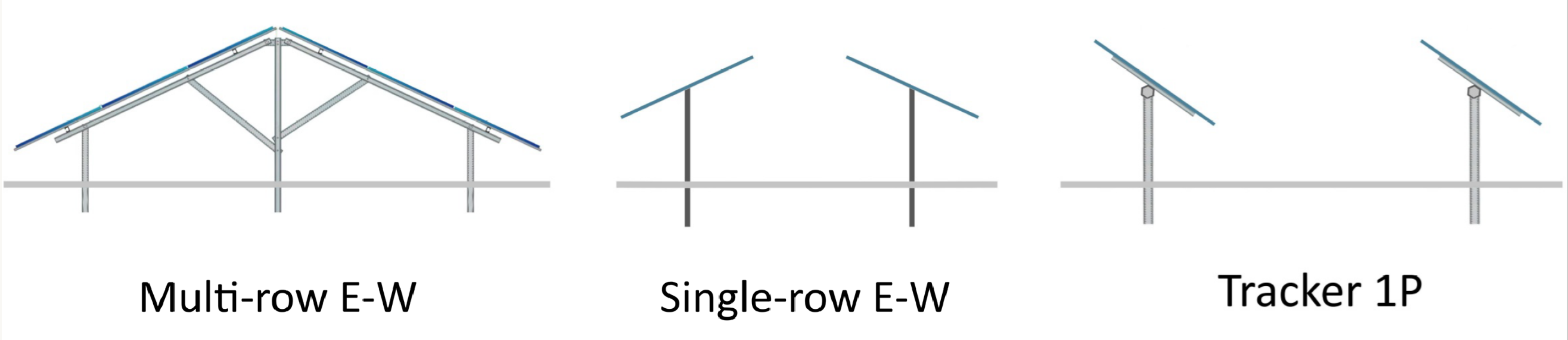
System-Level Engineering Analysis of Single-Row, High-Clearance Bifacial Photovoltaic Structures

This document presents a system-level engineering analysis of single-row, high-clearance, ground-mounted ifacial photovoltaic designed to utilize rear-side irradiance through passive geometric and temporal optimization, without reliance on active tracking or moving mechanical components. The study examines how row configuration, structural openness, and elevation above ground influence rear-side energy contribution, mechanical safety, operational predictability, and long-term performance, in comparison with conventional multi-row and tracking-based ground-mounted PV systems.

The objective of this work is to assess how structural simplicity and passive rear-side gain affect energy yield, system reliability, and lifetime economics at scale, particularly in large utility and national energy systems.

To enable system-level evaluation of passive rear-side utilization beyond annual energy yield, this analysis introduces the UTDBR (Useful Time-Distributed Bifacial Ratio), a metric quantifying how effectively bifacial rear-side generation is distributed over grid-relevant time periods rather than concentrated around midday production peaks.



Technological Context: The Era of Bifacial Modules

Contemporary solar energy has entered the era of bifacial modules, which utilize both direct radiation on the front side and reflected and diffuse radiation on the rear side of the cells. The theoretical potential of this technology is an increase in energy production of 20-30% compared to monofacial modules. However, realizing this potential requires a fundamental change in the approach to designing mounting structures.

Glass-Glass bifacial modules feature a glass-glass construction, which significantly differs from traditional modules with a backsheet. The double layer of 2 mm thick tempered glass creates a structure with high bending stiffness but is simultaneously extremely sensitive to tensile stress. While tempered glass can withstand compressive forces up to 900 MPa, its tensile strength is only 90 MPa – ten times less.

This fundamental asymmetry in strength has become the source of the biggest problem in the photovoltaic industry: the systematic cracking of the rear glass of bifacial modules in traditional mounting systems. Market data indicates that failure rates exceed 10% within the first three years of operation, generating enormous financial losses and undermining the profitability of investments in bifacial technology.

Fundamental Problem: The Trapezoidal Phenomenon

Traditional photovoltaic structures rely on a multi-row system with four or more support points per module. Such a system is statically indeterminate (hyperstatic), meaning that the slightest differences in foundation settlement, thermal expansion, or mounting tolerances generate secondary stresses. These stresses force the module's plane to twist – a phenomenon known as trapezoiding.

The mechanism of destruction proceeds as follows: the rear posts of the structure are significantly longer than the front ones (a height difference resulting from the panel's tilt angle). Under wind loads, the rear posts deflect more than the front ones, transforming the rectangular frame into a trapezoid. This forced deformation causes the module, instead of acting as a flat plate, to begin bending. The rear glass, located on the outer side of the bending arc, is subjected to tensile stress.

