Technical Feasibility Analysis of an Agrivoltaics System for Cotton Farms

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Abstract

Climate change has increased the value of sustainable methods, such as agrivoltaics systems which serve as the integration of agricultural practices and solar energy systems. Agrivoltaics systems allow farmers to contribute to the transition to renewable energy while providing security to agricultural businesses. This project introduces a portable agrivoltaics system, specifically tailored for cotton crops, and evaluates the structural integrity of its structure paired with the structure's shadow analysis. The portable structure could maximize the benefits of agrivoltaics and minimize the impact on agricultural activities, allowing farmers to access energy resilience while minimizing disruptions to the farmer's responsibilities. Additionally, a shadow analysis of the structure is performed to analyze the negative impact on the selected crop. This paper focuses on making the design portable, retractable, and height adjusting; therefore, optimizing the compatibility with cotton crops. These features allow the system's height to be adjusted accordingly with the crop height and make it suitable for allowing machinery access to the fields. A structural analysis of the design is conducted to assess its stability and resistance to extreme wind conditions. The shadow analysis code implemented for the design is developed using NOAA solar calculator equations, which allows for critical parameters, such as azimuth and elevation angles, to be determined to predict the shadow length and direction. The results of the study aim to support the development of agrivoltaics systems while minimizing disruptions to agricultural activities.

Keywords
Solar energy, agrivoltaics, structural analysis, shadow analysis

1. Introduction

As the popularity of renewable energy rises, so does the demand for land required to meet energy demands sustainably. Additionally, the growing population and the effects of climate change pose a threat to food security. Agrivoltaics is a possible solution to the increasing demand for energy and food security as it allows agricultural lands to generate renewable energy. However, it is important to balance the factors involved in the integration of agricultural and energy production, such as efficiency, cost , crop types, and soil health.

The paper builds on previous work based on the potential of agrivoltaics, the best strategy for optimizing land use, and relevant cotton production characteristics. As discussed early on in [1], the concept for agricultural practice and solar energy production involves optimizing solar panel density within the land, solar panel modeling, and assessing a crop's shade resistance. Dinesh and Pearce [2] further evaluated the potential for agrivoltaics using simulation models for solar energy and agricultural production. The results showed that farmers could experience a "30% increase in economic value" via agrivoltaics compared to traditional agricultural practices. Notably, the work considered shade-tolerant crops to manage crop yield losses caused by agrivoltaics structures. In this project, cotton has been selected as the low-input crop. Griffin, Buschemohle, and Barnes [3] provide insight into cotton production via the planting and harvesting capacities. In [4], the importance of knowing the machinery that will be used in farming operations and the relevant planting and harvesting dates is discussed. This method is relevant for the design of an agrivoltaics structure to accommodate the machinery and estimate the energy production during the crop's season. Relating to the solar panel density and agrivoltaics structure design, the authors [5] utilized the solar calculator created by the National Oceanic and Atmospheric Administration (NOAA) to determine the shadow area of the agrivoltaics structure. The work does this by utilizing the data and equations detailed in the calculator. This project seeks to determine the suitability of agrivoltaics in cotton fields by performing a technical feasibility analysis study. Cotton was selected as the crop since it is one of the most favorable rotational crops in Texas given its low-input nature [6].

2. Methodology

This section discusses the methods implemented for the structure's design and corresponding simulations. The calculations for the resulting soil pressure of the structure are also discussed. Additionally, the shadow analysis of the structure is completed by estimating the size of the structure's shadow using plotting features within MATLAB. The shadow analysis can help determine the optimal location for the structure within the farm but is limited by considering the generic overhead view shape of the structure and simulating one structure at a time.

2.1 Design Requirements

Multiple designs were explored, including a traditional canopy design and solar tree concepts. The final design was selected as a traditional canopy based on the constraints associated with cotton fields. These constraints include the usage of large irrigation machinery. Traditionally, cotton requires a center pivot irrigation system which consists of a large movable, swinging arm with sprinklers that moves in a circular pattern around a pivot point receiving a water source. As a result, the design was created to be portable, retractable, and height-adaptable to allow the structure to be moved and adjusted as needed. The folding mechanism would allow the structure to become a compact system prepped for storage when needed and protects the solar panels by having the solar cells face inwards when folded. Consequently, the structure size and weight were minimized to allow for easier movement and less damage to soil health. The effects on soil health were assessed by estimating the soil pressure caused by the structure. The design pursued a resulting pressure of less than 1,000 PSF, which is viewed as acceptable pressure to avoid soil damage. This value is derived from the assumption by [1] that the most used soil for farming consists of a loamy texture. Furthermore, a regulation [7] states that "loose to medium dense sands; firm to stuff clays and silts; alluvial fills" have an allowable soil bearing pressure of 1,000 PSF.

