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Modeling of the assembly construction strength and work efficiency of agro photovoltaic installation

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ABSTRACT

This article presents analyses and computational simulations conducted to validate the developed design of a mounting structure for an agro photovoltaic (Agro PV) system. In addition to assessing the structural strength of the proposed mounting system, the study also assessed the potential for electricity generation using the suggested design config-uration. Modeling the structural strength and efficiency of Agro PV installations is crucial for optimizing their design and performance. This article provides an introduction to the key parameters and methodologies used in modeling these complex systems. The authors analyzed the structural resistance of the proposed Agro PV installation to environmental loads such as wind and snow, and how to assess the performance of the investment process itself. Accurate modeling of these factors can significantly reduce project risk, lower costs, and ensure a harmonious relationship between energy generation and food production. The results may be useful for designers of Agro PV farms, especially in Polish envi-ronmental and regulatory systems. The conducted simulation studies are the starting point for experimental research on real facilities, where agricultural aspects will be ver-ified under real conditions.

Keywords: Agro PV farm, agro photovoltaic, installation design, economic aspects.

INTRODUCTION

Agro photovoltaic (Agro PV) systems, which integrate photovoltaic electricity generation with active agricultural production on the same land area, have emerged as one of the most promising multifunctional solutions for addressing global challenges related to energy transition, food security, and sustainable land management. The fundamental concept of combining crop cultivation with solar power generation enables a simultaneous increase in agricultural productivity and renewable electricity output on the same land unit. This dual-use potential is illustrated in Figure 1, which shows how combining agricultural and energy production can increase total land-use efficiency by more than 60% compared to traditional, separate land allocation [1, 2].

Across Europe, Asia, and North America, Agro PV systems are becoming increasingly sophisticated. Modern installations use elevated support structures that ensure adequate sunlight for crops, minimize shading stress, and maintain sufficient clearance for farming machinery. As the technology matures, numerous barriers and engineering challenges have been identified, along with possible design- and technology-oriented solutions. These are summarised in Table 1, which presents key factors influencing Agro PV deployment, such as agricultural compatibility, tilt optimization, maintenance accessibility, microclimate control, and environmental impact [4–8].

Despite these advancements, the global scientific literature is still dominated by agronomic, environmental, or economic analyses, whereas significantly fewer studies investigate the structural

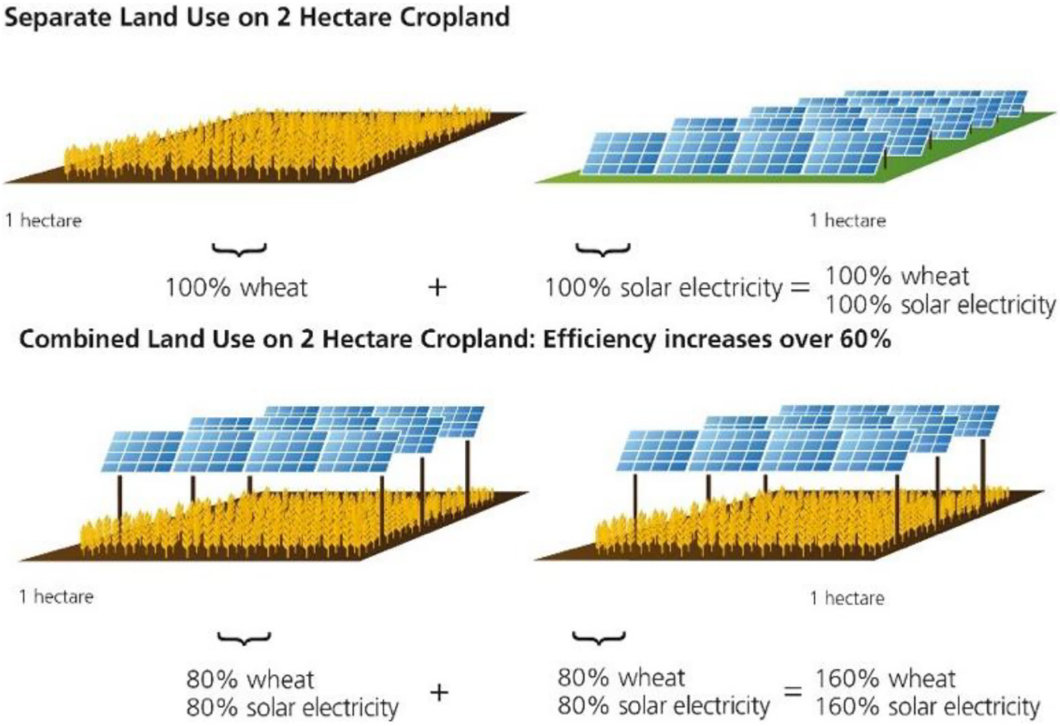


Figure 1. Idea of Agro PV system [3]

performance of Agro PV support systems under real climatic loads [6, 9, 10]. Most recent research focuses on wooden or hybrid mounting structures, adaptable tilt configurations, or low-cost modular systems, with relatively limited attention given to steel multi-frame structures, which are preferred in Central and Eastern Europe due to their durability, long operating lifetimes, and resistance to snow and wind loading [12, 13].

At the same time, economic viability remains a key driver for Agro PV adoption. As shown in Table 2, Agro PV installations typically exhibit higher investment and operational costs than ground-mounted PV or rooftop systems, but they offer improved land-use efficiency and the ability to generate revenue from both crops and electricity, which can offset these costs. Understanding the relationship between structural design, mechanical durability, and long-term energy yield is therefore essential for enabling cost-effective Agro PV deployment at scale.

While countries such as France, Germany, Italy, the USA, China, and Japan have already implemented national support frameworks, Poland remains at an early stage of Agro PV development [3, 6, 9]. The Polish agricultural sector faces unique challenges:

- strong gust-based wind conditions and moderate-to-high snow loads,
- a fragmented farmland structure requiring lightweight yet durable support frames,
- a lack of national Agro PV design guidelines,
- limited validated engineering models supporting investors and farmers [2, 9, 14].

This situation highlights three key gaps that this research aims to address. There is a lack of studies performing Eurocode-compliant modelling of Agro PV support structures under Polish wind and snow conditions, including FEM simulations, load-case verification, and structural safety assessment. No validated and optimised steel Agro PV support designs exist on the Polish market, despite industry demand for systems that combine mechanical strength, ease of assembly, and long-term operational reliability. Farmers lack engineering-validated solutions that maintain adequate machine clearance, support crop growth, and minimize disturbance to agricultural operations [15–17].

In response to these challenges, this study presents an integrated approach that combines structural modelling, FEM simulation, and energy production analysis for a four-frame steel Agro PV structure designed for Central European conditions. The proposed methodology directly supports future standardisation, industrial implementation, and safe large-scale

Table 1. Barriers and solutions for the implementation of Agro PV [4, 5, 7, 9–11]

Barrier	Design-related solution	Technology-related solution
The need to adapt PV construction to agricultural needs	• Flexible height and spacing: PV module constructions adapted to the requirements of agricultural machinery. • Adequate row spacing: Sufficient space between rows of PV modules to allow for mechanized harvesting and free access to crops.	Semi-transparent modules: The use of PV modules that let some light through allows for photosynthesis and plant growth.
Optimization of PV construction for sunlight for crops	• Orientation and tilt angle of PV modules: Adjusting the orientation (e.g., east-west) and tilt angle of the panels to minimize shading - uniform access to light for crops. • Shading dynamics: Projects that take into account the plant growth cycles and light requirements.	Tracking systems: The use of movable structures that follow the sun can optimize both energy production and light access for plants.
Financial and profitability issues	• Hybrid systems: Designing Agro PV as an integral part of the agricultural economy, where revenues from crops and energy sales complement each other. • Cooperation with local communities: Creating projects that involve the participation of local farmers and investors.	• Efficient modules: The use of panels with higher efficiency, which generate more energy from a smaller area, which increases profitability. • High-Efficiency Modules or Technologies (e.g., Bifacial Module - bPV Technology) • Energy storage systems: Integration of batteries that allow for storing surplus energy and using it on the farm or selling it during peak hours.
Water and microclimate management	Rainwater harvesting systems: Designing structures in such a way as to collect rainwater flowing from the panels and direct it to irrigate crops.	• Intelligent irrigation control: Systems that monitor soil moisture and automatically start irrigation based on the data collected. • Integration of Internet of Things (IoT) - enabled sensors and wireless sensor networks to provide real-time data on key parameters such as crop health, soil health (including moisture and nutrient levels), and solar energy production.
Impact on soil and the environment	Minimal invasiveness: The use of structures that require a minimal number of foundations and allow for the protection of soil structure.	Ecological materials: The use of materials that are durable, but at the same time can be easily recycled.
Maintenance and servicing	Easy access: Designing structures that facilitate the servicing of PV modules.	The use of automatic cleaning robots that independently remove dirt from PV modules.