Numerical analysis using the Finite Element Method (FEM) showed that for a typical multi-row structure, the bending moment is approximately 30 N·m/m. For 2 mm thick glass, this generates tensile stresses of around 4-5 MPa in a single load cycle. Although this value seems low compared to the theoretical strength of 90 MPa, the material fatigue effect is of crucial importance.

01

Differential Post Deflection

Longer rear posts deflect more under wind load, initiating the geometric deformation of the entire structure.

02

Transformation into a Trapezoid

The rectangular structural frame transforms into a trapezoid, forcing the modules mounted to it to bend.

03

Tensile Stresses

The module's rear glass, located on the outer side of the bending arc, is subjected to tensile stress, generating stresses in the glass.

04

Initiation of Microcracks

Microscopic cracks form at stress concentration points, propagating under cyclic loads.

05

Catastrophic Cracking

After tens of thousands of fatigue cycles, microcracks coalesce, leading to the complete destruction of the glass.

Material Fatigue: The Invisible Killer

Research conducted by VTT Technical Research Centre of Finland showed that a stress amplitude of ±40 MPa after 100,000 loading cycles causes a 60% increase in microcrack length in tempered glass. In real operating conditions, a photovoltaic installation experiences tens of thousands of wind load cycles annually. Even relatively small cyclic stresses of 4-5 MPa, repeated over years, initiate and propagate microcracks.

The process is irreversible and cumulative. Small cracks are initially neither visible nor detectable by standard diagnostic methods. However, they systematically grow with each thermal cycle and every gust of wind. Once a critical length is exceeded, a cascade of crack coalescence occurs, leading to catastrophic destruction of the entire glass pane. Therefore, the question is not "if" but "when" the failure will occur.

Consequently, investors incur multi-million dollar losses due to the replacement of damaged modules, production downtime, logistics, and service costs. What's worse, the problem is systemic – it does not result from manufacturing defects in the modules, but from a fundamental design flaw in the mounting system. No quality control of module production can eliminate it.

Second Challenge: Optical Losses in Rear Gain

The second critical problem with traditional designs is the drastic limitation of energy gain from the rear side of bifacial modules. In systems based on purlins and crossbeams, these elements are mounted directly beneath the module, creating linear obstructions for reflected and diffused light.

Research by the Fraunhofer Institute for Solar Energy Systems demonstrated that the presence of structure beneath the module causes a power loss of up to 58% on the least illuminated cell and 22% on the total rear-side irradiance. These values are not abstract theoretical predictions—they were measured under controlled conditions using ray-tracing simulations and validated with actual measurements.

The loss mechanism is twofold. First, purlins and crossbeams physically block light, casting linear shadows on the module's rear side. Second—and this is an often-overlooked aspect—they create illumination non-uniformity. Bifacial modules utilize Half-Cut technology, where cells are divided into serially connected segments. Shading even a small part of one segment causes a current mismatch effect, reducing the power of the entire string to the level of the weakest cell.

Third Challenge: Aerodynamic Loads

Traditional multi-row structures, especially those with low elevation above the ground, create unfavorable aerodynamic conditions. When air encounters the first row of panels, it detaches from their edges, forming a turbulent zone behind the panel. In multi-row arrangements, these turbulences superimpose on the flow reaching subsequent rows, creating complex pressure fields and large, persistent air recirculation bubbles.

The consequence is an increase in the effective pressure coefficient (Cp_net), which means greater suction and pressing forces on the structure. Additionally, irregular flow generates pressure fluctuations that can induce resonant vibrations in the structure. Open C and Z type profiles, characterized by low torsional stiffness, are particularly susceptible to such aeroelastic phenomena.

Flow Separation

Air detaches from the panel edges, creating dead air zones and increased negative pressure on the leeward side.

Inter-row Interference

In multi-row systems, turbulences from the first row disrupt the flow over subsequent rows, multiplying the loads.

Increase in Cp_net

The effective pressure coefficient increases from 0.6-0.7 for a single plane to 0.9-1.0 in multi-row arrangements.

A single-row, isostatic, high-clearance structure based on closed profiles

This section describes a single-row, high-clearance ground-mounted photovoltaic structure based on a statically determinate (isostatic) configuration, designed in accordance with fundamental principles of mechanics and structural physics.

