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Agrophotovoltaic system in Alagoas – Design contribution and performance analysis of support structures for photovoltaic solar panels

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Abstract. Agrophotovoltaic (APV) systems are widely used nowadays. They are shown as a sustainable strategy transition to renewable energies and are a "dual-farming" technique combining photovoltaic and crop cultivation. The sugarcane energy sector is the main economic activity in Alagoas. The electrical transmission structure and the available cultivated area offer optimal symbiotic conditions for implementing these systems. This work proposes a structure to support the photovoltaic solar panels and their loads as well as the flexibility to adjust the angle of the panels and modify the distance between the individual structures. The estimates of the structural loads were carried out through the combinations of the predicted actions, such as the weight of photovoltaic solar panels and structural elements and the action of the wind, considering the most unfavorable situation in the structure sizing. Structural analysis and design were carried out considering the Service Limit State (SLS) and the Ultimate Limit State (ULS) through the structural analysis based on the finite element method, SAP2000, considering the Brazilian standards. All results are within limits established in the Brazilian National Standards Organization, Associação Brasileira de Normas Técnicas (ABNT) in Portuguese.

Keywords: Agrovoltaic Systems; Agrivoltaic; Finite Element Structural Analysis; Sugarcane Crop Production.

1 Introduction

New renewable energy sources as a way to meet global energy demand and simultaneously replace fossil fuels are one of the biggest challenges of our time. In this regard, photovoltaic (PV) systems have great potential to meet this demand and are considered even more efficient at capturing solar energy than photosynthesis, as suggested by Blankenship et al. [1]. In addition to these factors, the low installation cost in open areas, according to Fraunhofer ISE [2], has led to the establishment of PV systems on agricultural land. However, this can result in a land-use conflict between energy and food production, resulting in problems for society, particularly in those with limited planting areas.

Concerns about the loss of arable land for more profitable PV power production due to the intensive installation of large-scale ground-mounted PV installations have led to a decline in the uptake of this technology in some regions. To appease these concerns, the development of agrophotovoltaic systems (APV) can be seen as a way to combine PV and food production in the same cropland area. This technology was idealized by Goetzberger and Zastrow [3] in the 80's. According to Schindele et al. [4], more than 2200 APV systems are installed worldwide.

In the state of Alagoas, the production of sugarcane is the main economic activity, so large areas are used for the cultivation of this crop, which is present in 54 of the 102 municipalities of Alagoas and generates about 90,000 direct jobs, according to SINDAÇUCAR [5]. Most sugarcane plants in the state of Alagoas have a well-developed electricity transmission structure that is favorable for the installation of APV systems for the sale of electricity.

It is necessary to have well-designed support structures capable of resisting the loads inherent to this type of system. In this work, the estimations of these loads were performed through the combinations of the expected actions, such as the self-weight of the photovoltaic solar panels and structural elements and the wind action, considering the most unfavorable situation in the design of the structure. This research was conducted in order to verify the steel structure designed to support the solar photovoltaic panels of photovoltaic panels of the agrophotovoltaic system, obtaining the resulting displacements and maximum longitudinal normal stresses using SAP2000. The model was evaluated considering the service limit and ultimate limit states.

2 APV Systems

As mentioned earlier, the concept of APV was intruded by Goetzberger and Zastrow as a method to obtain solar energy and crop production in the same area. The initial idea was to raise the panels about 2 meters above the ground and increase the spacing between them, decreasing the shading effects on the crop. Dinesh and Pearce [6] showed that applying this technique can increase farm income by more than 30% when losses from the shading effect are minimized by using suitable crops. Dupraz et al. [7] showed that productivity could be increased by about 70% by using APV systems.

APV systems are about sharing sunlight for the co-production of food and energy in the same land space; therefore, designs must be able to overcome physical soil constraints and adverse climatic conditions, besides promoting the best relationship between food productivity and energy production.