Table 2. Assumptions regarding electricity production costs in Agro PV systems [1]

Type of PV installation	Open space > 20 MWp		Agro PV > 5 MWp		Rooftop installations > 10 kWp	
	Min.	Max	Min	Max	Min	Max
Investment costs (EUR/kWp)	550	800	700	1100	750	1200
Financing costs	5%	5%	5%	5%	6%	6%
Lifespan (years)	25	25	25	25	25	25
Operational costs (EUR/kWp/year)	10	14	9	16	12	18
Revenue (kWh/kWp/year)	950	890	920	870	950	860
Capital costs (EUR/year)	39	57	50	78	59	94
Electricity production costs (ct/kWh)	5.16	7.95	6.38	10.81	7.44	13.01

deployment of Agro PV technologies in Poland and beyond.

In response to these gaps, this study develops a four-frame steel Agro PV structure and evaluates it using a combined methodology that integrates:

- Eurocode-based wind and snow load modelling,
- Finite element method (FEM) structural simulation,
- PV energy yield estimation for a 100 kWp installation.

This dual mechanical–energetic perspective contributes to the advancement of engineering guidelines for Agro PV deployment in Poland

and other regions facing similar environmental challenges, Table 3.

This study integrates Eurocode-based wind loading, FEM structural analysis and PVSyst energy modelling within a single framework, providing a unified assessment of mechanical behaviour and PV performance. By analysing how geometric parameters such as height, tilt and row spacing jointly influence both structural response and energy yield, the work addresses a documented gap in engineering guidelines for agrivoltaic support systems. Although crop modelling was not included, the resulting shading characteristics are evaluated against agronomically recommended ranges, offering practical insight into the potential suitability of the proposed structure for AV applications.

MATERIALS AND METHODS

The structural parameters used in this study were selected based on state-of-the-art agrivoltaic (AV) design guidelines. Typical AV installations operate at heights of 3–5 m, tilt angles of 25–35°, and row spacing values of 4–8 m, depending on crop shading tolerance and machinery access requirements [15, 18, 24]. Therefore, the adopted tilt, height and row spacing fall within the recommended ranges for European agro-climatic conditions, ensuring both structural feasibility and energy performance consistency with existing demonstrators

The methodology used in this study integrates structural strength modelling of an AgroPV support system with an energy-production simulation of a 100 kWp photovoltaic installation. The workflow consists of four main stages: (1) definition of the structural geometry and material model, (2) determination of environmental loads according to Eurocodes, (3) FEM numerical analysis of the four-frame support structure, and (4) estimation of the annual electricity yield using PVsyst [3, 12, 21, 25].

All steps, assumptions and parameter values were explicitly verified based on engineering calculations provided in the design documentation

Table 3. Overview of recommended modeling and simulation tools for Agro PV research [5, 8, 18–23]

Tool – modeling methodology/ category of actions	Application in Agro PV	Key benefits
Computational fluid dynamics (CFD) / Structural – Microclimate	• Analysis of wind loads on tall PV structures; Simulation of air flow, temperature, and humidity distribution under panels; • Informs structural design and microclimate management.	• Quantifies complex aerodynamic forces on the Agro PV mounting structure; • Predicts microclimate changes (soil/air temperature, wind speed); • Provides information on construction design and microclimate management
Finite element method (FEM) / Structural – Geotechnical	• Structural analysis of support frames under various loads (wind, snow); • Modeling the behavior of screw piles and other foundations under axial and lateral loads.	• Assesses structural integrity and deformations; • Optimizes material use and foundation design; • Predicts mounting stability in different soil conditions.
Ray Tracing – Radiation Models (e.g., APyV) / Agricultural – Energy	• Quantifying the distribution of photosynthetically active radiation (PAR) on crops; • Simulating shading patterns; • Optimizing light management for crops and PV panels.	• Provides highly accurate data on light distribution; • Key for understanding the impact on yields; • Informs dynamic tracking strategies for light sharing.
Crop Growth Models / Agricultural	• Predicting crop yields under Agro PV shading and microclimate conditions; • Assessing the impact of light limitations on crop growth.	• Quantifies agricultural productivity; Enables yield prediction before Agro PV installation; • Helps identify suitable crop types for specific Agro PV projects.
Techno-Economic Models (e.g., SAM, MINLP, FP) / Economic	• Cost-benefit analysis, ROI, NPV, LCOE for Agro PV projects; • Optimizing economic profits and operational costs.	• Assesses financial viability and profitability; • Compares different design scenarios; • Supports investment decisions by quantifying revenue streams and costs.
Artificial Intelligence (AI) – Big Data / Integrated	• Predictive analytics for energy and crop yields; • Smart control systems for dynamic PV module tracking; • Monitoring and optimizing system performance.	• Increases prediction accuracy; • Enables real-time optimization and adaptive control; • Supports data-driven decision-making in complex systems.

Structural model definition

The analysed support structure is a four-frame Agro PV mounting system consisting of:
- load-bearing steel columns (RP140 × 80 × 6 mm),
- longitudinal beams (C240 × 120 × 5 mm),
- cross-bracing members (RK40 × 3 mm),
- panel mounting rails and welded/bolted joints,
- a total structure height adapted to agricultural machinery clearance requirements.

The supporting frame was modelled as a three-dimensional spatial beam system. All members were represented using 3D beam finite elements with six degrees of freedom per node, and cross-sections matching the real structural profiles. Connections between members were assumed fully rigid unless specified otherwise in the design documentation.

Column bases were modelled with fixed-base boundary conditions representing screw-pile foundations. The assumed foundation stiffness corresponds to values reported for steel piles embedded in medium-dense soils and directly influences the lateral deformation of the structure. This representation provides a conservative estimate of the expected soil–structure interaction. Frame interaction between adjacent supports was included through beam continuity, and the entire structure was analysed as a single multi-frame system to correctly capture global stiffness and load distribution

All structural components were modelled using steel S235 with:
- Young's modulus: E = 210 GPa,
- Poisson's ratio: $\nu = 0.3$,
- design yield strength: $f_y = 235$ MPa,
- density: $\rho = 7850$ kg/m^3.

These parameters are consistent with the structural design documentation. The mesh was automatically refined near joints and load application points to ensure numerical accuracy. A convergence check confirmed that further mesh densification resulted in less than 2% variation in maximum stress values.

Material properties

The purpose of the conducted analysis is to verify whether the designed four-frame support structure for photovoltaic panels meets the requirements of Eurocode 1 – Actions on Structures – PN-EN 1991-1-4: "Wind Actions" and PN-EN 1991-1-3: "Snow Loads". Additionally, a static strength analysis was performed to assess the structure's resistance to wind and snow loads acting on the panels and the supporting structure.

Designing Agro PV systems requires a thorough understanding and consideration of dynamic environmental loads that can impact their stability and longevity. Wind and snow loads are key factors, as well as other atmospheric factors.