The analyzed architecture employs a continuous row of bifacial photovoltaic modules supported at two primary points, forming a mechanically determinate system rather than a multi-supported frame.
The number of modules per row is not a defining parameter of the structural concept and may be adapted to site conditions and span limits without altering the underlying mechanical principles.

This configuration represents a distinct design paradigm, in which structural simplicity is used as a primary means of ensuring mechanical reliability and long-term stability.

The condition of isostaticity is expressed by: $W = w + r = 0$

where W denotes the degree of static indeterminacy, w the number of constrained external degrees of freedom, and r the number of internal constraints.
A two-point support system inherently satisfies this condition.

As a result, the structure does not generate secondary stresses due to manufacturing tolerances, differential ground settlement, or thermal expansion.
If one foundation settles by several millimeters, the structure responds through rigid-body rotation, rather than internal stress accumulation.

No torsional moments, forced bending, or trapezoidal distortion are introduced. Mounting tolerances do not accumulate into stress concentrations, and thermal expansion does not create additional load paths.

Consequently, the system exhibits intrinsic resistance to real-world imperfections, maintaining structural integrity under conditions that typically induce fatigue and long-term degradation in statically indeterminate assemblies.

One practical implementation of this structural paradigm is realized in the BifacialMAX system.

Closed Profile: Foundation of Stiffness

The second pillar of the BifacialMAX structure is the use of closed profiles such as RHS (Rectangular Hollow Section) or Omega. This choice results from a comparative analysis of strength parameters in the context of requirements for photovoltaic structures, where torsional stiffness is of key importance.

For an RHS 100×50×3 mm profile made of S355 steel, the key geometric parameters are: moment of inertia Iy = 1.12×10^{-6} m^4, section modulus Wy = 2.24×10^{-5} m^3, polar moment of inertia J = 0.36×10^{-6} m^4. These values should be compared with an open C 100×50×3 mm profile of similar linear mass: Iy = 0.68×10^{-6} m^4, Wy = 1.66×10^{-5} m^3, J = 0.045×10^{-6} m^4.

The last value is crucial – the polar moment of inertia J, which determines torsional stiffness. The ratio JRHS/JC = 0.36/0.045 ≈ 8.0 means that the closed profile is eight times stiffer in torsion than the open profile for the same material mass. For an identical torsional moment T, the angle of twist $\theta = TL/(GJ)$ will be eight times smaller in the closed profile.

Moment of inertia Iy (m^4)	1.12×10^{-6}	0.68×10^{-6}	1.65×
Section modulus Wy (m^3)	2.24×10^{-5}	1.66×10^{-5}	1.35×
Polar moment of inertia J (m^4)	0.36×10^{-6}	0.045×10^{-6}	8.00×
Torsional stiffness GJ (kN·m^2)	29.2	3.65	8.00×

Elimination of Trapezoidal Distortion: Mathematical Proof

The combination of an isostatic system with a profile of high torsional stiffness creates a system in which the trapezoidal distortion mechanism has been eliminated at its source. This is not a matter of risk reduction or effect minimization – it is its complete elimination resulting from the laws of mechanics.

Consider a situation where one of the foundations settles by $\Delta h = 3$ mm (a pessimistic value for a well-executed foundation). In a four-point system, such a discrepancy induces a torsional moment, which for a typical support spacing $L = 2.5$ m and width $W = 2.0$ m is $T = F \cdot (W/2)$, where F results from the geometry of the forced deformation. For a structure with low torsional stiffness (open profile, $GJ \approx 3.65$ kN·m²), such a moment generates a twist angle $\theta > 0.5°/\text{m}$, which is destructive to the module glass.

In the BifacialMAX system, the same foundation discrepancy causes only the rotation of the entire structure as a rigid body. No torsional moment is generated because the system is statically determinate. Even if a hypothetical small moment were to arise (e.g., from asymmetrical snow load), the eight times higher stiffness $GJ = 29.2$ kN·m² would reduce the twist angle to $\theta < 0.05°/\text{m}$ – completely harmless to the modules.

0%

Trapezoidal Distortion Risk

Complete elimination of the mechanism generating secondary stresses in the glass of bifacial modules for the entire operational period.

8×

Torsional Stiffness

Eight times higher GJ value compared to open profiles, dampening all torsional moments.

50 years

Guaranteed Lifespan

Designed durability of the S355 steel structure with Magnelis 600 coating featuring self-healing properties.

