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Agrivoltaics: A Team-Based Analysis of Solar Energy and Agricultural Modeling

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Dr. Tony Kerzmann's higher education background began with a Bachelor of Arts in Physics from Duquesne University, as well as a Bachelor's, Master's, and PhD in Mechanical Engineering from the University of Pittsburgh. After graduation, Dr. Kerzmann began his career as an assistant professor of Mechanical Engineering at Robert Morris University which afforded him the opportunity to research, teach, and advise in numerous engineering roles. He served as the mechanical coordinator for the RMU Engineering Department for six years, and was the Director of Outreach for the Research and Outreach Center in the School of Engineering, Mathematics and Science. In 2019, Dr. Kerzmann joined the Mechanical Engineering and Material Science (MEMS) department at the University of Pittsburgh. He is the advising coordinator and associate professor in the MEMS department, where he positively engages with numerous mechanical engineering advisees, teaches courses in mechanical engineering and sustainability, and conducts research in energy systems.

Throughout his career, Dr. Kerzmann has advised over eighty student projects, some of which have won regional and international awards. A recent project team won the Utility of Tomorrow competition, outperforming fifty-five international teams to bring home one of only five prizes. Additionally, he has developed and taught fourteen different courses, many of which were in the areas of energy, sustainability, thermodynamics, dynamics and heat transfer. He has always made an effort to incorporate experiential learning into the classroom through the use of demonstrations, guest speakers, student projects and site visits. Dr. Kerzmann is a firm believer that all students learn in their own unique way. In an effort to reach all students, he has consistently deployed a host of teaching strategies into his classes, including videos, example problems, quizzes, hands-on laboratories, demonstrations, and group work. Dr. Kerzmann is enthusiastic in the continued pursuit of his educational goals, research endeavors, and engagement of mechanical engineering students.

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David V.P. Sanchez is an Associate Professor in the Swanson School of Engineering's Civil & Environmental Engineering department and the Associate Director for the Mascaro Center for Sustainable Innovation at the University of Pittsburgh. He serves as the Program Director for the Master's in Sustainable Engineering, the Undergraduate Certificate in Sustainability, the John C. Mascaro Faculty Fellows, and the Sustainability Global Engagement grant. He is the faculty lead for the University Honors College Food Ecosystem Scholar Community.

His research lab, Sustainable Design Labs, focuses on fusing analytical chemistry, sustainability design principles and data analytics to address Water and Sustainability grand challenges. Current thrusts focus on Smarter Riversheds, Microbial Fuel cells and advanced oxidation and separation processes.

Focused on co-creating long term partnerships that synergize community vision with Pitt's core competencies of research and education, Sanchez has built up Pitt Hydroponics in Homewood, founded Constellation Energy Inventor labs for K-12 students, and re-created the Mascaro Center's Teach the Teacher sustainability program for science educators in the region.

As a teacher he designed and created the Sustainability capstone course which has annually partnered with community stakeholders to address sustainability challenges at all scales. Past projects have included evaluating composting stations in Wilkinsburg, studying infrastructure resilience in Homewood, enabling community solar in PA, improving energy efficiency in McCandless Township, and improving

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Agrivoltaics in Pittsburgh, PA: A Team-Based Analysis of Dual-Use Solar Through Modeling

Abstract

An agrivoltaic system is one in which agricultural crops are grown, or livestock are raised on the same land area as a photovoltaic array. The practice of using land for both agriculture and solar power generation allows for the production of clean, renewable energy and food, two of the most important elements in sustaining a growing global population. Agrivoltaics is a very efficient use of farmland which has several additional synergies. The field of agrivoltaics is relatively new, and more research is needed to better understand how environmental factors and system configuration affect the yields of energy and agricultural production.

In an effort to further explore this topic, an interdisciplinary group of faculty and undergraduate students at the University of Pittsburgh are working to research and model how an agrivoltaic farm system would effectively operate near Pittsburgh, PA. Through a review of existing literature, interviews with subject matter experts, and collaboration between engineering students and faculty, the team was able to model the electricity and agricultural output of an agrivoltaic system using Microsoft Excel and OpenDSS, paving the way for future experiments at a local property.

These various perspectives from students studying mechanical, electrical, and environmental engineering, as well as the advising professors specialized in those disciplines, created a collaborative environment that amplified the team's effectiveness and enhanced the students' learning experience. This interdisciplinary cooperation mirrored the team dynamics which is often found in industry and provided valuable experience in both communication and project coordination. This paper will explore the findings of the agrivoltaics project, how students benefitted from hands-on undergraduate research, and how the interdisciplinary nature of the research team increased the educational value of the experience.

Introduction

Agrivoltaics is a system in which crops and/or livestock share the same land space with a photovoltaic array, allowing for renewable energy production and agriculture to coexist while reducing overall land use [1]. Due to the essential production of food and energy, agrivoltaic farms have the potential to be a key component to the clean, renewable energy transition which is currently underway throughout the world.

As the global population continues to grow, increases in the production of both renewable energy and agricultural products will be needed, but these two needs will be in conflict over limited land availability, raising concerns among some experts [2]. Drastic increases in renewable energy production are necessary to reduce greenhouse gas emissions and replace the electricity currently produced by fossil fuels. One issue with conventional solar farms is that they occupy a lot of land area per unit energy production and are typically located on fertile cropland, thereby eliminating the capability of the land to produce food. Agrivoltaics is proving to be a very effective use of land space which has created a great deal of optimism in the renewable energy domain. One recent survey found that 81.8% of respondents would be more likely to support solar development in their community if it were integrated into agricultural production [3].