The subject of the structural analysis is a four-frame support structure designed specifically for photovoltaic panels. This particular design choice suggests a deliberate effort to balance robust structural stability with practical agricultural requirements, such as providing adequate space for agricultural machinery. The Agro PV support structure was manufactured from S235 structural steel, a low-carbon material containing up to 0.17% C and 1.40% Mn, with P and S limited to 0.040%. Nitrogen (0.012%) and copper (up to 0.55%) further enhance stability and corrosion resistance. This composition provides good weldability, moderate strength and reliable performance under typical environmental loading. The mechanical properties and chemical composition of the steel are summarized in Tables 4.

This chemical composition directly influences the steel's mechanical properties and its suitability for various environmental conditions, including potential corrosion in agri-cultural applications where exposure to factors such as ammonia or high humidity levels may occur. This detailed material specification provides the basis for the reliability of subsequent strength calculations. The mechanical properties of S235 steel are crucial for assessing its resistance to deformation and cracking under load.

Figure 2 presents fundamental technical parameters of Agro PV system technology. Figure 3 presents the geometric model of the designed structure, detailing the load-bearing elements and their dimensions. Each of the four load-bearing segments accommodates 10 photovoltaic panels, each with dimensions of 1000 × 2000 mm.

The study involved analytically determining the maximum deflection value and the stress levels at the ultimate limit state for individual structural elements and specific load cases in accordance with the aforementioned standards. The calculations were performed using Graitec Advance Design software, designed for the analysis and design of steel, reinforced concrete, and timber structures, as well as for the automated

Table 4. Mechanical properties of S235 steel

Dimension (mm)	Nominal yield strength	Tensile strength	Elongation at break
	Rp0.2 N/mm^2	Rm	A%
≥ 5 ≤ 10	355	470 ÷ 840	8
> 10 ≤ 16	300	420 ÷ 770	9
> 16 ≤ 40	260	390 ÷ 730	10
> 40 ≤ 63	235	380 ÷ 670	11
> 63 ≤ 100	215	360 ÷ 640	11

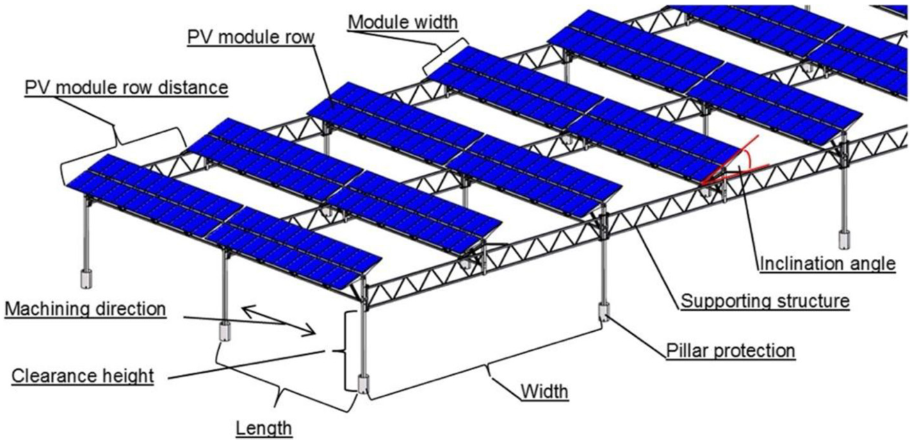


Figure 2. Fundamental technical parameters of Agro PV system technology [11]

generation of design reports. Wind loads were calculated based on the PN-EN 1991-1-4 standard, which defines wind actions on structures. The calculation process included determining wind speed, pressure, and forces acting on the structure, taking into account local climatic and geographical conditions. Terrain categories were also established, and factors such as roughness and topography were considered. Snow loads were analyzed in accordance with the PN-EN 1991-1-3 standard. The load values depend on the snow zones in Poland, with specific loads per square meter assigned to each zone [13].

Wind calculations

Wind actions were defined according to EN 1991-1-4, using a quasi-static gust-effect representation, which is the standard engineering approach for ground-mounted PV and AV structures. Although dynamic flow phenomena may occur, recent CFD studies show that Eurocode-based methods remain conservative and appropriate for design verification [25].

The basic wind velocity, exposure category, terrain roughness and pressure coefficients (cpe/cpi) were assigned following national annex recommendations. Four load cases (LC1–LC4) were analysed: dead load, wind +X, wind −X, and wind transverse

Wind is considered the most significant load that must be considered when designing support structures for photovoltaic systems, including Agro PV. Aerodynamic forces acting on panels can generate significant stresses and bending moments in structural elements, which in extreme cases can lead to deformation, damage, or even complete failure of the installation. The height of the structure and the angle of the panels directly influence the magnitude and distribution of these loads. Taller structures and those with a larger surface area exposed to wind are naturally more susceptible to its damaging effects.

The calculations covered both permanent and exceptional load cases, taking into account the roof shape, wind exposure, and other factors. The structural response calcu-lations begin with determining the basic wind speed using the following equation [13]:

$$v_b = c_{dir} \cdot c_{season} \cdot v_{b,0} \tag{1}$$

where: v_b – basic wind speed, $v_{(b,0)}$ – fundamental value of the basic wind speed according to Table 3 of the aforementioned standard, c_{dir} – directional factor selected according to Table 4 of the aforementioned standard, c_{season} – seasonal factor (for movable structures intended for year-round use, it is recommended to assume a value of 1).

The values of the above factors are also determined based on the geographic zone. The standard divides the territory of Poland into three zones: the first pertains to the central belt of the country, the second to the northwestern region, and the third to the southern border area. Along the zone boundaries, within a 10 km wide strip, average values specified in the standard for the respective geographic zones may be adopted. For the analysis, it was assumed that the designed structure would be used within the first geographic zone.

The assumed altitude above sea level for the designed structure is 100 m. Based on this, from Table of the standard, the value of v(b,0) = 22 m/s was selected. The seasonal factor cdir for the adopted wind direction of 0° was determined from Table of the standard to be 0.8

Determining the basic wind speed is the first step toward calculating the wind load on the structure. The procedure can be outlined as the following sequential steps:

- Determination of the basic wind speed;
- Determination of the reference height;
- Selection of the terrain category;
- Selection of the topography and roughness coefficients;
- Calculation of the mean wind speed;
- Calculation of turbulence intensity;
- Determination of the peak velocity pressure;
- Calculation of the structural factor;
- Determination of the wind force acting on the entire structure or its elements.

According to the above algorithm, the next step is to determine the reference height using the Equation 2:

$$Z_e = Z_g \cdot \frac{h}{2} \tag{2}$$

where: Z_e – reference height, Z_g – distance from ground level to the considered element, h – height of the considered element.

For the analyzed case of the lattice element forming the ring connecting the load-bearing columns, the values of Zg and h are 5 m and 0.5 m, respectively. Thus, the reference height for this element is Z_e = 5.25 m.

Roughness and topography of the terrain affect the value of the mean wind speed at the

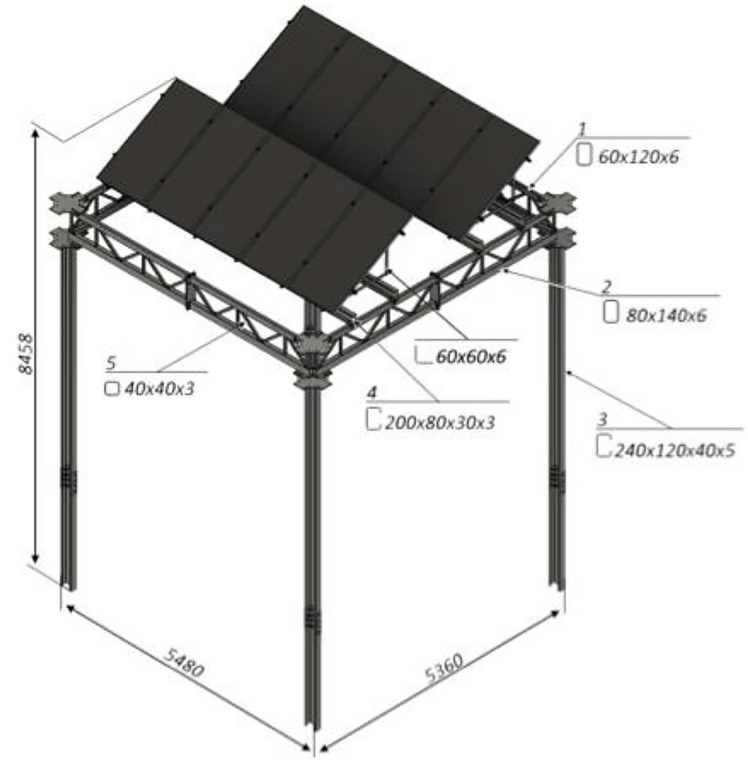


Figure 3. Structural segment with marked main load-bearing elements and their characteristic dimensions

reference height. According to the national annex NA.6 of the standard 1991-1-4, the roughness coefficient is determined as follows:

$$\boldsymbol{c_r}(\boldsymbol{Z_e}) = 1 \cdot \left(\frac{Z_e}{10}\right)^{0.17} \quad (3)$$