2.1 Existing concepts and designs

In recent years several commercial and research APV plants have been installed worldwide. In northern Italy, installed systems have a capacity of about 1500kWp using solar modules (4~5 meters high), Casarin [8]. Several designs have been studied in commercial and research plants, as shown in Fig. 1. In Germany, the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) is at the forefront of research on APV systems. In Heggeslbach/Germany, Fig. 1(d), the photovoltaic modules are mounted on stilts with a vertical height of 5m. In the Chilean subsidiary Fraunhofer Center for Solar Energy Technologies (Fraunhofer CSET), three different pilot plants have been installed near Santiago de Chile to investigate the implementation in Curacaví/Chile, Fig. 2 (f).

Figure 1. Commercial and research plants (a) Les Renardieres/France* (b) Castelvetro/Italy* (c) Jinzhai/China* (d) Heggeslbach/Germany** (e) Pionlec/France* (f) Curacaví/Chile**. * © Fraunhofer ISE ** © REM Tec.

3 Methodology

3.1 Description of the region and research site

The field research involved installing a suspended APV system above a sugarcane (*Saccharum ssp*.) crop. The site is within a commercial cultivation area of Usina Santa Clotilde, adjacent to the Campus of Engineering and Agricultural Sciences (CECA) of the Federal University of Alagoas (UFAL), with geodesic coordinates 09º 28' S; 35º 49' W and 127 meters above sea level.

3.2 Installation of the agrophotovoltaic system

The installation took place with three different configurations of photovoltaic panels. The structures that allow the elevation of the PV system will be the same in all configurations, a structural unit (stilt unit) with two columns and a horizontal axis composed of 15-meter stringers on which the photovoltaic panels will be fixed.

The densities of photovoltaic panels, which will be tested, will have the following ratios between the area of photovoltaic panels and the area of sugarcane cultivation 0.285, 0.33, and 0.40 which will be provided by the respective spacing between structural units, 10, 8 and 6 meters.

3.3 Characteristics of photovoltaic modules

The solar photovoltaic panel installed on the structure, Fig. 2, is from JA Solar, with the characteristics shown in Tab. 1, and its dimensions and mass were employed in the structural design.

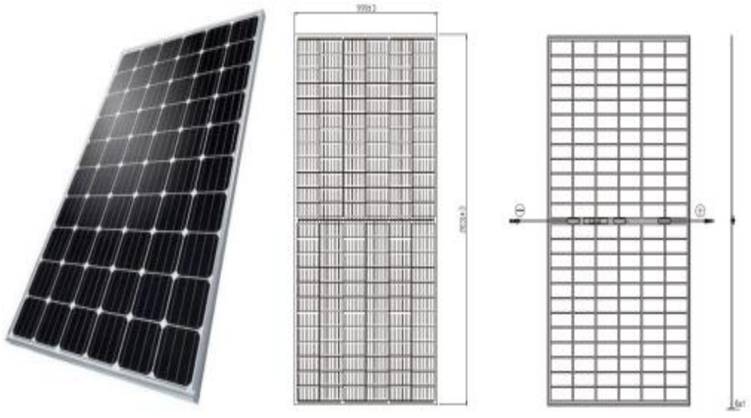

Figure 2. Photovoltaic module employed in the APV system.

Table 1. Properties of the photovoltaic module

Specification	Data
Cell Type	Monocrystalline
Cell Arrangement	144(6x24)
Dimensions	2031x999x25mm
Mass	29.1kg
Frame material	Anodized aluminum alloy

3.4 Structural analysis and design

The analysis and design of the structure were performed by the structural analysis software based on the finite element method, SAP2000, adopting the coefficients presented in Tab. 2. Two cases were considered with respect to wind direction: frontal wind (1) to the panels and rear wind (2). For the Service Limit State (SLS), frequent service combinations were considered, and for the Ultimate Limit State (ULS), normal ultimate combinations were assumed based on NBR 14762 [9].

