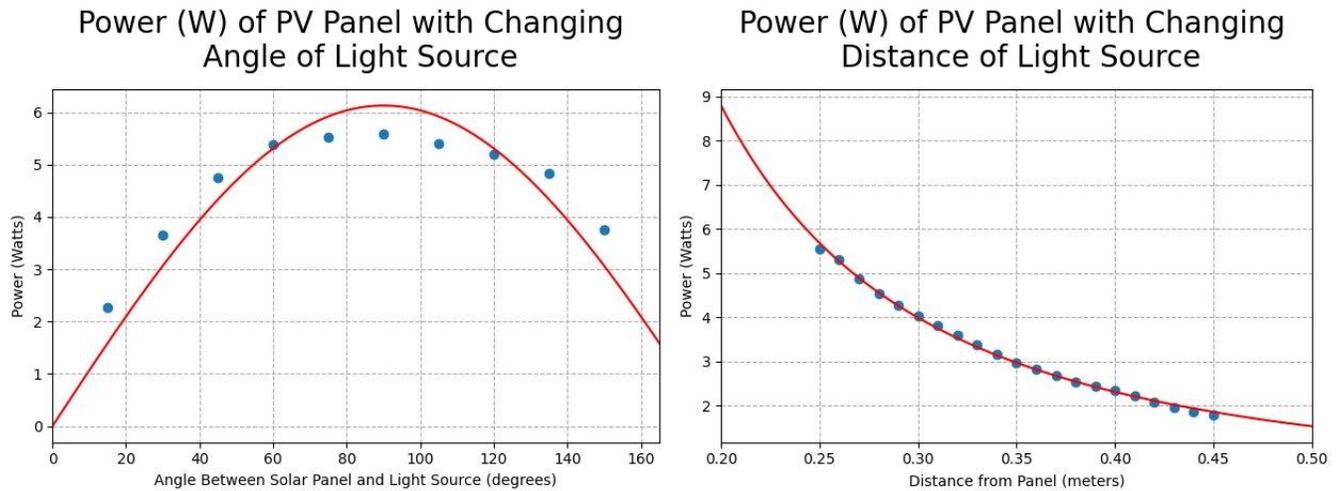


Figure 2.

## Results

At each configuration, electrical output data were collected over a fixed time interval to ensure stable readings. The corresponding power ( $P = IV$ ) and energy production over time were calculated for each setup. These results were compared to the Gardyn system’s recorded energy requirements to determine the feasibility of integrating solar power into hydroponics.

Our method of generalizing our results to hydroponics required a few assumptions. First, we made a correlation between the angle between the solar panel and the light source in Figure 2, and the time of day. This change of variables makes a direct relation from the power supplied by the solar panel, and the time of day (which corresponds now to the angle that the sun would interact with a solar panel).

Additionally, this type of analysis also disregards the distance parameter. Across all trials, the panel generated its maximum power when directly facing the light source ( $0^\circ$ ), with power decreasing sharply as the angle increased. Similarly, increasing the distance between the panel and the light source resulted in a significant decline in output, consistent with reduced irradiance. These trends validated our assumption that angle can serve as a reliable analog for time-of-day and allowed us to ignore distance in the integrated daily-power model by treating the maximum measured wattage as the system’s amplitude.

Essentially, our analysis is in 3 steps (see Figure 3 below). Step 1 is converting the independent variable (angle between the light source and the panel) to time, from sunrise to sunset. Step 2 is integrating the oscillating harmonic power produced by the solar panel, with respect to the new variable and time. Finally, step 3 involves comparing the energies produced by the panel over the period of a day to the power required by the GARDYN hydroponic units and determining how much solar panel area would be required to efficiently operate these agriculture systems.

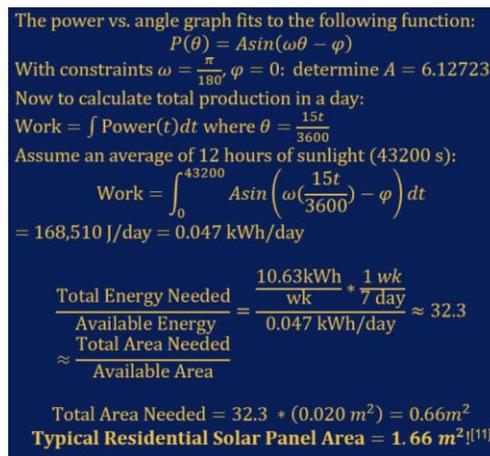


Figure 3.