To maintain below the maximum capacity, the footing area of the structure must be adjusted depending on the structure's weight. Equations 1 and 2 were used to determine that this relationship was maintained.

$$Weight\ (lbs)/\ area\ (ft^2) \leqq 1{,}000\ PSF \quad (1)$$

$$Footing\ area\ (ft^2) = \frac{area\ (ft^2)}{4} \quad (2)$$

2.2 Shadow Analysis

The work assessed the shadow effects of the agrivoltaics structure by implementing data and equations from the NOAA calculator into MATLAB. In particular, the method previously completed by Martinez-Gomez [5] was implemented to determine the shadow area compared to the total farm area. Particularly, the equations derived from the NOAA calculator provide the required data for the calculations corresponding with the time range of the harvesting period for cotton [8]. This allows for the best estimation of the azimuth angle and zenith angle. The development of the shadow area throughout the day allows for the optimal location of the agrivoltaics structure within the farm. The optimal location is considered as one where the structure's shadowed area is located outside the farm as much as possible. Thus, it results in the crop experiencing elevated amounts of shade [5].

3.3 Solar Energy Potential Estimation

The final agrivoltaics structure requires an assessment of its solar energy production to justify the design. In particular, the solar energy potential of the structure can be assessed using HOMER under two different settings: non-tracking and tracking. The HOMER simulation location is based in a small field located in Kingsville, Texas. Additionally, HOMER uses the global horizontal irradiance data from the National Solar Radiation Database. The results for each setting are discussed under the results section.

3. Results

3.1 Design

The final conceptual design of the agrivoltaics structure is shown in Fig. 1, which shows the structure's portable, retractable, and height-adjustable features. The structure holds six panels which have been indicated via an arrow within Fig. 1a. The design has a height range of 18.2 ft to 31.3 ft and the capability of folding the frame to decrease the width from 12.4 ft to 4.6 ft. The structure at its maximum height is displayed in Fig. 1a and the folded frame is displayed in Fig. 1b. The folding mechanism of the frame requires the panels to complete an equivalent movement, as seen in Fig. 1c.

Given that the final design has a total weight of 12,000 lbs., the estimated footing area required per foot is approximately $3.025\ ft^2$. Although this footing area allows for the soil pressure to be below the maximum load bearing capacity, a smaller footing area would be more ideal. Provided that a smaller area would reduce the impact on crop growth and correspond with less material used for the agrivoltaics structure.