There are numerous advantages to co-locating solar and agriculture beyond the obvious necessity for society to have abundant food and energy. The income from selling electricity can greatly assist farmers in stabilizing their income. Farmers deal with variable crop commodity markets, supply costs, equipment costs and even variable weather patterns, including significant increases in droughts and floods due to climate change [4]. These variabilities and other factors have affected farmers to the point that 2021 farming bankruptcy rates were at their highest level since 2005 [5]. Unlike the variability issues seen by traditional farms, solar electricity income is very consistent year after year and, in most cases, the income from solar power production far exceeds that of the agricultural produce. Another important agrivoltaic synergy is the reduction of water and heat stress on the crops due to the shade provided from the PV panels. In fact, there are a number of crops that benefit from these reduced stressors which can lead to greater crop yields [6]. Finally, solar panel efficiency gains are achieved due to the reduced temperature provided by the plant's evapotranspiration process. This process cools the air surrounding the plant through water evaporation from the plant's surface, creating a cool micro-climate under the solar array.

Educational Elements

Research-based education allows students to explore topics of interest in much further detail than would normally be possible through traditional study. By allowing students to investigate a topic of interest, experts believe that research-based education can stimulate engagement and ultimately be a transformative experience by allowing students a glimpse into how scientific knowledge is synthesized [7]. Experts also consider research in education to be beneficial to students' competitiveness in the modern, global market, as developing specialized research competencies allows students to meet the never-ending demand for further technological developments [8]. These benefits allow research-based education to serve as a useful addition to a college curriculum, exposing students to the processes behind academic progress and preparing them with valuable skills for success after graduation.

Seven of the eight students involved in the agrivoltaics undergraduate research project were surveyed to gain a better understanding of the students' perspectives of their research experience. Multiple choice questions were provided based on ABET's Criterion 3: Student Outcomes 1-7 where a score of 1 represents that the student strongly agrees with the statement and a score of 5 represents that the student strongly disagrees with the statement [9]. Table 1 shows the results of survey where most of the 7 respondents indicated a strong agreement that the research project had enhanced their ability in all seven ABET outcomes. Question five and seven scored the highest with all seven students indicating a strong agreement. Q5 was related to functioning effectively on a team and Q7 was related to acquiring and applying new knowledge. In many engineering programs these two categories of ABET assessment can be the most difficult to assess and score highly when evaluating student opinions. Although seven respondents is a minimal sample size, the investigators were pleased to receive such high scores in all seven categories. We believe that the high scores are directly tied to student motivation and interest in the project. It was evident from the start of the AgPV research project that the students were interested and enthusiastic about the research category. The students also expressed a high level of motivation because of the real-world implications of this research and the potential positive societal impacts that the research conclusions could provide. Question 6 scored the lowest, although an average of 1.71 is still a very encouraging response.

Question	**Mean**	**Std Dev**
Q1	1.14	0.35
Q2	1.14	0.35
Q3	1.14	0.35
Q4	1.43	0.49
Q5	1.00	0.00
Q6	1.71	0.70
Q7	1.00	0.00

Table 1: Average Scores from Seven Student Responses to Seven Likert Scale Questions Based on the Seven ABET Outcomes. A Score of 1 Represents Strong Agreement and a Score of 5 Represents Strong Disagreement

Survey Questions – Based on ABET Outcomes
Q1 - To what extent do you agree with the statement: "This research project has enhanced my ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics."?
Q2 - To what extent do you agree with the statement: "This research project has enhanced my ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors."?
Q3 - To what extent do you agree with the statement: "This research project has enhanced my ability to communicate effectively with a range of audiences."?
Q4 - To what extent do you agree with the statement: "This research project has enhanced my ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts."?
Q5 - To what extent do you agree with the statement: "This research project has enhanced my ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives."?
Q6 - To what extent do you agree with the statement: "This research project has enhanced my ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.
Q7 - To what extent do you agree with the statement: "This research project has enhanced my ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Table 2: Likert Scale Survey Questions Based on the Seven ABET Outcomes

Another important aspect of this project was the interdisciplinary nature of the team. The project team consisted of eight students and three faculty within the environmental, electrical, and mechanical engineering departments. This collaboration of students and faculty with varying academic backgrounds and specialties made the project an exercise in interdisciplinary education. Interdisciplinary education is the integration of multiple academic disciplines, often through projects. Experts believe that this method of educating students nurtures problem-solving skills and develops complex perspectives, preparing students to succeed in the modern world [10]. We believe that the interdisciplinary nature of the project team made it more effective in achieving its goals and significantly benefitted the students’ educational experience.

The survey consisted of four open-ended questions to allow students to provide feedback from their experiences. The list of open-ended questions and responses can be found in Appendix A. One of the open, free-form questions asked was, “How did working in an interdisciplinary team affect your understanding of agrivoltaics?”. Student responses reflected an appreciation for the opportunity to learn more about other engineering disciplines, with one student responding, “It helped me to understand the problems and solutions as a whole when considering a proposed design.” Another student said, “Working with many different types of engineers was great because they all brought good questions and different perspectives on agrivoltaics. It’s always good to have different perspectives because people can catch things that I missed and vice versa.". Students also expressed that working within an interdisciplinary team increased their own productivity.