Using this method, the integrated daily energy production of a single Dr. FuelCell PV cell was calculated to be approximately 0.047 kWh/day, whereas the Gardyn hydroponic tower requires approximately 1.52 kWh/day. This yields a power balance ratio of 32.3, indicating that 0.66 square meters of solar area is needed to power a vertical hydroponic Gardyn tower.

Based on our analysis, a typical residential solar panel produces 2.5 times the energy required by a hydroponic unit in a day. This surplus indicates that solar integration is not only feasible but highly practical, especially when scaled across multiple units in a commercialized setting. Moreover, these findings highlight the possibility for hydroponic units being operated in sustainable agricultural settings with minimal reliance on grid electricity. In regions with high solar irradiance, solar-powered hydroponics could significantly reduce financial strain and carbon emissions, advance accessibility, and minimize environmental impact. Ultimately, our results demonstrate that pairing PV systems with vertical hydroponics provides a pathway toward energy-autonomous indoor agriculture and further supports the broader vision of sustainable food production systems.

## Limitations

Because all solar measurements were conducted under white indoor light source rather than full-spectrum sunlight, the absolute wattage values of the PV cell are lower than what would be observed outdoors. Additionally, real solar irradiance does not follow a perfect sinusoidal pattern due to atmospheric scattering and cloud variability. Because of this fluctuation, the harmonic model provides a reasonable first-order approximation of daily solar exposure. This allowed us to integrate the panel's angular response data into a continuous time-domain function without requiring complex atmospheric modeling. As a result, our integrated daily-power model is best interpreted as a relative output profile, not an absolute prediction of real-world photovoltaic performance.

The angle and distance measurements also faced many experimental limitations. The lack of specialized angular mounting equipment meant that panel orientation had to be adjusted manually, introducing small but unavoidable alignment errors in each trial. Because the light source emitted from a finite area rather than a point source, shifting the angle changed the illuminated area on the panel in ways that could not be precisely controlled. In both the distance and angle experiment, current measurements fluctuated and did not settle at a single steady-state value, making it difficult to capture a perfectly consistent power output for each angle. However, the relationships that were established between power and angle, and power and distance aligned with our expectations, which allowed us to utilize our data to create an appropriate feasibility model.

## Applications

Solar-powered hydroponic systems offer strong applications in settings where energy cost, infrastructure reliability, or environmental impacts create barriers to food production. Photovoltaic integration enables hydroponic units to function with little or no reliance on grid electricity, making them especially valuable in remote communities and urban areas with limited arable land. As previously mentioned, evidence demonstrates that substituting grid electricity with PV energy can reduce CO<sub>2</sub> emissions by over 94%, highlighting the substantial environmental benefit of integrating solar with hydroponics (Abdelhamid 2025). Additionally, the energy model from our project shows that a standard residential solar panel can generate more than twice the daily energy required to operate a Gardyn vertical

hydroponics tower, confirming the feasibility of scaling such systems beyond household use. These applications strengthen the case for PV-hydroponic installation across community agriculture programs, rooftop farms, educational spaces, and sustainability-focused food initiatives.

### **Local Applications**

The Plant2Plate program at the University of Pittsburgh provides a direct context for the implementation of solar-powered hydroponics on campus. Because Plant2Plate emphasizes sustainable, student-driven food production and donates harvests to the Pitt Pantry, solar-integrated hydroponics aligns naturally with its mission. Our findings indicate that a single residential solar panel can more than meet the daily power demand of a Gardyn tower, meaning Plant2Plate could expand its year-round growing capacity without increasing energy costs within the greenhouse. This integration would reduce reliance on the grid, increase crop yield, and create an educational demonstration of renewable energy agriculture for University of Pittsburgh students and community partners. Implementing a PV-supported hydroponic system at Plant2Plate would strengthen the program's sustainability goals, enhance its contribution to campus food security, and serve as a model for scalable, environmentally conscious urban agriculture.