Table 2. Coefficients of NBR 14762 [2]

	SLS 1	ULS 1	SLS 2	ULS 2
Wind action	0,3	1,4	-0,3	-1,4
Self-weight	1	1,25	1	1,00
Panel Weight	1	1,5	1	1,00
Max. displacement	L/250*	-	L/250*	-

*L = the gap between columns.

The structural units that support the panels are made of A-36 structural steel, and their properties are presented in Tab. 3. Each unit is composed of four 15-meter-long beams, two 3-meter-long transversines, and two 7-meter-long columns. Between columns, there is an 8.5-meter gap, which will allow for the passage of equipment and the growth of sugarcane. The structure holds a total of 30 photovoltaic solar panels, as shown in Fig. 3, and has a system to adjust the inclination angle of the panels.

Figure 3. Overview of the structural unit supporting the photovoltaic solar panels.

Table 3. Mechanical Properties of A-36 Structural Steel

Constitutive relation	Value
Specific mass	7850 kg/m³
Longitudinal elasticity module	199,947.98 MPa
Poisson coefficient	0.32
Yield strength	250 MPa

3.5 Wind speed and force

The wind characteristics, such as speed, force, and pressure, as a function of the soil characteristics, obstacles, and shape of objects, were obtained based on NBR 6123 [10]. The wind force acting on the panel was calculated according to Oliveira [11], as shown in Eq. 1.

$$F_v = \frac{1}{2} \cdot \rho \cdot (V_k)^2 \cdot A \cdot sen(\theta_{max}) \quad (1)$$

where ρ is the air density, F_v is the wind force, A is the area of the panel, V_k is characteristic wind speed, calculated according to NBR 6123 [10] and θ_{max} is the angle of inclination of the painel.

4 Results and discussion

When dimensioning the structure, a rectangular tubular profile was adopted for the columns with the following dimensions: 250 mm x 150 mm and 4.75 mm thick. For the transverse, a stiffened U profile was adopted with the following dimensions: 200 mm (height) x 75 mm (width) x 25 mm (flange) and 4.75 mm thick. For the beams, the hardened U-profile was adopted with the following dimensions: 200 mm (height) x 75 mm (width) x 25 mm (flange) and 3 mm thick. The wind action is the main external force acting on the structure. According to the adopted environment features and NBR 6123 [10], the wind velocity characteristic is 28.5 m/s, and the force acting on the panel is 525.04 N.

For SLS 1 the maximum resultant displacement was 29.2 mm. The sensory acceptability limit for the displacement is 8500/250 = 34mm. Therefore, the value found in the simulation, according to Fig. 4(a), is below the recommended by NBR 6118 [12]. This means that the support structure of the panels will deform within the accepted sensorial limit, which means not being perceptible to users of the installation area of the photovoltaic solar panels. The simulation shows that the largest displacements are in the beams, especially in the uppermost beam.

For ULS1, the maximum longitudinal normal stress found was 154 MPa, being compressive, Fig. 4(b). As this stress is lower than the yield strength of A-36 steel (250 MPa), there will be no yielding of the material and consequently no damage to the structure. The safety factor is given by 250/154 = 1.62. It is also possible to notice stresses close to 120 MPa (tensile) in the transverse/longitudinal contact region, possibly caused by the overhang region of the structure. However, this would not compromise the structure for the same reason cited above.

For the SLS 2, Fig. 4(c), the maximum resulting displacement was 34 mm. The sensory acceptability limit for the displacement is 8500/250 = 34mm. The analysis suggests again that the largest displacements are found in the beams, mainly at the ends of the outermost beam.

For ULS 2, Fig. 4(d), the maximum longitudinal normal stress found was 148 MPa, being tensile. Similarly, if the wind acts posteriorly to the photovoltaic solar panels, there will be no yielding of the material and, consequently, no damage to the structure. The safety factor is given by 250/148 = 1.69.