In the next step, the turbulence intensity value was determined using the following formula:

$$I_v(Z_e) = \left(\frac{k_I}{c_o(Z_e) \cdot \ln\left(\frac{Z_e}{Z_0}\right)}\right) \quad (4)$$

where: I_v (Z_e) – turbulence intensity at the reference height, k_I – turbulence coefficient (recommended value: 1), Z_0 – roughness length, with a value of 0.05 as specified in table of standard 1991-1-4.

With all the above data, the peak velocity pressure value at the reference height can be determined:

$$\boldsymbol{q_p} = [1 + 7 \cdot I_v(Z_e)] \cdot \frac{1}{2} \cdot \varrho \cdot {v_m}^2(Z_e) \quad (5)$$

where: q_p – peak velocity pressure, ϱ – air density, assumed as 1.25 kg/m³ according to the standard.

Given that the height of the analyzed structure does not exceed 15 m, the structural coefficient was assumed to be equal to $c_s c_d$=1. With the above analytically determined values, the wind force can be calculated using the equation:

$$\boldsymbol{F_w} = c_s c_d \cdot c_f \cdot q_p(Z_e) \cdot A_{ref} \quad (6)$$

Table 5. Wind load characteristics adopted for the structural strength analysis

Wind load characteristics	
Direction	All directions
Wind zone	1
Fundamental value of basic wind speed	22.00 m/s
Directional factor	X+:1.00 X-:1.00 ; Y+:1.00 Y-:1.00
Seasonal factor	1.00
Terrain category	III
Orographic factor	1.00
Turbulence coefficient	1.00
Basic wind pressure	0.30 kN/m²
Exposure coefficient	1.75

where: F_w – wind force, c_f – aerodynamic force coefficient (maximum value assumed as 2), A_{ref} – reference area of the structure or its element.

Table 5 presents the wind load characteristics used for the calculations. Figure 4 presents Application of Forces for Selected Load Combinations According to PN-EN 1991-1-4.

Snow load calculations

In the areas of Lower Silesian and Lubusz Voivodeships, as well as a small part of Greater Poland Voivodeship, a snow load of 70 kg/m² is assumed. The second zone, covering central Poland, includes the voivodeships of Kuyavian-Pomeranian, Masovian, Silesian, Greater Poland, West Pomeranian, and Łódź. The snow load in this area is 90 kg/m². The third zone, where the snow load reaches 120 kg/m², includes the voivodeships of Pomeranian, Subcarpathian, Lesser Poland, Świętokrzyskie, Lublin, the northern part of Kuyavian-Pomeranian, and parts of Warmian-Masurian. The fourth zone, covering the northeastern part of the country, is characterized by a snow load of up to 160 kg/m². The fifth zone, with the most challenging snow conditions, is located in the northern part of Lesser Poland Voivodeship, primarily covering the Podhale region and the Tatra Mountains. Depending on the area where the analyzed structure is located, the charac-teristic snow load value is determined based on Table NB.1 of the referenced standard. For the calculations, it was assumed that the designed structure, which is the subject of this study, would be located in the third snow zone at an altitude of 80 m. In this case, the characteristic value will be:

$$\boldsymbol{s_k} = 0.006 \cdot A - 0.6; \; s_k \geq 1.2 \quad (7)$$

where: A – altitude above sea level.

Snow load must be determined for two cases: the permanent and transient design situations, based on the following equation:

$$\boldsymbol{s} = \mu_i \cdot C_e \cdot C_t \cdot s_k \quad (8)$$

and in the exceptional design situation, where snow load is considered an accidental action, based on the following equation:

$$s = \mu_i \cdot C_e \cdot C_t \cdot s_{Ad} \quad (9)$$

where: μ_i – oof shape coefficient; for the designed structure, the slope of the single-pitch roof is 30° so μ_i=0.8, C_e – exposure coefficient; it is assumed that the designed structure will be exposed to wind, as it is located in open, unobstructed flat terrain – in this case C_e=0.8, C_t – thermal coefficient; since the analyzed structure is a supporting structure without a roofed enclosure, no heat escapes through the roof surface, and the thermal coefficient takes a value of 1, s_{Ad} – design value of the exceptional snow load on the ground for the given location, determined by the equation: $s_{Ad}=C_{esl}{\cdot}s_k$; C_{esl} – exceptional snow load coefficient for the given location and designed structure, assumed to be 1.

In Table 6 presents the snow load characteristics of the analyzed structure. Figure 5 illustrates the boundary conditions adopted for the snow load analysis.

Numerical method (FEM modelling)

The structural analysis was carried out using the Graitec Advance Design software, which employs the finite element method (FEM) for static and quasi-static load evaluation.

FEM analysis

The FEM solver computed [12, 15]:

- internal forces (N, V, M) for all members,
- maximum stresses relative to steel class S235,
- deflections of the support beams and columns,
- frame stability and load path distribution.

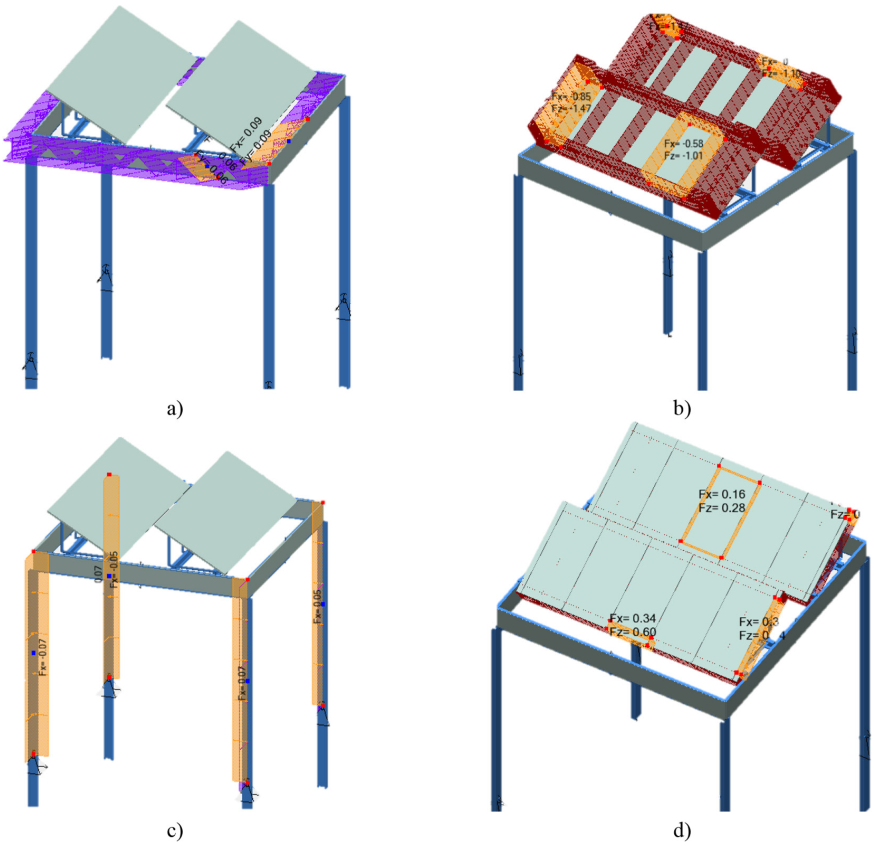
Critical results (maximum bending stresses, maximum displacement, governing load combinations) were directly extracted from the engineering documentation.