### **International Applications**

One of the most promising use cases of combining PV and hydroponic systems is in remote and rural areas. Unreliable grid power is a serious issue in developing countries, and it is only exacerbated in rural areas, which may not have access to the grid in the first place (Nahim 2025). Even when grid power is available, rising electricity costs and inefficiencies in using grid energy also decrease profits (Nahim 2025). Adopting PV cells can encourage energy independence and allow farmers to take charge of their own energy needs, especially appealing for small farms (Xu, Elomri, Al-Ansari, Kerbache, and Mekkawy 2022).

An especially promising study was performed by Ghosami-Mobtaker, which analyzed the feasibility of adopting PV cells for a hydroponic system, also growing strawberries in the Zagros Mountains, Iran. They found only 120 square meters of panels were needed to produce enough electricity for the 3000 square meter greenhouse, which only covered 4% of the available roof area (Ghasemi-Mobtaker 2024). An important caveat is that 80% of energy usage for their hydroponic system stems from diesel fuel which is used for heating the greenhouse (Ghasemi-Mobtaker 2024). Due to outdated equipment and economic conditions, it is more cost-effective to use diesel fuel despite its negative environmental impact. This may reflect a general challenge of farmers in remote areas getting access to the latest technology. Unfortunately, addressing the distribution of PV technology to remote areas is outside the scope of this paper; however, solutions to economic barriers are discussed in the following section.

Finally, in demonstrating the viability of hydroponic systems, it is important that we do not limit our discussion to crops for human consumption. Indeed, the most energy intensive processes in agriculture are cultivating livestock, due to the rules of energy transfer between organisms. In this regard, a solar-powered hydroponic system to produce fodder for livestock in Bangladesh has been analyzed by Masud & Bhowmik (Masud and Bhowmik 2018). The advantages of this approach are surprisingly numerous.

For one, having a specialized hydroponic system allows for specialized fodder crops (instead of scraps from previous harvests) which can be targeted toward the digestive needs of livestock, e.g., cows. Hydroponic systems are not only more space efficient, but easier to control pests and diseases, which leads to a long-term increase in livestock yield. (Shashank and Teja 2012). Hydroponics can be thought of as a tool that serves more than just humans. Its economic and environmental benefits can be felt in many distinct areas, and this is what makes it such a promising technology for the future.

### **Economic Feasibility**

The long-term savings and self-reliance that solar panels provide would be attractive to farmers except for the base cost of adoption, which is particularly challenging for small farms to field as their profit margins are narrower (Folorunso, Schmautz, Gebauer, and Mraz 2023). To overcome this, researchers have explored using various government subsidy schemes as motivators to adopt PV technology. Xu et al. (Xu, Elomri, Al-Ansari, Kerbache, and Mekkiawy 2022) considered a hypothetical scenario with a 600 square meter hydroponic farm in Qatar and analyzed the effects that various changes in government tariffs and subsidy schemes had on PV system adoption. They found that in all cases, less than a 20% total increase from the existing electricity tariff would result in 100% rates of solar adoption (Xu, Elomri, Al-Ansari, Kerbache, and Mekkiawy 2022). Their results show that using a Feed-In Tariff (where governments buy energy back from the PV system as necessary) and Investment Co-Funding (governments provide an up-front subsidy to help purchase PV systems) are generally the best options, while a surplus Feed-In tariff (where governments only buy back excess energy) outperforms other methods if the area available for solar adoption exceeds the minimum area needed to sustain the hydroponic system (Xu, Elomri, Al-Ansari, Kerbache, and Mekkiawy 2022).

To present such a plan of action to governments, one could perhaps point to existing studies which demonstrate the economic viability of commercial hydroponic systems in rural areas. Folorunso (Folorunso, Schmautz, Gebauer, and Mraz 2023) performed a case study of adoption of commercial-scale hydroponics in Nigeria and found it profitable on a medium-scale (for the economically inclined, with an IRR of 83% and positive NPV for a 15% discount rate, about 3.5% higher than Nigeria's actual discount rate). Small-scale farms were found to be more sensitive to changes in the running cost, with a 13% increase in the cost of operations enough to ensure a net loss for the season, while medium-scale farms had a tolerance of a 58.4% change (Folorunso, Schmautz, Gebauer, and Mraz 2023). Challenges to make small-scale operations profitable may be due to small farms "incurring more costs per unit area." (Folorunso, Schmautz, Gebauer, and Mraz 2023).