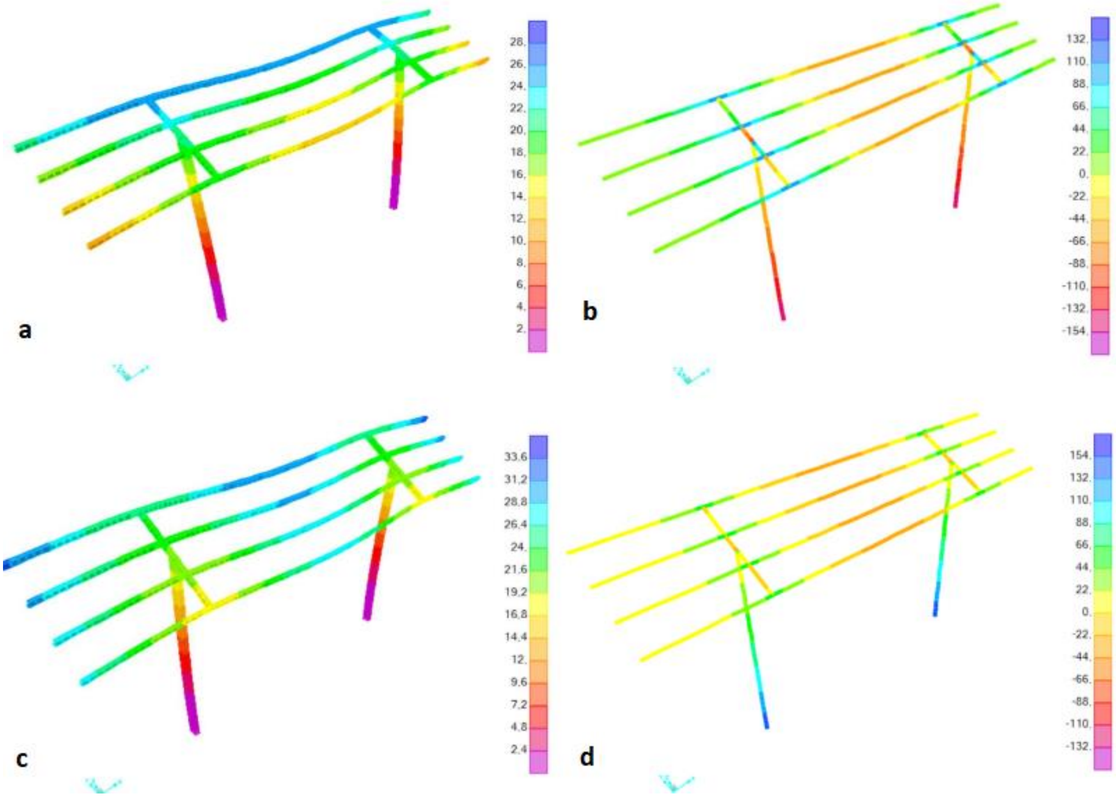

Figure 4. (**a**) Displacement (mm) for SLS1 (**b**) Maximum Longitudinal Normal Stress (MPa) for ULS 1 (**c**) Displacement (mm) for SLS2 (**d**) Maximum Longitudinal Normal Stress (MPa) for ULS 2.

5 Conclusion

The profiles used to make the support structure are cold-formed and relatively easy to find on the market and proved to be a viable option from the structural point of view. The structural analysis based on the finite element method, employing the SAP2000 software, considering Brazilian standards, proved very efficient. The maximum resulting displacement of the structure was 29.2 mm for SLS 1 and 34 mm for SLS 2, and they are in the gap between the columns, being practically imperceptible and within the normative standard.

The maximum longitudinal normal stress found was 154 MPa (compressive) and 148 MPa (tensile) for ULS 1 and ULS 2, respectively, lower than the yield stress of the steel employed in the structure. The safety factors are also within safety standards. All results found in the simulation are within limits established by the Brazilian Association of Technical Standards (ABNT).

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