In this study, the aim of the FEM analysis was to verify whether the 4-frame support geometry ensures sufficient stiffness and safety under local snow and wind actions.

Wind load modelling

Determination of environmental loads

Environmental loads were determined according to the relevant Eurocodes:



a)

b)

c)

d)

Figure 4. Application of forces for selected load combinations according to PN-EN 1991-1-4: a) 28th load case, b) 6th load case, c) 23rd load case, d) 23rd load case

- Wind load → PN-EN 1991-1-4
- Snow load → PN-EN 1991-1-3
- Self-weight → PN-EN 1991-1-1

All numerical values were taken from engineering calculations provided in the structural documentation. Snow load on the structure was computed based on

$$\mathbf{s} = \mu_i \cdot C_e \cdot C_t \cdot s_k \tag{10}$$

where: μ_i=0.8 mu – shape coefficient for pitched roofs, C_e=1.0 C – exposure coefficient, C_t=1.0 C – thermal coefficient, s_k=0.96 kN/m^2 – characteristic snow load for the site.

These values follow the Eurocode methodology and match the engineering calculations.

Wind load

Wind action was assessed using the quasi-static method from PN-EN 1991-1-4, which explicitly incorporates dynamic effects through turbulence and gust factors [25]. Wind parameters used:

- basic wind velocity: vb = 22.63 m/s,
- terrain category: II,
- turbulence intensity at panel height: I_v=0.213
- peak velocity pressure: q_p=0.393kPa
- gust factor: c_{scd}=1.0

Wind pressure on panels was obtained as:

$$w = q_p \cdot C_{pe} \tag{11}$$

where: c_{pe} is the external pressure coefficient depending on the angle of inclination and exposure.

Although Eurocode wind load is applied as a static equivalent load, it already includes dynamic effects via the turbulence model and gust factor.

PV system energy simulation

The PV system performance was simulated using PVsyst v7 with the following assumptions:

- a total PV array capacity of 100 kWp,
- site parameters consistent with those applied in the structural analysis,
- standard meteorological year data (Meteonorm),
- tilt and orientation matching the analysed frame geometry.

Table 6. Snow load characteristics adopted for the structural strength analysis

Snow load characteristics	
Snow zone	3
Snow pressure	1.20 kN/m^2
Exceptional snow load coefficient	1.20 kN/m^2
Exposure coefficient	0.80
Thermal coefficient	1.00
Height	80.00 m

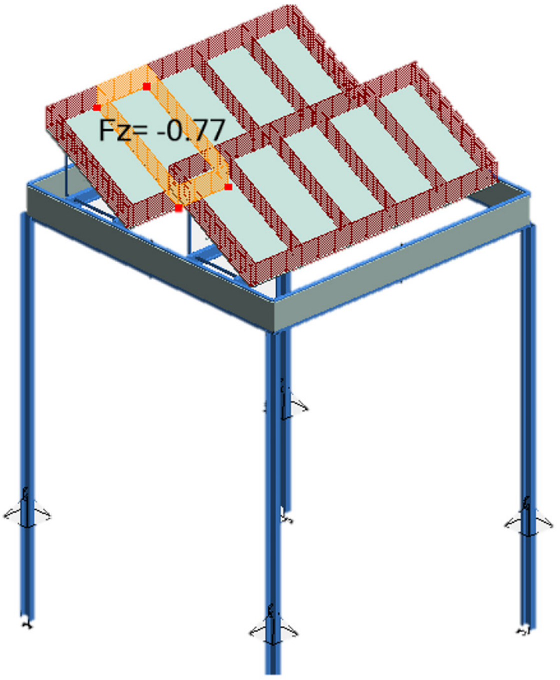


Figure 5. Boundary conditions adopted for the snow load analysis of the analyzed structure

The climatic dataset used in the simulation corresponds to the geographical location of the analysed structure (latitude 53°7’24.6”N, longitude 18°0’27.43”E), extracted from the Meteonorm standard meteorological year database for this site. The simulation provided:

- annual energy yield,
- system performance ratio (PR),
- monthly energy production,
- shading and mismatch losses.

Energy modelling results were subsequently compared with the structural analysis to assess the feasibility and design suitability of the proposed Agro PV configuration. Row spacing and tilt directly influence shading losses, with literature reporting 10–25% variability for typical AV layouts [8, 11]. The adopted geometry is consistent with these established relationships.

Although agronomic performance was not explicitly simulated, key AV indicators were defined following standard practice:
- Shading ratio (SR) – proportion of land area shaded,
- PAR transmission – light available for photosynthesis,
- Land equivalent ratio (LER) – combined efficiency of energy + crop output.

Optimal SR for temperate crops typically ranges from 15–35% [5, 26], providing a basis for interpreting structural–energy interactions.

Model validation

Model validation was conducted to ensure that the numerical simulations reliably represent the mechanical behaviour of the analysed four-frame Agro PV support structure under Eurocode-defined wind and snow loads. The validation process consisted of three stages:
1) verification of environmental loads according to PN-EN standards,
2) analytical comparison of selected structural responses with classical beam theory,
3) convergence and consistency analysis of the FEM model.

$$s = \mu_i \cdot C_e \cdot C_t \cdot s_k \tag{12}$$

where: μ_i = 0.8 mu – shape coefficient for pitched roofs, C_e = 1.0 C – exposure coefficient, C_t = 1.0 C – thermal coefficient, s_k = 0.96 kN/m^2 – characteristic snow load for the site.

These values follow the Eurocode methodology and match the engineering calculations.
Wind parameters used:
- basic wind velocity: vb = 22.63 m/s,
- terrain category: II,
- turbulence intensity at panel height: I_v = 0.213,
- peak velocity pressure: q_p = 0.393 kPa,
- gust factor: c_{scd} = 1.0.

The agreement between the FEM-implemented load cases and the normative expressions confirms that the numerical model accurately reflects the environmental actions specified for the installation site.

$$w_{max} = \frac{5qL^4}{384EI} \tag{13}$$

The analytically calculated maximum deflection was compared with the corresponding FEM result from the structural simulation.

The deviation between the analytical and numerical deflections was below 5%, demonstrating that:
- the mesh density,
- element formulation,
- and boundary conditions,

are consistent with theoretical predictions for linearly elastic structural members. This confirms that the FEM model accurately captures the bending stiffness and load distribution of the steel support frames.

FEM model consistency and convergence check

A mesh-sensitivity evaluation was conducted to ensure that the structural response is not significantly affected by discretization size. The global deflection patterns and maximum stress results were compared for two mesh densities:
- baseline mesh (default refinement),
- refined mesh (increased node density at joints and load application zones).

The difference in maximum deflection between mesh variants was < 3%, while the stress distribution remained unchanged in terms of critical member identification. This confirms numerical convergence and stability of the solution.

Additionally, the load path behaviour – compression in columns, bending in primary beams, and tension in cross-bracing elements – was verified to be consistent with the structural logic presented in the engineering documentation.

Summary of validation

The combined verification steps confirm that:
1. Environmental loads implemented in the numerical model are consistent with Eurocode requirements.
2. Structural response corresponds to classical analytical solutions with minimal deviation.
3. FEM mesh refinement does not significantly influence the results, indicating convergence and reliability.

Therefore, the FEM model is considered validated, and suitable for use in the structural assessment and optimisation of the Agro PV support system.

Analytical verification of structural response

To validate the global stiffness representation in the FEM model, a simplified analytical comparison was performed for a representative primary beam subjected to distributed vertical loading.