Communication skills were another area that benefitted from students' participation in this project. Within the team itself, students had ample opportunities to hone their soft skills like communication. Students worked closely with one another to set goals and delegate tasks, keeping the team focused and the project on track. Students also practiced effective communication through problem-solving meetings where assumptions and methods of calculation were decided through debate and collaboration. Communication between student researchers and advising faculty members was also an important aspect of the project. During weekly meetings and through regular correspondence, students gained experience asking questions and receiving guidance from their faculty advisors. Students also had extensive opportunities to speak with experts outside of the university through interviews. Students indicated their particular interest in these interviews in the open-ended section of the survey, one expressing "[The interviews] allowed us to learn things we never expected and get perspectives from a wide range of people studying [agrivoltaics] across the country." The students took advantage of these opportunities to improve skills in communication, and all agreed that the experience in this area was beneficial. In the survey, all seven students replied, "Strongly Agree" or "Agree" to the statement, "This research project has enhanced my ability to communicate effectively with a range of audiences." Students benefitted from the opportunity to develop their communication skills through this project, as evidenced by responses to both multiple choice and open-ended survey responses.

This project also benefited students by providing opportunities for site visits, which provided motivation through tangible experiences and allowed the group to gain a better perspective on the project's goals. The first experiential learning trip comprised of a visit to a farm where a local landowner, in cooperation with the research team, plans to install an agrivoltaic system in the near future. Students participated in an investigation of the onsite electrical hardware, considered the effect of geographic features like sloped terrain and a pond, and spoke with the landowner about his experiences in solar development. Students also participated in a second site visit during which they toured a solar farm which was in the middle of the construction process; installing the racking systems and interconnection equipment. Through these hands-on experiences, students obtained a greater understanding of the challenges involved in establishing an agrivoltaic system. They also gained motivation through concrete experiences with the solar systems and locations which they hope to use to establish an experimental system. These types of experience-based learning trips provide an excellent student value, as they provide memorable experiences that connect students to their academic work. David Kolb, an expert on educational theory at Case Western Reserve University, theorizes that experience itself is the precursor to knowledge. He posits that learning is a process whereby "concepts are derived from and continuously modified by experience" [11]. These memorable trips worked to integrate real-world experiences with discussions, calculations, and explorations of existing literature, allowing the students to reinforce what they learned through research.

Ultimately, this project helped students to develop a wide variety of skills and provided them with valuable experiences to reinforce their learning. Students affirm this, as can be seen through their survey responses to the statement, "This research project has enhanced my ability to acquire and apply new knowledge as needed, using appropriate learning strategies." All seven respondents replied, "Strongly Agree". This finding is salient, as the ability to acquire and apply new knowledge is a foundational skill that will serve students throughout their lives.

Model Development

The first step to the creation of a model to predict an agrivoltaic system's production in Pennsylvania was to collect data reflecting the state's yearly produce outputs. Data was pulled from the Pennsylvania Agricultural Statistics Annual Bulletin for 2021-2022 [12]. The data used in the development of this model was that of 2017, as it was the latest year with full data for all crops. Issued by the USDA's National Agricultural Statistics Service, this report compiles the overall production of crops in the state. Using these data, a model of yearly crop yield, land use, and economic production was created in Microsoft Excel. This production model served as the foundation for our later work and could be modified through user input to adjust the level of agricultural output based on the amount of land used for solar power production.

Crop	Bushels per Acre	Total Production Before Solar Replacement (bushels)	Total Production After Solar Replacement (bushels)	Price per Bushel
Barley	52.5	5250.0	3937.5	$ 4.60
Corn	109.7	10970.0	8227.5	$ 3.87
Oats	33.1	3310.0	2482.5	$ 3.57
Soybeans	47.6	4760.0	3570	$ 9.70
Winter Wheat	51.4	5140.0	3855	$ 5.21

Crop	Yield per Acre (tons)	Total Production Before Solar Replacement (1000 tons)	Total Production After Solar Replacement (1000 tons)	Price per Ton
Hay	2.6	260.0	195	$164.00
Forage	2.9	290.0	217.5	N/A

Crop	Yield per Acre (pounds)	Total Production Before Solar Replacement (1000 pounds)	Total Production After Solar Replacement (1000 pounds)	Price per pound
Tobacco	2344.4	234440.0	175830	$2.04

Crop	Yield per Acre (cwt)	Total Production Before Solar Replacement (1000 cwt)	Total Production After Solar Replacement (1000 cwt)	Price per cwt
Bell Peppers	209.1	20910.0	15682.5	$63.20
Cantaloupe	137.8	13780.0	10335	$32.90
Pumpkins	156.0	15600.0	11700	$17.60
Snap Beans	64.3	6430.0	4822.5	$21.20
Sweet Corn	59.9	5990.0	4492.5	$38.60

Figure 1: Image of the AgPV Excel Model

A sample of the data imported for the agricultural model is shown in figure 1, as well as the crops' color coding for shade tolerance. Very shade tolerant, moderately shade tolerant, and shade intolerant correspond to green, yellow, and red shading, respectively [13] [14] [15] [16] [17] [18] [19] [20] [21]. Forage, hay, and tobacco are not color-coded due to varying shade tolerance based on specific species and/or a lack of available data. Though not incorporated into model calculations, the shade tolerance of various crops is essential information and will be incorporated in future model iterations.