Souza (Souza, Gimenes, Almeida, Farinha, Bernardo, and Ruviano 2023) on the other hand, kept to minimum wage regulations then analyzing the viability of adopting hydroponic systems in rural Brazil. They find that using substrate (i.e., sand) as the medium for plant growth results in a complete return on investment in 3.69 years, well ahead of the 12-year project lifetime (Souza, Gimenes, Almeida, Farinha, Bernardo, and Ruviano 2023). However, this does not include any initial investment in PV technologies, which would likely drastically lengthen the time until the investment is returned. Financial analysis revealed human labor and variable taxes to be the main cost burdens at ~25% and ~16% respectively of the total cost, while electricity and fuel only represented ~4% and ~5% (Souza, Gimenes, Almeida,

Farinha, Bernardo, and Ruviaro 2023). This indicates that the viability of solar energy in hydroponic systems might vary by economic condition and location. While it may not be beneficial to immediately adopt solar technology in this scenario, once the return on investment is established farmers can choose to adopt solar more freely, especially by introducing the tariff strategies discussed earlier. Souza also ran a Monte Carlo simulation, randomizing the unit price of each vegetable, and found that in 95% of cases, a net positive return was still achieved, providing more support for economic viability (Souza, Gimenes, Almeida, Farinha, Bernardo, and Ruviaro 2023).

## Optimization

Expanding the ability of solar panels to provide the energy needed to run a hydroponic system requires improving the efficiency of photovoltaic cells. Efficiency of solar panels is generally measured as output electric energy per second divided by incident light energy per second (Kumbhar 2023). There is a theoretical maximum called the Shockley-Queisser limit, putting top efficiency at about 33.7%. This limit is achieved in idealized conditions, although solar panels generally operate at an efficiency range of 15-20% (Abdel-Aziz 2025). Environmental factors such as operating temperatures, wind, dust, shading, and more influence efficiency, making that limit generally unrealistic (Nahim 2025). Maximizing the efficiency towards this limit is being studied through a variety of approaches, most notably through changes in panel material, optimal tilt, and cooling techniques. Advancements of each of these approaches can improve the efficiency of solar cells, ultimately allowing for more of the energy used by hydroponic systems to be replaced by solar energy.

### Optimal Tilt

Solar panel material influences the rate at which energy conversion occurs, but increasing efficiency can also be done through maximizing the amount of light the panels are exposed to. This is done through orienting the panel at an optimal tilt angle. The optimal tilt angle is the angle at which the light reaches the panel is maximized, and it changes by season and geographic location (Nahim 2025). There are generally two methods of installing solar panels, including fixed and tracking systems (Nahim 2025). Tracking systems use technology to constantly follow the optimal angle for maximum light exposure, while fixed solar panels require manual adjustment. Fixed systems are less expensive in both installation and maintenance (Nahim 2025), making them ideal for smaller projects. However, this reduction in cost must be compared with the improved efficiency of achieving an optimal tilt angle, leading to a variety of choices for how and when to adjust panels manually throughout the year.

A case study in Lebanon measuring the influence of optimal tilt angles on solar panel energy output found a 13.7% increase in annual power yield with solar panels fixed at an optimal tilt as opposed to horizontal (Nahim 2025). Additionally, efficiency increases were found with periodical adjustments, potentially making the use of tracking systems unnecessary for smaller systems. Studies show energy production increases of 3-4% with two adjustments of the panels a year, with a 20% energy absorption increase with monthly adjustments (Nahim 2025). Daily adjustments, however, were found to cost more

than they were worth in improving efficiency, making monthly changes to the tilt of the panels an ideal way to maximize solar absorption.

The same study found that changing the solar panel orientation to match the optimal tilt angle could reduce costs of 1kWh of electricity by up to 67% compared to the cost of using the national electric grid in Lebanon, promoting cost efficiency as well.