Strength Analysis: Extreme Loads

To prove the safety of the structure under extreme conditions, a detailed wind load analysis was conducted in accordance with Eurocodes EN 1991-1-4 and EN 1993-1-1. Calculations were performed for a wind speed $U = 60$ m/s (216 km/h), which corresponds to hurricane zones and provides a significant safety margin for most locations.

Dynamic wind pressure is calculated using the formula $q = 0.5 \times \rho \times U^2$, where $\rho = 1.25$ kg/m³ is the air density. For $U = 60$ m/s, we get $q = 2250$ Pa. The surface load on the panel is $p = q \times Cp_{net}$, where Cp_{net} is the effective pressure coefficient. For a single, raised plane with the possibility of free airflow under the bottom edge, a conservative value of $Cp_{net} = 0.80$ was assumed (pessimistic, actual values are lower due to the bleed-through effect).

The linear load on the support profile, assuming a tributary width of 1.0 m, is $w = p \times 1.0 = 2250 \times 0.80 = 1800$ N/m. For a simply supported single-span beam of length $L = 2.1$ m (typical length of a bifacial module), the maximum bending moment occurs at the mid-span and is $M_{max} = wL^2/8 = 1800 \times 2.1^2 / 8 = 992$ N·m.

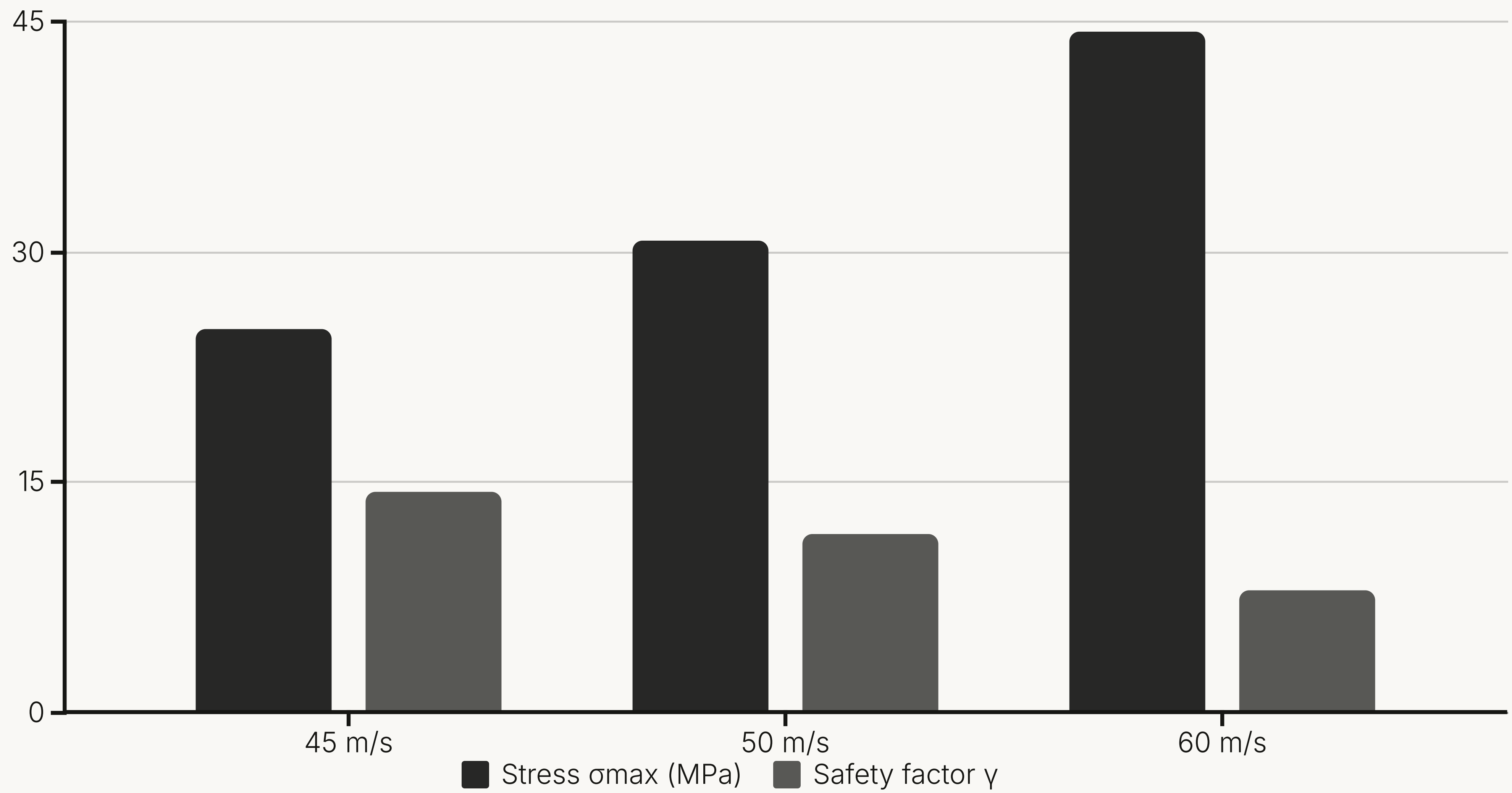
The maximum stress in the extreme fibers of the profile is calculated using the formula $\sigma_{max} = M_{max} / W_y = 992 / (2.24\times10^{-5}) = 44.3$ MPa. For load combinations in the ultimate limit state (ULS) with a partial safety factor $\gamma_f = 1.5$, the design stress is $\sigma_{ULS} = 44.3 \times 1.5 = 66.4$ MPa.