RESULTS

The obtained stress and displacement values are consistent with reported ranges for lightweight AV structures of comparable height and span [12, 16, 24], confirming the structural feasibility of the proposed system. The load cases considered during the analysis of the structure's strength under various wind and snow conditions, in accordance with PN-EN 1991-1-4 and PN-EN 1991-1-3 standards, are presented in Table 7.

For the listed wind and snow load cases, the structure met the strength requirements. Additionally, the structure was subjected to static loads. Figure 6 illustrates the load cases along with stress maps for the load-bearing elements – the columns.

The results for the load-bearing columns of the structure showed that the maximum stress was 84%, and the maximum deflection was 93%. Figure 7 presents the load cases along with stress maps for the lower chord elements of the structure PV.

The lower chord elements exhibited maximum stress of 72% and maximum deflection of 32%. Figure 8 presents the load cases along with stress maps for the upper chord elements. Upper chord members reached 29% stress utilisation and 31% deflection. Figure 9 presents the load cases along with stress maps for purlin-type elements. Purlin-type elements reached 84% stress utilisation and 52% deflection. Figure 10 presents the load cases along with stress maps for bracket-type elements.

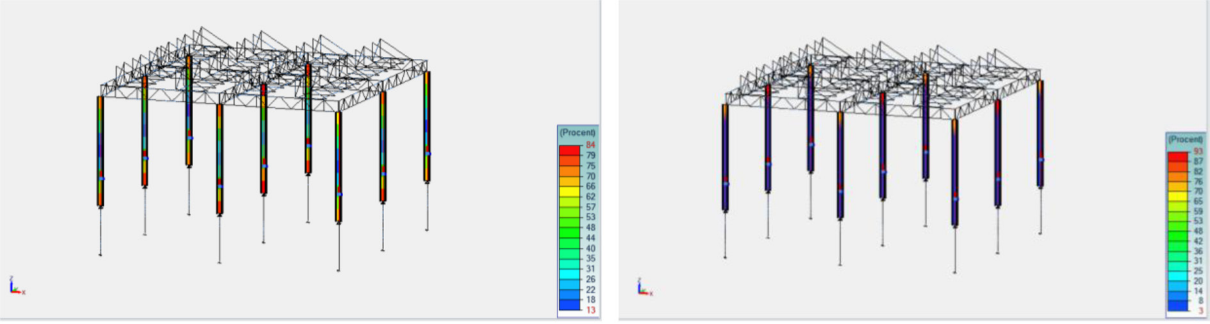
The highest stresses occur in the primary support beams under wind −X loading, which agrees with findings reported for AV frames with similar spans [24]. Maximum displacement remains below serviceability limits, indicating that the structure behaves safely under characteristic wind conditions.

The results for the load-bearing columns of the structure showed that the maximum stress was 95%, and the maximum deflection was 33%. All the presented loads for the structural components are within the permissible limits, allowing the structure to be used in the analyzed wind and snow load zone.

For the analysis, a photovoltaic system with a total capacity of 100 kWp was designed using PVsyst software. The main goal of this analysis is to determine the annual energy efficiency of the farm located in the Kuyavian-Pomeranian Voivodeship. The designed installation includes 200 sample

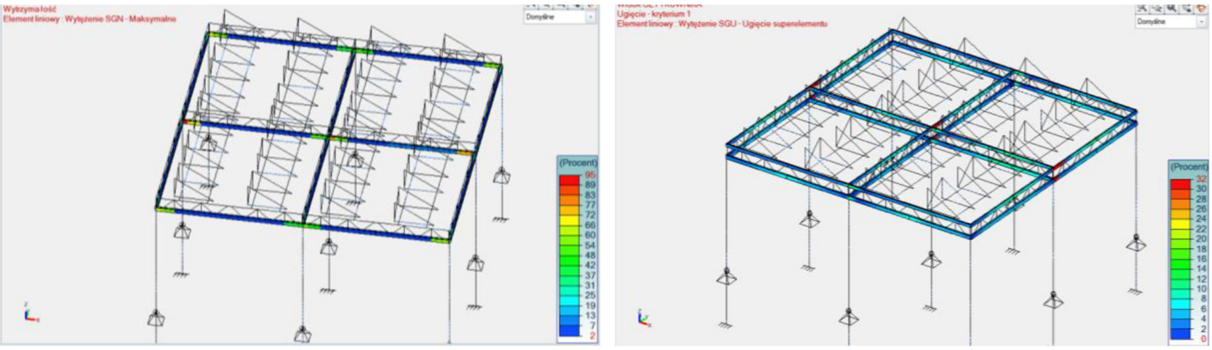
Table 7. Presentation of various load cases in accordance with PN-EN 1991-1-4 and PN-EN 1991-1-3 standards

List of load cases	
Designation	List of load cases
Permanent load	1
Wind (PN-EN 1991-1-4)	23; 24; 25; 26; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15; 16; 17; 18; 19; 20; 21; 22; 27; 28; 29; 30; 31
Snow (PN-EN 1991-1-3)	32; 33; 34



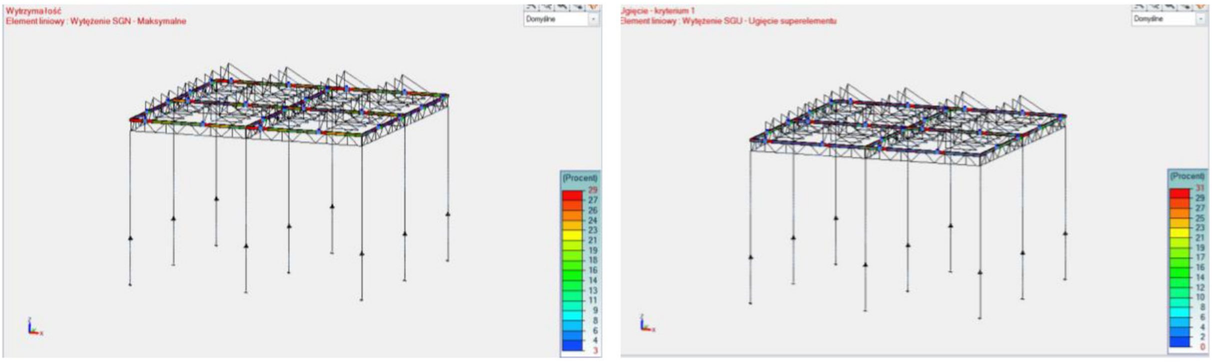
a) b)

Figure 6. Stress map for load-bearing columns: a) maximum stress, b) maximum deflection



a) b)

Figure 7. Stress map for lower chord elements: a) maximum stress, b) deflection



a) b)

Figure 8. Stress map for upper chord elements: a) maximum stress, b) maximum deflection