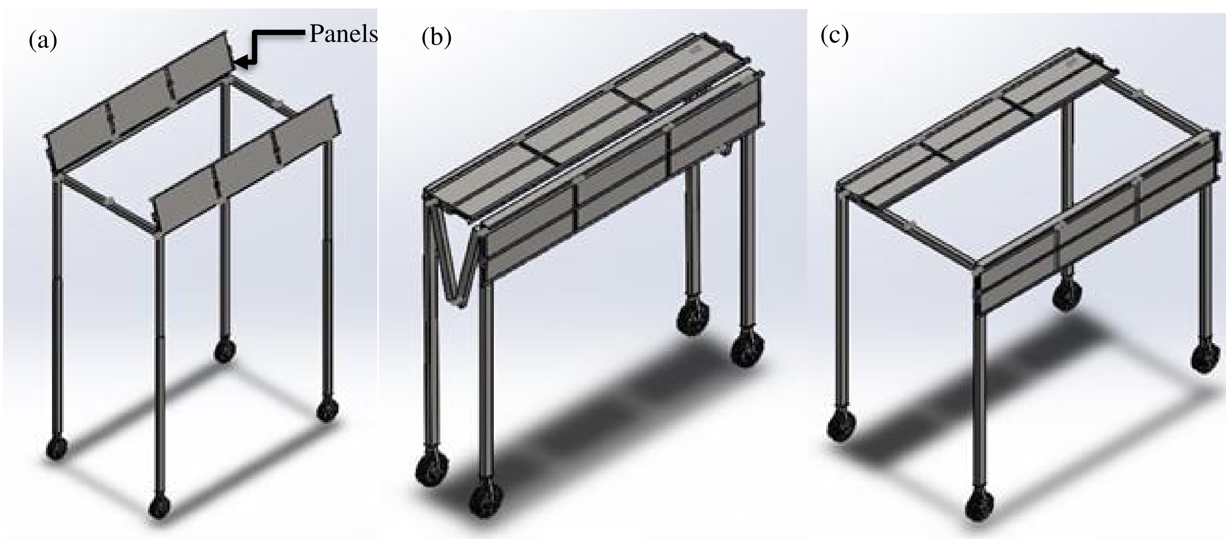

Fig. 1: The conceptual canopy design: (a) extended; (b) frame and panels folded; (c) panels folded.

The three main features would allow the structure to be extended vertically, folded horizontally, and for its panels to be folded to lay horizontally or vertically. SolidWorks finite analysis was conducted to simulate the structure's stability and response to the maximum wind speeds, which can be obtained from the National Solar Radiation Database (NSRDB) [9]. Notably, the initial design showed large stress and displacement values in the SolidWorks simulation. As a result, the frame thickness increased from 0.25 in. to 0.5 in. to improve reliability and stability. The simulations seek to evaluate the effectiveness of the structure against the solar panel system's weight and wind loading. The weight of the solar panel system acts as a force on the rectangular frame. A solar panel system consists of three solar panels, two solar array frames, two clamps, two actuators, two actuator supports, two vertical frames, two hinges, and one secondary frame. The solar array is the frame that holds the solar panels. Clamps are used to connect the solar panels to their frame (the solar array). Actuators are mechanical devices that rotate the angle of the solar panels, allowing the system to follow the sunlight. Hinges are used to connect the solar array with the panels to the main frame.

The weight of a single solar panel system is calculated via the summation of the weight of all components, approximately 295.3 lb. To define the fixtures, the bottom face of the supporting legs is set as fixed geometry. A gravity load (magnitude 9.81 m/s2 or 32.17 ft/s2) is applied to the top plane of the assembly in the downwards direction. The weight of the solar panel system acts as a force on the rectangular frame, and the load is applied to the top faces of the rectangular frame as seen in Fig. 2. In the simulation, all bodies of the assembly have a mesh size of 0.19 inches, but the hinges that connect the frame require finer mesh. Therefore, a mesh control is applied to give these bodies a mesh size of 0.08 inches. Materials for all parts have been defined, and no interferences were found in the assembly allowing SolidWorks to complete the simulation. The maximum stress of the frame is 2.960E4 psi and the minimum stress of the frame is 0.181 psi. The maximum displacement of the frame is 0.053 inches, and the minimum displacement of the frame is 3.937E-32 inches.

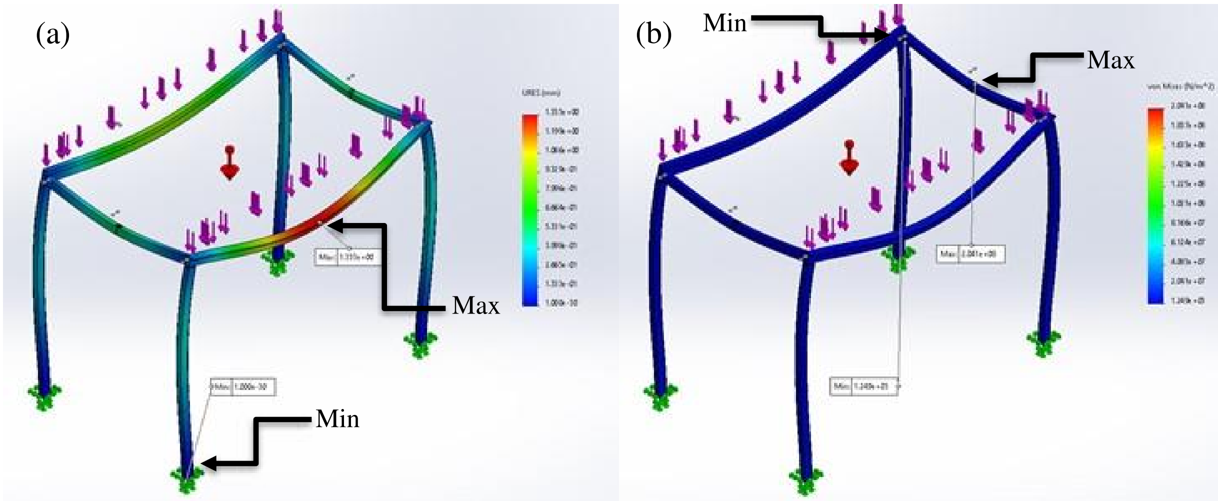

Fig. 2: Simulations results of the solar panels load via (a) stress and (b) displacement.