A knowledge-based decision tool was created in Microsoft Excel to serve as a prototype of a real-world, interactive system. A knowledge-based system is a computer program that uses data and computer logic to solve calculation problems. This preliminary model could eventually be used to educate investors about the potential advantages and disadvantages of an agrivoltaic system. Designed to predict the expected agricultural production and revenue from both PV electricity and agricultural production, this model could then report these findings to the user. The user has the ability to input a variety of parameters including farm acreage, crop selection, investment capital, and solar panel type. Through calculations using these inputs and the various data sets, the user is presented with an "outputs" page, which includes a solar array installation cost estimate, as well as an AgPV revenue proforma based on market rates and compares it to traditional farming. The model provides an opportunity cost measure which is the loss of potential gains when one option is chosen over another option. For the AgPV model, the projected revenue is compared to the income from the S&P500's inflation-adjusted yearly average return of 8.5% [22]. The AgPV decision model allows a user to take advantage of a preselected dataset to weigh their options as they decide how they want to configure their agrivoltaic system and to decide what the best investment strategy is for them. This first version of the decision tool did not model solar panel output, but instead relied on listed wattage for solar panels and wholesale purchase prices, providing an estimate that would not reflect real-world revenues and costs. Aiming to correct these inaccuracies, the team resolved to complete a full model that outputs similar financial figures but computed more accurate solar energy production based on environmental data and simulation of a PV panel's production using OpenDSS.

Moving on to the modeling of the electricity production, the team worked to develop an electrical model that could later be integrated with the agricultural model. This would require a simulation of each PV panel's output, in order to forecast how much energy an agrivoltaic system would produce. To design the electrical model, OpenDSS, a program made by the Electric Power Research Institute (EPRI), was used. OpenDSS is a power distribution system simulator, for which a device model called PVSystem was recently released. PVSystem provides a combined model of photovoltaics and the associated inverter, seen below in Figure 2 [23].

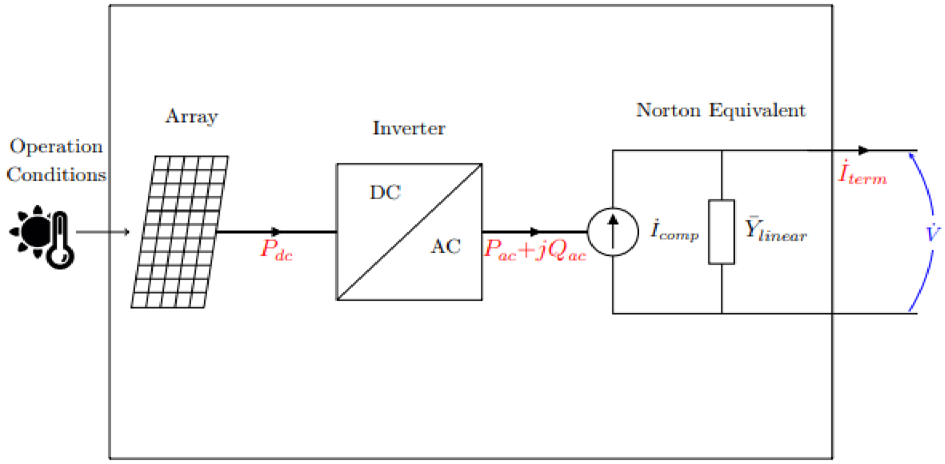

Figure 2: PVSystem Block Diagram

The AgPV model uses input operating conditions such as the geographical location of solar array and the solar panel/inverter specifications. To determine these operational conditions, data was collected from the National Renewable Energy Laboratory (NREL) using their National Solar Radiation Database (NSRDB) [24]. The AgPV model incorporated agricultural data from 2017, so the research team chose to use operational conditions data that matched the same year. The team decided to use meteorological data for Pittsburgh, Pennsylvania, as this is the location for a planned experimental agrivoltaics system. From this database, temperature and irradiance data were extracted. Temperature, measured in degrees Celsius, can be seen in Figure 3.1, where the zero hour is January 1st, 2017, and the 8760th hour is December 31st, 2017. For the purposes of the mode, the irradiance which was measured in watts per meter squared, was converted to "per unit" using a base value of 1 $\frac{kw}{m^2}$, as seen in Figure 3.2.