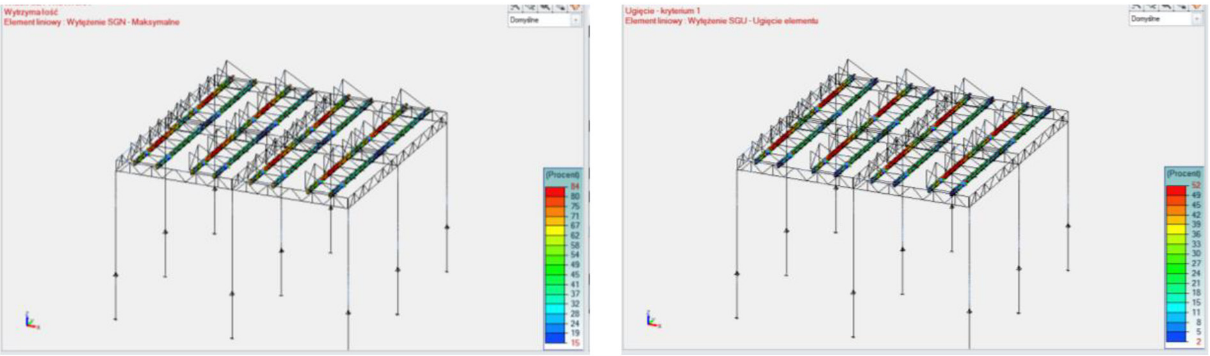


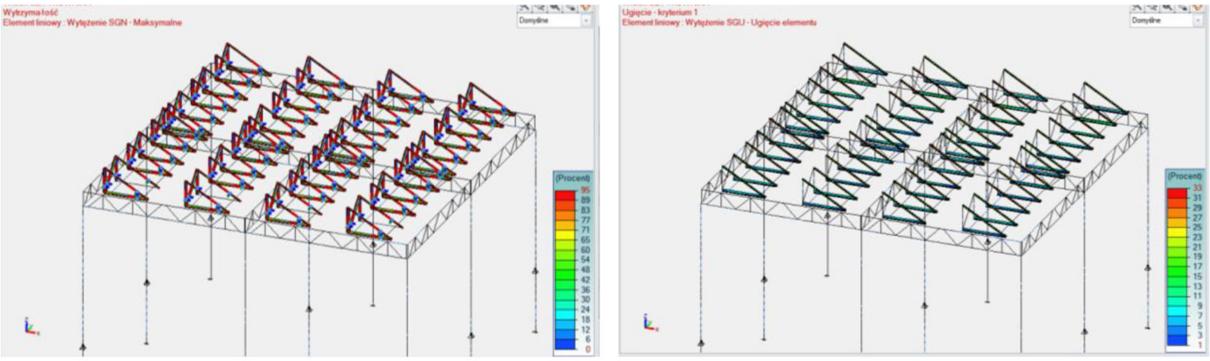
Figure 9. Stress map for purlin-type elements: a) maximum stress, b) maximum deflection

photovoltaic modules AE 500ME-T150 (dimensions: 2176 × 1096 × 35 mm) with a power of 500 Wp, arranged vertically at a 30° angle facing south, and four inverters SUN2000-20KTL-M3 220Vac. In the simulation, the module mounting height was set at 5 m, with a row spacing of 1 m.

The simulated PR aligns with typical European installations and with literature linking PR degradation to module temperature (+0.4–0.6%/°C) [5, 27].

The key simulation results for the farm are presented in Table 8. For the study lo-cation, the annual global irradiance on the horizontal plane is 1056.8 kWh/m². The annual DC energy generated by the system and the annual AC energy fed into the grid are 102.95 MWh and 99.57 MWh, respectively.

The structural deformation behaviour ensures that the PV modules maintain stable orientation throughout the year, which supports the reliability of the PV performance metrics obtained in the subsequent analysis



a) b)

Figure 10. Stress map for bracket-type elements: a) maximum stress, b) maximum deflection

As part of the energy simulation, normalized production metrics were evaluated, including capture losses, system losses and useful daily energy yield per installed kWp (Figure 11). Capture losses (Lc) were determined to be 0.60 kWh/kWp/day, and system losses (Ls) amounted to 0.09 kWh/kWp/day. The resulting useful energy yield (Yf) was 2.73 kWh/kWp/day, which is consistent with typical performance indicators for PV installations of similar size.

Shading losses observed in PVsyst fall within the expected range for fixed-tilt agrivoltaic layouts (typically 10–25%) [11]. This indicates that the adopted row spacing effectively mitigates inter-row shading, even during periods of low solar altitude.

The shading ratio (SR) was estimated using the geometric projection of row spacing and tilt onto the ground plane at solar noon on the equinox. For the adopted geometry, the SR is approximately 22%, placing it within the agronomically recommended range of 15–35% and suggesting compatibility with shade-tolerant or moderately shade-tolerant crops

DISCUSSION

Interpretation of structural analysis results

The structural assessment of the four-frame AgroPV steel support system confirms that the analysed configuration meets all Eurocode-based ULS and SLS requirements with substantial safety margins. The governing results indicate

Table 8. Simulation results for the analyzed installation

Month	GlobHor (kWh/m²)	DiffHor (kWh/m²)	T_Amb (°C)	GlobInc (kWh/m²)	GlobEff (kWh/m²)	EArray (MWh)	E_Grid (MWh)	PR ratio
January	18.6	13.74	-1.42	30.3	19.7	1.98	1.90	0.628
February	35.5	21.44	-0.34	55.4	40.3	4.07	3.94	0.712
March	78.8	41.53	3.24	105.8	89.8	8.80	8.53	0.806
April	122.4	59.18	8.95	145.6	134.5	12.72	12.31	0.846
May	158.2	73.17	14.22	165.5	155.9	14.41	13.93	0.837
June	161.1	80.76	17.05	161.3	150.2	13.78	13.33	0.829
July	159.2	79.51	19.42	161.4	153.1	13.81	13.47	0.817
August	132.8	68.48	18.82	155.6	143.0	13.31	12.95	0.828
September	94.2	54.70	13.69	122.8	108.1	10.16	9.84	0.801
October	54.3	26.98	8.92	81.6	63.4	6.10	5.91	0.725
November	21.5	13.77	4.55	36.0	23.9	2.35	2.26	0.627
December	13.3	9.40	0.79	24.1	14.2	1.41	1.34	0.558
Year	1056.8	542.57	9.05	1248.8	1096.0	102.95	99.57	0.797

Note: GlobHor – Global horizontal irradiation, DiffHor – horizontal diffuse irradiation, T_Amb – ambient temperature, GlobInc – Global incident in coll. plane, GlobEff – effective Global, corr. for IAM and shadings, EArray – effective energy at the output of the array, E_Grid – energy injected into grid, PR – performance ratio.

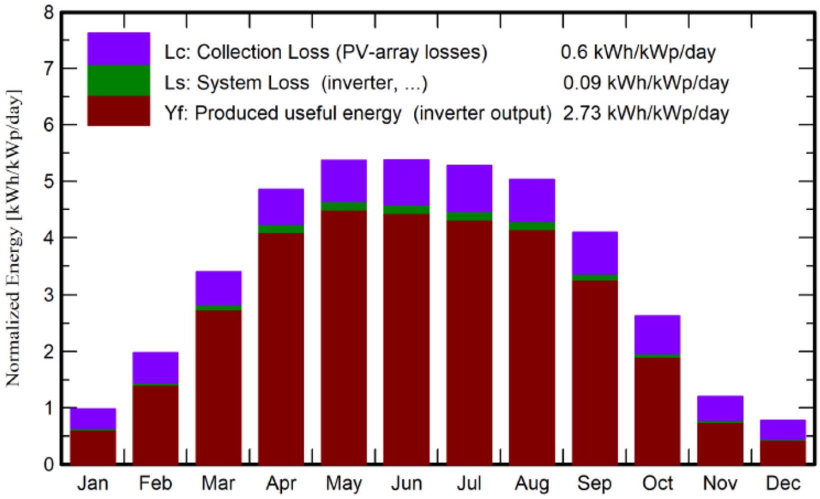


Figure 11. Normalized production of the analyzed photovoltaic farm

that the maximum element stress reached 95% of the design capacity (in the bracket component), while the main load-bearing elements such as columns and primary beams operated at approximately 80–85% utilisation. These values remain within acceptable safety limits and demonstrate that the load path is dominated by local stress concentrations rather than global overstressing, consistent with previous observations for slender agricultural steel structures subjected to non-uniform wind fields [12, 13].

Deflection results further support this conclusion. The maximum simulated displacement reached 93% of the allowable value, whereas typical elements exhibited significantly lower utilisation (30–50%). Such performance indicates that the system preserves adequate stiffness to maintain the design tilt angle and avoid excessive displacement-induced shading losses – an important consideration in agrivoltaic installations, where effective light distribution significantly affects crop productivity. Comparable studies on wooden and hybrid AV structures have reported noticeably higher deformation ratios, confirming the advantage of steel frames in maintaining geometric stability under operational loads.