### Optimal Tilt in Pittsburgh

Determining the optimal tilt angle for a solar panel begins with two geometric parameters: tilt (the angle between the panel and the horizon) and azimuth/orientation (the compass direction the panel faces). In the Northern Hemisphere, the azimuth for fixed installations is almost always due south ( $180^\circ$ ) to maximize annual exposure to sunlight. However, the most optimal tilt angle depends on the latitude of the location (Gharakhani and Pillay 2012). Since Pittsburgh lies at approximately  $40^\circ$  N, a fixed solar panel tilted at approximately  $40^\circ$  above the horizon would produce the highest overall yearly energy yield.

In winter, the sun sits lower on the horizon, so optimal tilt angles tend to increase by  $10\text{-}15^\circ$  and decrease by the same amount in summer due to the sun being higher on the horizon (Gharakhani and Pillay 2012). Thus, Pittsburgh expects an optimal tilt of  $40^\circ$  in the fall and spring, with small fluctuations to  $25\text{-}30^\circ$  in summer and  $50\text{-}55^\circ$  in winter. These seasonal adjustments follow basic solar geometry: panels generate the most electricity when sunlight strikes their surface at or near a  $90^\circ$  incident angle, minimizing reflection and maximizing absorption. By adjusting tilt to track the Sun's seasonal elevation, households or small systems can meaningfully increase annual energy production without the cost of mechanical tracking, making them especially practical for agricultural applications such as solar-powered hydroponics in Pittsburgh.

A particular study in Pittsburgh experimentally determined the suitable ranges for PV tilt angles and orientations (Sui 2023). Two experiments were run, the first establishing the PV system at an azimuth angle of  $180^\circ$ , with the tilt angle for the PV system being varied between  $0^\circ$  and  $90^\circ$  at  $5^\circ$  intervals (Top of Figure 4). In the second experiment, a tilt angle of  $35^\circ$  was set, and the orientation was modified from  $0^\circ$  to  $360^\circ$  in  $45^\circ$  intervals (Bottom of Figure 4).

These findings both determined the optimal range of azimuth angle and tilt angle to be approximately  $180^\circ$  and  $35^\circ$ , respectively, which aligns with our previous generalization due to the latitude and geographic position of Pittsburgh (Sui 2023).

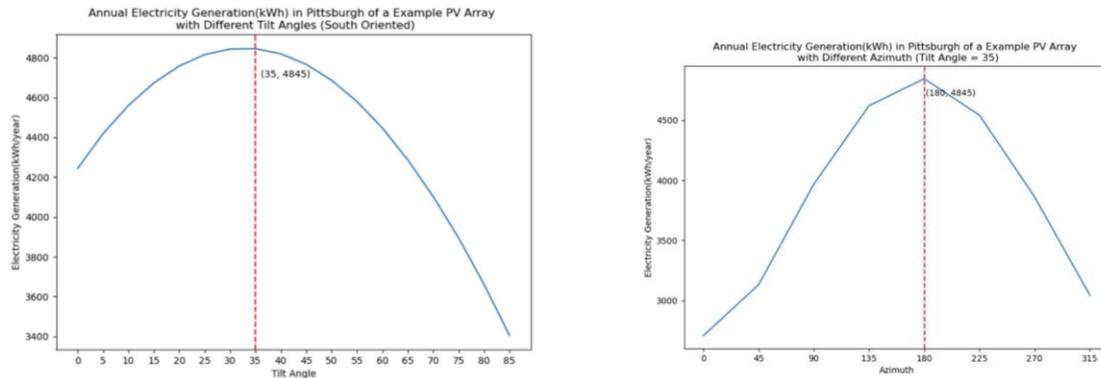


Figure 4. (Sui 2023)

## Materials

As used in the studies on solar panel use with hydroponics at Ain Shams University in Egypt (Kumbhar 2023). and at Muhummadiyah University of Jakarta (Abdel-Aziz 2025), monocrystalline solar panels are generally used for their efficiency and longevity (Kumbhar 2023). Monocrystalline panels are generally black and are composed of sliced pure silicon crystals (Kumbhar 2023). Alternatively, polycrystalline panels are formed from silicon pieces melted together in a mold, with this lack of purity causing a lack of efficiency as opposed to monocrystalline (Kumbhar 2023). Polycrystalline panels are generally less expensive but are more sensitive to high temperatures. Monocrystalline panels have an efficiency of 8.14% compared to 7.57% for polycrystalline panels, making monocrystalline the better choice to maximize efficiency (Abdel-Aziz 2025).