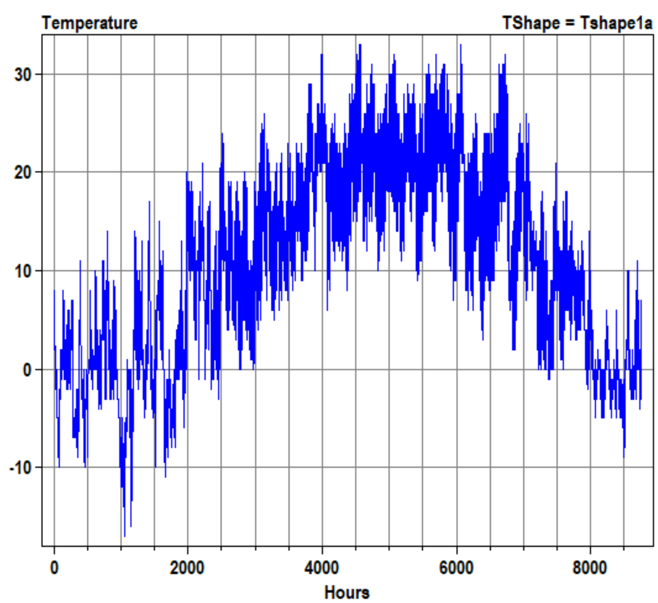

Figure 3.1: Temperature vs. Time Pittsburgh, PA 2017

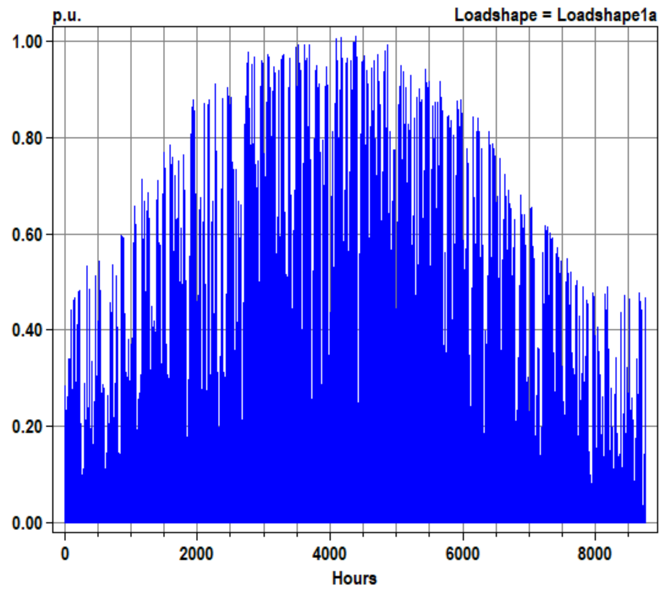

Figure 3.2: Irradiance vs. Time Pittsburgh, PA 2017

The other inputs to the model were PV and inverter properties, operating voltage, and grid parameters. The solar panel chosen for the model simulation was a 435 W SunPower panel (SPR-E20-435-COM) with a 20.3% efficiency [25]. The inverter chosen was a SolarEdge single-phase inverter (SE10000A) rated at 10kW. The inverter efficiency has an operation efficiency of 98% with the efficiency curve shown in Figure 4 [26].

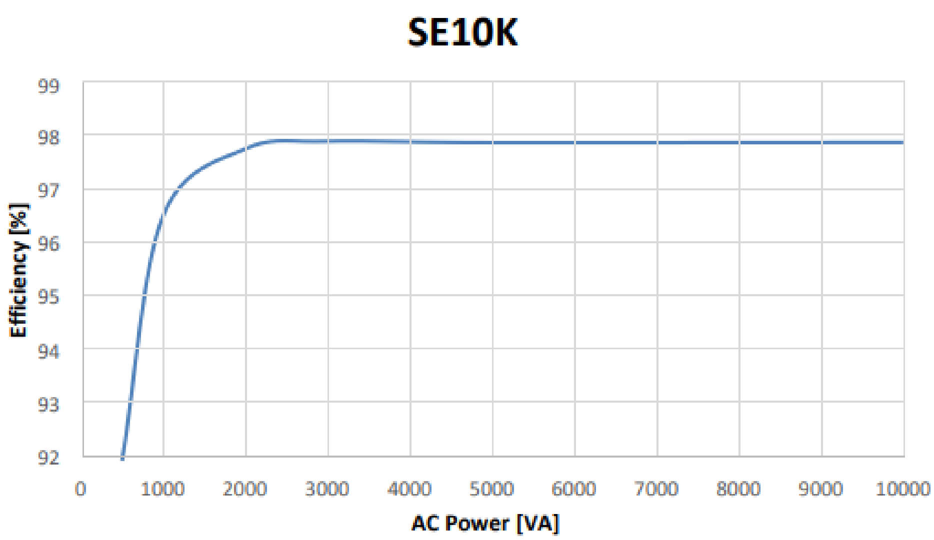

Figure 4: SolarEdge SE10000A Inverter Efficiency Curve

The bus that connects the PV panel to the grid was rated at 23kV with a 0.8 power factor. Once all the electrical parameters were input into the OpenDSS model, the power output per panel was graphed for each hour of the year as seen in Figure 5. As the PV panel in this model is producing power which flows out of the system, the graphed values are shown as negative. These power outputs were then sent to the AgPV model to be used in the overall agrivoltaic system calculations.