For the wind loading assessment, wind data from the previous 22 years is obtained via the NSRDB and sorted to determine the maximum wind speed, 11.5 m/s. This value is used to simulate the stress and displacement results of the agrivoltaics structure when experiencing gusts of wind. The maximum wind speed is converted to a force to allow the application of the corresponding load in the simulation. This process is completed via Equation 3, which represents the simulation of the wind loading.

$$force\ (N) = \left(\frac{kg}{m}\right) \times \left(\frac{m^2}{s}\right) = (area\ \times\ air\ density\ ) \times (wind\ speed^2\ ) \qquad (3)$$

These simulations intend to determine the frame's performance; therefore, the stress and displacement values found for the wind analysis are probed from the frame and not just taken as the given maximum and minimum values because these include the solar panels. The maximum stress of the frame is 1,232.51 psi and the minimum stress of the frame is 6.261E-3 psi. The maximum displacement of the frame is 0.404 inches, and the minimum displacement of the frame is 3.937E-32 inches. The results from the wind loading assessment can be seen in Fig. 3.

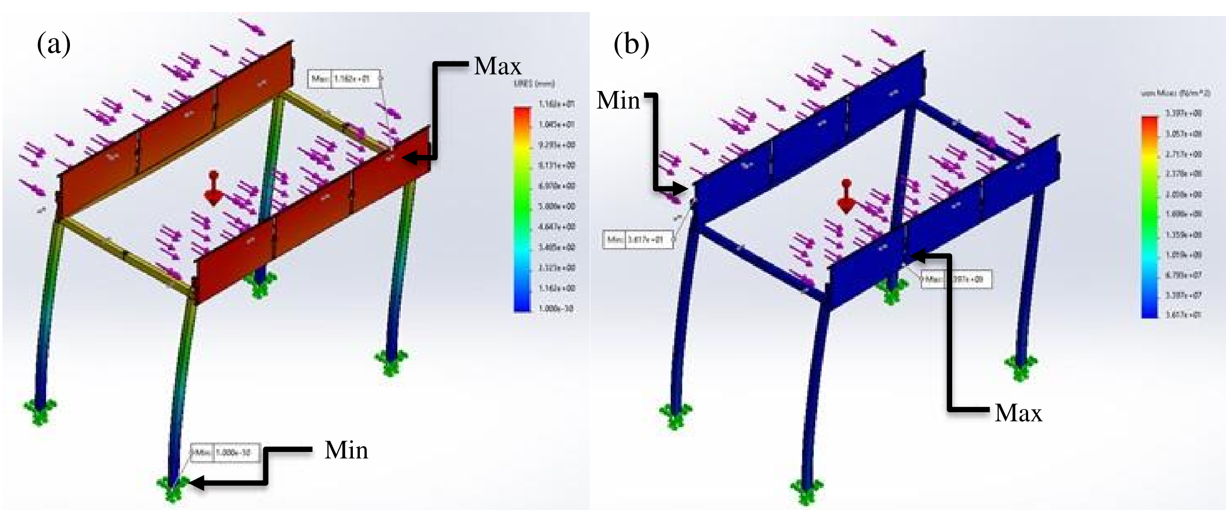

Fig. 3: Simulations results of the wind analysis via (a) stress and (b) displacement

The FEA results are listed in Table 1. As stated, the initial design of the agrivoltaics structure had a frame thickness of 0.25 inches and the final design implemented a frame thickness of 0.5 inches. The modification resulted in an improvement in the max stress and displacement experienced.

Table 1: FEA results

	Initial Design Max Stress (psi)	**Final Design Max Stress (psi)**	**Delta**	**Initial Design Max Displacement (in.)**	**Final Design Max Displacement (in.)**	**Delta**
Weight FEA	6.398e5	2.960e4	95.37%	4.307	0.053	98.78%
Wind FEA	6.769e5	1,232.53	99.82%	5.248	0.404	92.30%

3.2 Shadow Analysis

As discussed, the NOAA solar calculator equations were converted into a MATLAB code [7]. This allows for the visual assessment of the structure's shadow. In particular, Fig. 4. demonstrates the estimated shadow area generated by the structure at three different times. Each time-specific visual provides the shadow area for the minimum and maximum height of the structure. These estimations allow for the optimal location for the structure to be selected. Based on the simulated results, the ideal location would be near the outer, southern perimeter of the farm. By minimizing the shadow impact on the crops, it is expected to minimize the impact of the agrivoltaics structure on the cotton yield.