Despite the theoretical limit of 33.7% efficiency, researchers are looking into expanding this limit through manipulating materials. Solar cells work through converting the light energy in a photon into electricity essentially one particle at a time, with one photon resulting in one excited electron (Kumbhar 2023). This excited electron leaves space for electric current to flow. However, a process called carrier multiplication allows for one photon to excite multiple electrons, maximizing electrical output per area of solar panel (Kumbhar 2023). This process has been found to occur in perovskites, a family of crystals that, if used in solar panels, could increase energy conversion efficiency (Kumbhar 2023). Physicists at the University of Amsterdam have found that perovskites have the property of carrier multiplication, and with this process, maximum efficiency is predicted to jump from 33.7% to about 44% (Kumbhar 2023).

## Cooling Techniques

One of the major problems faced by solar panels in terms of operating efficiency is their sensitivity to heat. High temperatures change the properties of the semiconductors in the panels, meaning they have less voltage despite increased current (Kumbhar 2023). This inverse relationship means solar panels cannot operate as effectively at high temperatures, creating an avenue for efficiency in methods of cooling the panels.

Cooling methods are generally divided into active and passive, with active techniques generally including circulation of fluids to transfer heat off the photovoltaic cell while passive techniques involve evaporation, convection, radiation, and other processes that do not require an energy input. A lack of

continuous electricity often makes passive techniques easier and more affordable, with recent innovations shortening the gap in effectiveness between active and passive methods.

For example, Passive Daytime Radiative Cooling (PDRC) utilizes surface coatings to radiate heat into the surroundings without any external (Abdel-Aziz 2025). One study in by mechanical engineers at King Abdulaziz University (KAU) in Saudi Arabia used polydimethylsiloxane (PDMS) and polyethylene terephthalate (PET) as the polymeric coatings on photovoltaic cells (Abdel-Aziz 2025), finding that 200 $\mu$ m thick applications increased the transmissivity of the glass on the panels while allowing for the surface to release heat.

Additionally, passive radiative cooling was used with semi-transparent photovoltaic (STPV) glass in a study from researchers at the Hong Kong University of Science and Technology and Hong Kong Polytechnic University, finding that the addition of coatings could reduce heat input by about 15% while producing energy at rates 3% greater than STPV glass panels on their own (Abdel-Aziz 2025).

### Exergy Analysis

One way to analyze the efficiency and environmental impact of systems is with the Cumulative Exergy Demand (CExD) framework, as demonstrated by Dewulf et al. (Dewulf 2008). Exergy is commonly known as the “available energy” of a system, or its potential to do useful work as the system is brought to equilibrium with its environment (Dewulf 2008). In the context of hydroponics, this could include the energy used by pumping water, spraying pesticides, or human labor (Ghasemi-Mobtaker 2024). Exergy analysis is beneficial in this context because it considers inefficiencies in particular processes which a traditional energy analysis would miss. For example, exergy analysis has been used to identify wasteful drainage processes and to promote water recycling (Hosseinnejad, Saboohi, Zarei, and Shayegan 2023). However, there has not been any comprehensive CExD analysis (to the authors’ awareness) of an entire system. This could constitute a direction for future research.

Regarding solar energy, exergy describes the efficiency at capturing electromagnetic radiation, as well as the input cost to manufacture each component of the panel. While material production is outside the scope of this paper, Photovoltaic-Thermal (PV/T) cells present a theoretical improvement in efficiency upon regular PV cells by capturing more of the electromagnetic spectrum. A particular study (Hosseini-Fashami, Motevali, Nabavi-Pelesaraei 2019) conducted a simulation which used to meteorological data to calculate the effectiveness of PV and PV/T cells and compared their effectiveness in powering a strawberry greenhouse in Alborz province, a mountainous region in Northern Iran. They found that 150 PV or 147 PV/T cells were needed to completely replace the diesel fuel system, showing PV/T cells do not provide a statistically significant advantage in this context (Hosseini-Fashami, Motevali, Nabavi-Pelesaraei 2019). However, they determined that the location of study significantly influenced results, as PV/T cells are less efficient in colder climates and the temperature parameter for the simulation only varied between 5°C and 10°C (Hosseini-Fashami, Motevali, Nabavi-Pelesaraei 2019). PV/T cells perform best in hot environments, but no studies to the authors’ knowledge directly test PV/T cells to power a hydroponic system in a more temperate/tropical climate. This may be especially relevant toward future hydroponics research considering that deserts and arid areas are both highly suitable for regular PV cells and regions where food security is a vital concern (Xu, Elomri, Al-Ansari, Kerbache, and Mekkawy 2022).