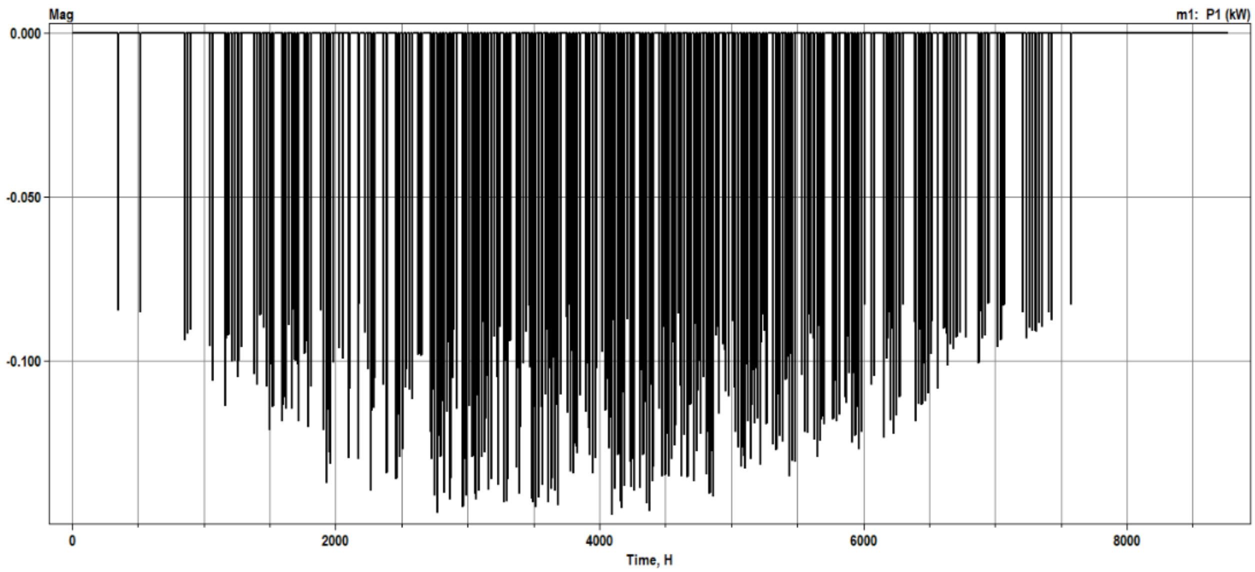

Figure 5: Power Output Per Panel vs. Time.

Through the modeling of the power output of the photovoltaic panels, the model's accuracy to predict electricity output and resulting revenue was improved. By inputting real-world environmental/climate data, future iterations of the model could adapt to a multitude of locations, and the solar installation's output could be predicted through simulation.

After considering both agricultural and electrical factors, separately, work began on the integration of the two elements into one comprehensive model. In order to begin the calculations, the user must input the acreage of the property they plan to develop for agrivoltaics, as well as the percentage of that farmland to be filled with panels, which the team called the "solar replacement factor". The next important consideration is the amount of shade produced by the panels, which is important when estimating crop choice and farm yield. Due to the partial-shading nature of agrivoltaics, a major factor to consider is the shade tolerance of the selected crops. This is an area of focus for many experts studying agrivoltaics, as crop performance can vary based on levels of photosynthetically active radiation [27]. Due to a lack of concrete data on the effect of shading on each crop's performance, the team decided that first the first iteration of the AgPV model we would forgo incorporating the effects of partial shading and instead use a conservative calculation methodology that calculates planting area based on the area under the solar panels that receives eight hours of sunlight per day ("full sun") on the winter solstice. In reality, a farmer would expect to plant some crops within the partially shaded areas, though the exact amount would depend greatly on crop selection and environmental factors. In future model interactions, the model will be adapted to predict agricultural yield more accurately within the partially shaded regions.

The next step in the development of AgPV model was to compute the area in which crops would receive full sun. For this purpose, a shading geometry calculation was developed. The user is required to input the angle and height at which the panels will be installed, as well as the physical dimensions of the panel. The panels are assumed to be inclined, facing south, and positioned side-by-side. By placing panels in a row, only the length of the shadow extending behind the panels must be calculated. The shading calculation then uses solar data from Pittsburgh, PA on the 21st of December 2017. This is the winter solstice and therefore the day of the year that receives the least amount of sunlight; meaning that any area receiving full sun on this day is guaranteed to also receive it during any other day of the year. This day was chosen in order to continue developing a conservative calculation methodology, providing the user with the amount of land they are guaranteed to be able to plant. This solar input data contains the sun's altitude and azimuth throughout the day in 30-minute increments. Using geometry to relate the height and angle of the PV panel with the position of the sun, the length of the shadow is calculated. To begin, the team created a large right triangle with a height equal to the highest point of the solar panel, "h_{top}", and a smaller right triangle with the height of the lowest point of the solar panel, "h_{bottom}". The base of the small triangle represents the length of the area under the panel which is not shaded. Subtracting the base of the small triangle from that of the large triangle gives the length of the area that is shaded. Using trigonometric calculations, the effects of the azimuth of the sun are also incorporated into the calculations, giving a minimum row length necessary to prevent panels from shading the next row. Finally, to calculate the net shadow created by the panel, the lower bound (solar noon) for the base of the small triangle is subtracted from the upper bound (eight hours before solar noon) of the base of the large triangle. By taking the difference between these values, the shade calculation computes the length per row of the area which does not receive eight hours of sunlight a day due to the shadow cast by the line of panels. From this, the length of area per row that is available to plant crops in full sunlight is calculated. Using these values, the area of shadow cast per panel is calculated using the panel size and shadow length. This area is then compared to an "allowed" shadow area for the entire property based on the user-input solar factor and total farm acreage to find the number of panels that should be installed. To output the recommended number of panels, the area of allowable shade is divided by the area of shadow created per panel.