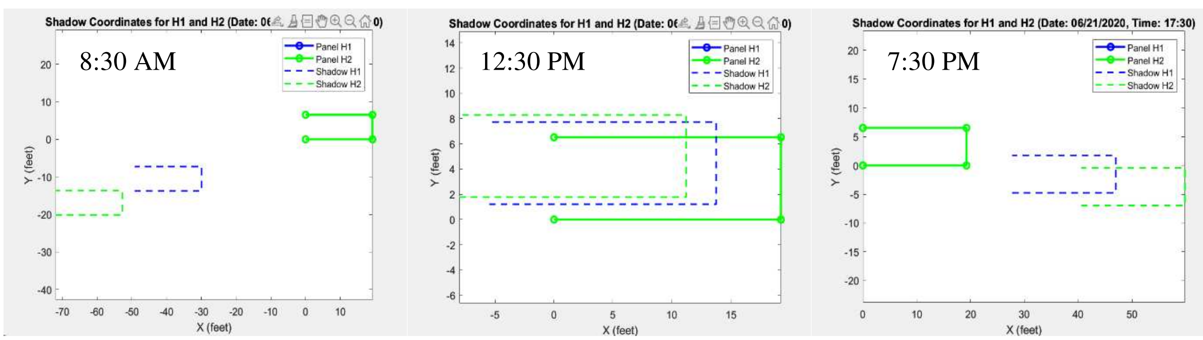

Fig. 4: Results from the MATLAB code showing the different shadows generated on June 21, 2020.

3.3 Solar Energy Potential Estimation

The final conceptual design allowed for six panels per structure. The simulations via HOMER utilized a 72 cell, monocrystalline module with a rated capacity of 0.345 kW and an efficiency of 17.8%. Table 2 summarizes the results of the simulations for two system types: Non-tracking and tracking. The geolocation parameters previously used for the shadow analysis were implemented into HOMER to estimate the annual solar energy generation. The data collected for the simulations aligned with the planting, irrigation, and harvesting timeline for the Coastal Bend region in Texas. Typically, within the region, late March and April are for planting the crops with August through October being considered harvesting season [8]. HOMER simulations estimated that six systems with a fixed angle can produce 19,492 kWh/yr. With daily adjustable angle, the energy production increases to 20,535 kWh/ yr. The results of the simulations are summarized in Table 2.

Table 2: HOMER results showcasing energy production per agrivoltaics system

System Type	**Estimated Energy Production (kWh/year)**	**Capacity Factor**
Non-tracking, limited	19.492	17.9%
Tracking, limited	20,535	18.9%

4. Conclusions

The project designed a portable, retractable, height-adjusting agrivoltaics system as an alternative design option suitable for cotton crops compared to the traditional canopy agrivoltaics design. Since this design is intended for crops with specific growing requirements, it can be adjusted accordingly. The study evaluated the shadow impact of the final conceptual design, estimated the structure's potential energy generation, and evaluated the structure's stability via FEA. The FEA results show that the stress values were well below the allowable limits and the maximum displacement is within the allowable range. The shadow analysis method implemented could decide the structure's placement within the farm. The method allows the assessment of the shadow's placement and size throughout the day. The energy generation simulations reaffirmed that the system produces a viable amount of energy, supporting the structure's position as a sustainable resolution. Future work can be done to optimize the weight of the system with respect to increasing energy production and minimizing shadow area. Similarly, future research should address the limitations of the structural analysis, particularly focusing on stress analysis during the relocation process. The economic feasibility of the system is required to confirm the advantageous opportunity for cotton farmers. Additional future research should include assessing the impact of the shadow on the yield for the cotton crops.

The advancement of sustainable energy has led to various technological developments including agrivoltaics. However, the practice of agrivoltaics still requires various considerations to successfully merge solar energy production and agriculture. The needs of the system must be considered and challenges that follow must be anticipated. The optimal configuration for the solar panel system must be selected depending on the type of crop the system is intended for. Additionally, the design must consider optimizing the reduction of the impact on crop growth and soil.

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