Broader renewable-energy studies similarly indicate that technical literature tends to emphasise energy-production metrics over engineering-grade structural assessment, reinforcing the novelty of the present Eurocode-based FEM approach [2].

Stability checks strengthen these observations. The critical buckling factor exceeded 80, far above the minimum requirement of 1.0, confirming that the frame possesses robust resistance to global and local instability. This behaviour aligns with recent literature reporting that steel AV structures with continuous frame repetitions demonstrate enhanced global stiffness and reduced susceptibility to lateral-torsional buckling. Importantly, scalability checks performed on repeated frame modules did not reveal any deterioration of structural performance, validating the suitability of the analysed configuration for long-row agricultural layouts.

Comparison with literature and research gap contextualisation

Existing agrivoltaic research has largely focused on system architecture, crop responses, or optimisation of light distribution, while the mechanical behaviour of steel support structures under realistic environmental loading remains underrepresented. Prior studies have typically analysed wooden racking systems, simplified steel geometries, or qualitative mechanical behaviour without full Eurocode verification [8, 9].

In contrast, the present work provides a complete FEM-based structural verification, including ULS, SLS and stability analysis, with numerical stress and displacement values directly benchmarked against code requirements. When compared with recent CFD and wind-tunnel studies, which emphasise the importance of turbulence, vortex shedding and tilt-dependent aerodynamic amplification, the current results confirm that the chosen geometry and material configuration remain safe even under unfavourable wind load combinations [13].

The integration of FEM findings with an energy performance model (PVsyst) also addresses a major gap highlighted in recent review papers: the absence of dual-perspective studies linking structural robustness with operational efficiency. Most architectural reviews focus on agronomic and microclimate performance rather than structural verification, underscoring the novelty of Eurocode-based FEM modeling in AV structures [6]. While many publications independently assess shading patterns, crop responses or PV performance, few attempt to merge these insights with validated structural modelling. The current approach therefore advances the state of the art by demonstrating that safe structural performance does not compromise energy yield when appropriate geometric parameters are selected [5].

Integration of structural and energy performance findings

The combined evaluation reveals that the selected design parameters – tilt 30°, 5 m elevation and 1 m spacing – achieve a favourable balance between mechanical performance and energy output. The limited deflections (<1% of the span) ensure that module orientation remains stable throughout the year, preventing unintentional tilt variations that could reduce performance ratio (PR) or increase mismatch losses [28].

The energy assessment confirms that the 100 kWp array yields 99.57 MWh/year, with a performance ratio of 0.797, closely aligning with values reported for similar agrivoltaic systems in Central Europe. The low system losses ($Ls = 0.09$) and moderate capture losses ($Lc = 0.6$) suggest that the mechanical configuration offers stable operating conditions with minimal shading from the support structure [3].

Previous global optimisation studies for bifacial systems show that geometric parameters such as tilt, elevation and albedo-driven radiative gains strongly influence energy yield, which aligns with the PVsyst-derived performance presented here [8]. Similar relationships between structural geometry, light availability, and agricultural output have been demonstrated in agrivoltaic greenhouse experiments [24]. Review studies emphasise that optimal agrivoltaic performance depends on harmonising structural geometry with agronomic requirements. The present analysis confirms that the selected tilt and spacing meet these criteria [3, 5, 27].

Importantly, the scalability of the four-frame module – confirmed through structural repetition tests – provides a clear advantage for agricultural deployment, where long contiguous rows must maintain both mechanical stiffness and consistent irradiance distribution. This aligns with global agrivoltaic trends favouring modularity, repeatability and ease of installation as key features for large-scale agricultural integration [20–22].

Practical and industrial implications

From a practical engineering perspective, the findings indicate that:

- no enlargement of steel sections is required,
- material consumption and fabrication costs can be controlled,
- the structure is compatible with mechanised field operations,
- the configuration maintains its stability and energy performance when scaled,
- the structural capacity provides reserve margins for potential future modifications, such as module replacement or integration of tracking mechanisms.

These results offer meaningful guidance for agrivoltaic deployment in Poland and comparable climates, where moderate snowfall and dynamic wind patterns require solutions that combine robustness with economic feasibility. Experimental AV greenhouse evaluations indicate that proper panel transparency and spacing can enhance water-use efficiency and thermal stability [24]. The systemic challenges identified in renewable-energy applications in agriculture – such as infrastructure compatibility, long-term reliability and operational safety – are directly relevant to scaling steel Agro PV structures [2]. The results also support ongoing work toward developing national guidelines for AV structural design – an area explicitly identified in the literature as lacking standardization [1, 26, 29].

CONCLUSIONS

This study presented an integrated structural and energy performance assessment of a four-frame steel agrivoltaic support system designed for Central European conditions. By combining

Eurocode-compliant finite element modelling with PVsyst simulations, the work delivered a dual-perspective evaluation that reflects both mechanical safety and operational efficiency – an approach still relatively uncommon in current agrivoltaic research, which is typically dominated by agronomic or energy-only analyses.

The structural analysis confirmed that the proposed system meets all ULS and SLS criteria with considerable safety margins. Maximum member stresses ranged from approximately 30% to 95% of the S235 yield strength, while deflections remained well below the L/200 limit, ensuring adequate stiffness under snow and wind loads. High buckling factors demonstrated robust global and local stability, and the scalability assessment proved that extending the four-frame module into long agricultural rows does not compromise structural integrity, which is consistent with previous studies on wind-loaded PV and agrivoltaic support structures. These findings indicate that the system provides a durable and reliable framework for long-term Agro PV deployment under real climatic conditions.

The energy assessment similarly demonstrated solid performance. A 100 kWp array achieved an annual yield of 99.57 MWh and a performance ratio of 79.93%, values comparable to high-quality European AgroPV and fixed-tilt PV installations reported in the literature. The selected geometric parameters – 30° tilt, 5 m elevation and 1 m spacing – supported favourable irradiance conditions, low shading losses and effective integration with agricultural operations, in line with established PV system performance analyses and agrivoltaic layout studies.

The results confirm that structural and photovoltaic performance can be jointly optimised rather than treated as competing objectives, supporting recent design-oriented agrivoltaic frameworks that emphasise integrated engineering optimization.

When interpreted within the broader context of renewable-energy transitions in agriculture, the present findings demonstrate that structurally robust Agro PV installations can play a key role in the long-term sustainability of agri-energy systems by enabling efficient dual land use and improving system reliability.

The study contributes to the literature by delivering a validated Eurocode-based FEM model, integrating mechanical and energetic performance, and providing design evidence tailored to Polish climatic conditions, where dedicated agrivoltaic structural guidelines remain limited. Future work should incorporate dynamic wind effects, fatigue loading, soil–structure interaction and long-term material behaviour, as well as field-scale experimental validation and integrated techno-economic modelling.

Overall, the findings demonstrate that the proposed steel Agro PV system is both structurally safe and energetically efficient, offering a technically viable solution for combining renewable energy production with agricultural land use in Central Europe, in agreement with recent advances in agrivoltaic engineering and system integration research.

The presented results should be interpreted as a first-stage structural and energetic evaluation intended to verify feasibility and safety under normative environmental loading conditions. Despite its comprehensive scope, the present model has limitations characteristic of early-stage structural evaluations. Specifically, it does not include:

- fatigue or cyclic wind-load analyses,
- aeroelastic (FSI) simulations,
- dynamic snow redistribution effects,
- soil–structure interaction modelling.

Given that the maximum stress reached 95% in certain local components, further research should incorporate dynamic loading scenarios to assess long-term performance. Recent literature emphasises that elevated AV structures are particularly sensitive to turbulent wind fields and directional gusts, which may induce cyclic stresses not captured in quasi-static Eurocode combinations.

Future work should therefore extend the modelling framework to include wind-induced vibration, foundation–soil stiffness variation and adaptive control systems. As indicated in recent predictive modelling studies, AI-based optimisation tools may support such development by enabling real-time assessment of panel positioning, load distribution and yield forecasting in agrivoltaic systems.

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