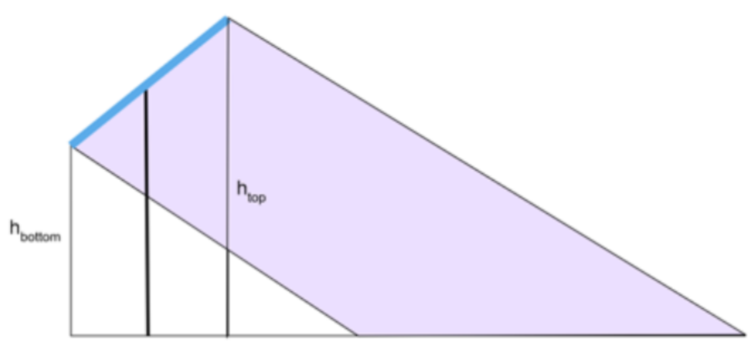

Figure 6: Diagram of the Shadow Cast by a PV panel.

Using this information, and with the aim of improving upon the previously created advisory system, the team created a financial analysis module to predict the costs and revenues of the agrivoltaic installation based on the user's parameters. Using an industry average installation cost per MW [28], the team found the year-one costs associated with establishing the agrivoltaic system. By comparing these generalized installation costs with the projected revenue based on energy production, the number of years to breakeven was calculated. These financial values could be used by farmers or potential investors to weigh the opportunities presented by agrivoltaics with other viable alternatives.

Conclusion

The energy transition from fossil fuels to renewable energy, along with the security of our future food production are two of the most important research topics of our generation. Agrivoltaics provides a key solution to a clean, renewable energy transition while also providing a stable means to produce food. The research conducted within this project establishes a foundation for further modeling of agrivoltaics. In this first iteration of an AgPV model, the team was able to predict electricity production and agricultural production.

This project provided the AgPV undergraduate research team with many valuable learning experiences related to agrivoltaics. The team also gained experience in conducting team-based, hands-on research. As could be seen through the results of the end-of-semester survey, students believed the experience to be highly valuable by expanding their understanding of agrivoltaics, exposing them to other disciplines within engineering, as well as developing their teamwork and communication skills. The results from the survey were promising and students were united in their sentiments that the project was an experience of great value.

Future AgPV research teams will continue this work and build upon the foundations set forth in this project. Future teams hope to continue refining the model and to establish an experimental system in partnership with a local landowner and solar investor. The experimental demonstration will evaluate the effects of various environmental and system configuration factors on the production of the agrivoltaic system. The research team can then use the measured data from the demonstration AgPV farm to validate the findings of the model, and to improve the model.

Future iterations of the AgPV model could be useful for informing farmers, and other users, about the costs and benefits of establishing an agrivoltaic system. Potential areas of improvement include the solar electricity production calculations, integration of the agricultural model and implementing automatically updating data streams that can be scraped from publicly available databases like those on the USDA website.

The model’s methods for predicting solar electricity production could stand to be improved in a variety of ways. First, the model bases its projections on data from the winter solstice, in order to create a conservative estimate. To bring the model to a range of more accurate final figures, daily production calculations could be incorporated. Another source of potential error is that the current model only uses data from 2017. The use of time-averaged data over a number of recent years would provide a more accurate prediction. The current model also uses a very general figure for installation costs by using an industry average from literature. Installation costs vary greatly from year to year and based on location, installation considerations, access to grid interconnection and a host of other variables. Future models will incorporate more user-defined installation options to provide a more customized solution. The model could also be improved by including areas of partial shade in calculations. Partial shade has been shown to improve the agricultural yield from some crops, so including partially shaded areas could be a major improvement for future iterations of the AgPV model. Finally, more options for types of solar panels could be included as user inputs. Single-axis tracking systems and vertical bifacial panels are viables alternatives to inclined south-facing panels which any farmer or investor would consider when designing an agrivoltaic system.

Better implementation of the agricultural portion of the AgPV model should also serve as a goal for future researchers. The team recognized early on that agricultural production accounted for a relatively small proportion of the agrivoltaic system’s economic output, so the current financial outputs of the model focus on the return on investment for the solar energy. The agricultural production, on the other hand, were calculated separately from the solar cost analysis and improvements to the model could incorporate revenue from crop production into the financial output as well as crop yield adjustments based on shade tolerance.

Finally, the model could benefit from real-time updates for its input data. If the model were to be used as a real-world advisory system, data would need to be as current as possible in order to give investors the most complete information possible. Data for average agricultural output per acre, market rates for agricultural products and electricity, and changing climate/environmental factors could all be automatically updated.

In summary, the undergraduate AgPV modeling research team was successful in developing the first iteration of the AgPV model. The students had a strong educational research experience through reviewing existing literature, interviewing subject matter experts, collaborating closely with research faculty, and developing a working AgPV model. The interdisciplinary nature of this research incorporated students from mechanical, electrical, and environmental engineering, which provided a collaborative environment that enhanced the overall student learning experience. The topic of agrivoltaics with its clean, renewable, and sustainable themes provided the students with additional motivation as they saw this project as bigger than simply a research project, but a project with vast, societally important, real-world implications. The survey results indicated that the students had a high level of interest, organization, and motivation due, in part, to the real world and interdisciplinary nature of the research.