## Conclusion

Our literature review and experimental findings both demonstrate that solar energy can entirely offset the electrical demand of vertical hydroponic systems. Our results show that while a single small PV cell is insufficient to power a hydroponic tower on its own, scaling to realistic solar panel areas makes full energy autonomy both practical and economically viable. The modeling approach used angle variation as a proxy for sunlight distribution and provides a simplified but effective method for preliminary system sizing setup. The use of white light and variations in orientation due to manual equipment create limitations in exact real-world modeling, however, consistent relationships between power and angle as well as power and distance measurements provide a strong basis for analysis. A standard residential solar panel can supply more than twice the daily energy needs of a vertical hydroponic unit, highlighting the strong potential for solar-powered agriculture in both residential and commercial contexts.

The future development of PV-hydroponic systems will likely emphasize increased energy efficiency and lower operating costs. Advances in solar materials, passive cooling techniques, and optimized tilt modeling continue to improve panel output, bringing performance closer to theoretical efficiency limits. Recent research shows that monthly or seasonal adjustments to solar tilt can increase energy production by 4-6%, and that optimized PV orientation can reduce the effective price of electricity by up to 90% in certain regions. As perovskite-based PV cells, radiative cooling coatings, and real-time solar-tracking systems become more accessible; smaller panel arrays could reliably power hydroponic units year-round in locations with moderate irradiance, such as Pittsburgh. Looking forward, integration with other systems, incorporation of battery storage, and greenhouse-wide PV adoption represent promising directions for scalable, climate-resilient agriculture.

Further research should test this work by studying full-spectrum outdoor solar integration in a greenhouse setting, incorporating battery storage dynamics, and evaluating more advanced photovoltaic technologies such as perovskites and hybrid PV/T systems. These studies are essential in strengthening the accuracy of these findings and further optimizing the design of solar-integrated hydroponics. Researching such integration with renewable energy benefits agriculture by reducing the long-term operation cost, lowering carbon-footprint, and increasing accessibility, especially in regions experiencing food insecurity, remote communities, and climates where solar irradiance is abundant.

## Acknowledgements

We would like to acknowledge and credit Professor Joaquin Rodriguez for advising this project and offering helpful advice throughout the research process. We would also like to thank the Plant2Plate team for partnering with us to install Solar Panels in their greenhouse. Also, we acknowledge Dr. Michael McMahon, for allowing us access to data collection with the Dr. FuelCell solar panel. Finally, we would like to thank the Frederick Honors College MAP initiative for extensive support and a platform for academic sustainability research.

## References

- Abdel-Aziz, M. M., and A. A. ElBahloul. "Innovations in Improving Photovoltaic Efficiency: A Review of Performance Enhancement Techniques." *Energy Conversion and Management* 327 (March 2025). <https://doi.org/10.1016/j.enconman.2025.119589>.
- Abdelhamid, M. A., et al. "Sustainable Hydroponic Production Using Solar Energy and Treated Greywater Within the Water-Energy-Food-Environment Nexus." *Scientific Reports* 15, no. 31200 (August 2025). <https://doi.org/10.1038/s41598-025-16030-4>.
- Dewulf, J., et al. "Exergy: Its Potential and Limitations in Environmental Science and Technology." *Environmental Science & Technology* 42, no. 7 (April 2008): 2221–2232. <https://doi.org/10.1021/es071719a>.
- Folorunso, E. A., Z. Schmautz, R. Gebauer, and J. Mraz. "The Economic Viability of Commercial-Scale Hydroponics: Nigeria as a Case Study." *Heliyon* 9, no. 8 (August 2023): e18979. <https://doi.org/10.1016/j.heliyon.2023.e18979>.
- Gharakhani Siraki, A., and P. Pillay. "Study of Optimum Tilt Angles for Solar Panels in Different Latitudes for Urban Applications." *Solar Energy* 86, no. 6 (June 2012): 1920–1928.
- Ghasemi-Mobtaker, H., F. S. Ataiee, A. Akram, and A. Kaab. "Feasibility Study of Using Photovoltaic Cells for a Commercial Hydroponic Greenhouse: Energy Analysis and Life Cycle Assessment." *e-Prime: Advances in Electrical Engineering, Electronics and Energy* 8 (June 2024): 100597. <https://doi.org/10.1016/j.prime.2024.100597>.
- Haryanto, L., et al. "Utilization of Solar Energy in Hydroponic Systems for Enhancing Energy Independence in Farming Communities." *Abdimas: Jurnal Pengabdian Masyarakat Universitas Merdeka Malang* 9 (November 2024). <https://doi.org/10.26905/abdimas.v9i4.14545>.
- Hosseinnejad, A., Y. Saboohi, G. Zarei, and J. Shayegan. "Thermoeconomic Analysis of Reducing Exergy Losses in Greenhouses with Hydroponic Cultivation Systems Through Drainage Recycling and Formation of Water Quality Pyramid." *Energy Engineering and Management* 13, no. 1 (March 2023): 74–89. <https://doi.org/10.22052/jeem.2023.113602>.