Factor of Safety

Structural steel S355 is characterized by a yield strength Re = 355 MPa. The factor of safety is defined as γ = Re / σULS = 355 / 66.4 = 5.3. This signifies a more than five-fold safety margin even at hurricane wind speeds of 60 m/s and pessimistic assumptions regarding the pressure coefficient.

For typical operational conditions (U = 45 m/s, which corresponds to wind zone III according to Eurocode), ULS stresses drop to 37.4 MPa, yielding a safety factor γ = 9.5. Such design conservatism is a conscious choice, ensuring reliability throughout the entire 50-year service life.

Equally important are the deflections of the structure. The maximum deflection of a simply supported beam under uniformly distributed load is $f_{max} = 5wL^4/(384EI)$, where E = 210 GPa is the Young's modulus of steel. For our case, fmax = 1.94 mm. This value is more than 15 times smaller than the typical limit deflection criterion of L/200 = 10.5 mm, confirming that the structure remains practically undeformable under operational load.



The charts show nominal stresses before applying the ULS safety factor. Even at 60 m/s, the most extreme scenario, stresses represent merely 12.5% of the yield strength.

Optimization for Hurricane Zones

In regions with particularly high hurricane risk, the BifacialMAX system offers an additional optimization option: the use of shorter modules, 1.7 m long instead of the standard 2.3 m. This strategy leverages a fundamental mechanical relationship: the bending moment in a beam is proportional to the square of its span length.

The moment reduction factor is $RM = (L_2/L_1)^2 = (1.7/2.3)^2 = 0.546$, which means a 45.4% reduction in loads. For a wind speed of 60 m/s, the maximum moment drops from 992 N·m to 542 N·m, and stresses decrease from 44.3 MPa to 24.2 MPa. The safety factor increases to $\gamma = 9.8$ – nearly a tenfold safety margin.

This option does not require modifications to the basic structural geometry or changes to the profiles. It is a simple adaptation to local conditions by choosing the appropriate module format, which confirms the flexibility and versatility of the BifacialMAX concept.

Reinforced Module–Structure Connection

The third element of the safety system, complementing the isostatic system and the closed profile, is the reinforced connection between the module and the structure. The BifacialMAX system uses glass-glass modules with a 2 mm thick aluminum frame – 67% thicker than the standard 1.2 mm frame used in typical photovoltaic modules.

The frame strength index, which defines its bending resistance, is proportional to the square of its thickness. Increasing from 1.2 mm to 2.0 mm results in a strength increase by a factor of $(2.0/1.2)^2 = 2.78$. This means almost three times greater local stiffness at the mounting points, which is crucial for distributing forces from the mounting bolts over a larger area and reducing stress concentrations in the glass.

Additionally, BifacialMAX uses an eight-point module mounting instead of the standard four-point mounting. Assuming an even load distribution, the force per single bolt is halved. In practice, this reduces both shear stresses in the bolts and surface pressures at the frame-support profile contact points.

Ladder-Free Installation: A Safety Revolution

The lower edge of the panels in the BifacialMAX system is at a minimum height of 110 cm, allowing all critical assembly operations to be performed from ground level by a person of standard height. This seemingly simple design decision has fundamental implications for safety, efficiency, and installation quality.

Eliminating ladders removes the primary source of accidents on photovoltaic construction sites. According to industry statistics, falls from height account for approximately 35% of all serious accidents during PV system installation. Every descent from a ladder is a potential source of injury, especially when the operator is carrying a heavy panel (the weight of a typical bifacial module is 28-32 kg) or working in adverse weather conditions.