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Appendix A

Q8 - Which tasks did you find to be most beneficial to your learning?
R1 - I liked being forced to interview a lot of people. This allowed us to learn things we never expected and get perspectives from a wide range of people studying this across the country.
R2 - Giving multiple presentations and writing an interim report made it easier to do the final things in the end and kept us focused on the end goal. The interview requirements for the project was something I haven't done before, so that also had a big effect on what I gained from working on the project.
R3 - Sitting in on meetings with engineers outside of my department. Helped me to understand different ways of looking at problems when it comes to design.
R4 - Developing the agricultural model was a good exercise in trying to direct my own path--to pull useful insights from data. I also found doing the solar panel shading calculations to be a really educational experience, as multiple team members contributed knowledge to create the best model possible.
R5 - The tasks I found most beneficial to my learning were the interviews that we had to conduct. It was interesting to see what other people were doing across the country with Agrivoltaics. Because we spoke to such a wide verity of people of many different backgrounds, I feel like I got a holistic view on Agrivoltaics. I also like that we were able to ask questions that related to what we were confused about because sometimes the literary documents did not have everything we were looking for.
R6 - Helping to calculate the shade of the panels.
R7 - Visiting the farm was the most beneficial to my learning, as it allowed me to visualize what an agrivoltaic farm would look like in real-life.

Q9 - How did researching a topic with real-world implications enhance or diminish your learning, motivation, and/or understanding?
R1 - Agrivolatics is a very new and up and coming field, so it very much enhanced my learning experience
R2 - Having actual stakeholders and frequent group meetings kept me invested in the project and finding out how new agrivoltaics is through our research made it feel like we really contributed to the resources out there about it.
R3 - It made the stakes of the project much higher as it could be something that could very much make an immediate impact on the lives of the users.
R4 - It definitely benefited my learning, as I knew that in future there may be an agrivoltaic system that exists because of the groundwork we're putting in now. That motivated me to do the best work I could, and to try to understand the topic on a deep level.
R5 - Researching a real-world topic enhanced my learning because I find agrotechnology interesting and a super important topic. Also, as an electrical engineer who is looking to work in some type of sustainable energy agrivoltaics really caught my interest. It's cool to work on relevant projects that are currently being addressed and seeing my work as a student make a difference is valuable. Sometimes it is hard to see how what you learn in school relates to real world situations and be hard to find motivation to do the task, but this was not the case for this project.
R6 - It helped me stay motivated because it kept me interested. It helped me learn because we were using real world numbers which were not ideal like most practice problems.
R7 - Researching a topic with real-world implications enhanced my learning by allowing me to think about how certain aspects of the agrivoltaic farm would work in real-life, but my motivation was also diminished when researching funding opportunities, as the nature of the project did not meet many of the application requirements.

Q10 - What lessons or skills have you learned through this research project?
R1 - I learned how to better manage a project. I learned to think ahead of the schedule so that the team was never unprepared for an assignment of meeting.
R2 - I learned more about project management and organization because of how many people we had to work with for the project.
R3 - Definitely a lot more professional communication, as well as project planning.
R4 - I learned to conduct independent research, something I had never done at this scale before. Beyond directing my own research project, I also improved my skills in teamwork, as I feel that we worked very hard to remain organized and to communicate effectively between team members.
R5 - I have learned a lot about how solar panels work as well as how farms work. I also have learned a lot about how to conduct an interview as well as how to present my technical findings to non-technical people.
R6 - I have learned how to better work with a group to meet different deadlines.
R7 - I have learned to be more patient when researching funding opportunities for this project, as the process can be frustrating when trying to find something that matches the requirements of the project.

Q11 - How did working in an interdisciplinary team affect your understanding of Agrivoltaics?
R1 - I got to focus on things that I enjoyed while also learning about electrical engineering tasks. Having many disciplines added a depth to the project that I am very thankful for. When I was lacking in a skill, I knew that someone else would be able to accomplish what I couldn't, which eased the stress of this project a lot.
R2 - This was one of those projects where everyone was able to make a unique contribution using their specific background and major, so none of us would have been able to get as much work done or learn as much just on our own.
R3 - It helped me to understand the problems and solutions as a whole when considering a proposed design. I very much enjoyed the experience.
R4 - It definitely benefited it. Coming from a mechanical engineering background, I had, at best, a basic understanding of electrical and environmental engineering concepts. By having team members with experience in these fields, they were able to cover my blind spots and to keep the project moving. The project simply would not have been as successful if any one team member was responsible for all of it: both due to the volume of work and the imperfect knowledge of each teammate.
R5 - Working with many different types of engineers was great because they all brought good questions and different perspectives on Agrivoltaics. It is always good to have different perspectives because people can catch things that I missed and vice versa.
R6 - It was really cool to see all the different aspects of engineering come together to find a solution. I was particularly interested in the electrical engineering aspect of it because I have not learned much about that field before.
R7 - Working with an interdisciplinary team affected my understanding of agrivoltaics by allowing me to listen to different perspectives about the specific requirements of an agrivoltaic farm. For example, an electrical engineering major might have different ideas than an environmental engineering major, but by hearing both perspectives, I was able to gain a deeper understanding of the specific requirements for an agrivoltaic farm.