- Hosseini-Fashami, F., A. Motevali, A. Nabavi-Pelesaraei, S. J. Hashemi, and K. Chau. "Energy–Life Cycle Assessment on Applying Solar Technologies for Greenhouse Strawberry Production." *Renewable and Sustainable Energy Reviews* 116 (December 2019):109411.  
<https://doi.org/10.1016/j.rser.2019.109411>.
- Kumbhar, C. "How Is Solar Panel Efficiency Measured?" *EE Power*, March 2023.  
<https://eepower.com/technical-articles/how-is-solar-panel-efficiency-measured/>.
- Masud, Md. T., and S. Bhowmik. "Feasibility Study of Solar-Powered Hydroponic Fodder Machine in Bangladesh." In *Renewable Energy in Developing Countries*, edited by H.-Y. Chan and K. Sopian, 85–94. Cham: Springer International Publishing, 2018.  
[https://doi.org/10.1007/978-3-319-89809-4\\_6](https://doi.org/10.1007/978-3-319-89809-4_6).
- Nahim, H. M., et al. "Optimizing Solar Panel Tilt Angles for Enhanced Energy Production: Case Studies in Lebanon." *Case Studies in Thermal Engineering* 73 (September 2025).  
<https://doi.org/10.1016/j.csite.2025.106720>.
- Sinsinwar, Shashank, and K. C. Teja. "Development of a Cost Effective, Energy Sustainable Hydroponic Fodder Production Device." Unpublished manuscript, 2012.  
<https://doi.org/10.13140/RG.2.2.30533.81120>.
- Souza, V., R. M. T. Gimenes, M. G. De Almeida, M. U. S. Farinha, L. V. M. Bernardo, and C. F. Ruviano. "Economic Feasibility of Adopting a Hydroponics System on Substrate in Small Rural Properties." *Clean Technologies and Environmental Policy* 25, no. 8 (October 2023): 2761–2775. <https://doi.org/10.1007/s10098-023-02529-9>.
- Sui, J. *The Solar PV Potential of Urban Rooftops and Parking Lots*. May 5, 2023. Treftz, C., and S. T. Omaye. "Hydroponics: Potential for Augmenting Sustainable Food Production in Non-Arable Regions." *Nutrition & Food Science* 46, no. 5 (September 2016): 672–684.  
<https://doi.org/10.1108/NFS-10-2015-0118>.
- Velazquez-Gonzalez, R. S., et al. "A Review on Hydroponics and the Technologies Associated for Medium- and Small-Scale Operations." *Agriculture* 12, no. 5 (April 2022).  
<https://doi.org/10.3390/agriculture12050646>.
- Xu, Z., A. Elomri, T. Al-Ansari, L. Kerbache, and T. El Mekkawy. "Decisions on Design and Planning of Solar-Assisted Hydroponic Farms Under Various Subsidy Schemes." *Renewable and Sustainable Energy Reviews* 156 (March 2022): 111958.  
<https://doi.org/10.1016/j.rser.2021.111958>.