Working at ground level increases assembly precision. The operator has a stable position, both hands free, and full control over tools. They can precisely position the module, evenly tighten screws with the appropriate torque, and check electrical connections. Installation quality directly translates into long-term reliability.

Zero Accidents from Height

Eliminating ladders removes the primary source of injuries during photovoltaic system installation.

Reduced Installation Time

Ground-level work is 30-40% faster than installation requiring continuous ladder movement.

Higher Installation Quality

The operator's stable position allows for precise tightening of connections and quality control.

100% Structural Bifaciality: Definition

The term "structural bifaciality" refers to the optical transparency of the structure in the module's rear hemisphere—that is, the structure's ability not to obstruct light access to the rear side of the cells. This is a critical parameter that is dramatically limited in traditional systems by the presence of purlins, girts, and cross beams running under the module.

The BifacialMAX system achieves 100% structural bifaciality by radically eliminating all elements beneath the module plane. There are no transverse purlins, no girt beams, no physical obstructions in the acceptance cone of reflected light. Modules are mounted directly to two longitudinal support profiles that run along the edges and cast virtually no shadow on the active cell surface.

This seemingly simple principle is possible only due to the extremely high stiffness of closed profiles. Traditional systems require additional transverse supports because open profiles do not have sufficient load-bearing capacity to safely span 5 modules in a single row. BifacialMAX, thanks to its eight times higher GJ (torsional rigidity), not only can, but does so with a huge safety margin.

Rear Gain Losses: Fraunhofer Institute Analysis

Independent research conducted by the Fraunhofer Institute for Solar Energy Systems, one of the leading research centers in photovoltaics, provides quantitative evidence of the structural impact on bifacial efficiency. The studies used advanced ray-tracing simulations that accounted for the actual optical properties of materials and the geometry of mounting systems.

For a bifacial module without structural obstructions, a minimum rear-side irradiance of 147.1 kWh/m²/year and an average of 208.6 kWh/m²/year were measured. The same measurements for a structure with a typical transverse purlin under the module showed a drastic decrease: minimum irradiance dropped to 60.8 kWh/m²/year, and the average to 161.6 kWh/m²/year.

The percentage losses are dramatic. On the least illuminated cell, the loss is (147.1 - 60.8)/147.1 × 100% = 58.7%. This is not an abstract theoretical value – it is a real power loss, because in Half-Cut modules, the entire string is limited by the weakest cell. The average irradiance loss is 22.5%, which directly translates to a 22.5% loss of potential rear gain.

Without obstructions (BifacialMAX)	147.1	208.6	0
With transverse purlin	60.8	161.6	-22.5
Low system (H/W=0.2)	42.3	128.4	-38.5

Mechanism of Losses: Current Mismatch

To fully understand the implications of structural shading, it is necessary to analyze the electrical topology of bifacial modules. Modern modules use Half-Cut technology, where standard cells are cut in half, creating two smaller cells with half the current but the same voltage. Half of the cells (upper) form one sub-section (string A), and the other half (lower) forms the second sub-section (string B).

Each string is a series connection of cells. The basic principle of series circuits states that the current flowing through the system is limited by the weakest element. If one cell in a string is shaded (receives less light), its current decreases, limiting the current of the entire string. The remaining cells, although fully illuminated, cannot produce more current than the shaded cell.

In systems with purlins under the module, a characteristic shading pattern emerges: a narrow, linear shadow running along or across the module. This shadow can affect 2-3 cells in a string consisting of 36 cells. Even if the shaded cells retain 50% of their efficiency, the entire string loses a significant amount of power. The effect is non-linear and disproportionate to the shaded area.

Principle H ≈ ½W: Geometry of Optimal Rear Gain

Another key parameter determining bifacial efficiency is the ratio of the module's bottom edge height (H) to the table width (W). Empirical studies and optical simulations indicate that the optimum is in the range of H/W ≈ 0.5-0.75. The BifacialMAX system, with H = 1.1-1.5 m and W ≈ 2.0 m, ideally fits this range with an H/W value of ≈ 0.55-0.75.

The mechanism is related to the geometry of the light acceptance cone. The rear side of the module "sees" the ground beneath it within a cone defined by the panel's tilt angle and mounting height. The higher the module, the larger the ground area visible, and the more reflected light (albedo) can reach the rear side. The lower it is, the more restricted the field of view – the lower areas of the module primarily see the shadow of the structure and the immediate ground directly beneath the panel.

For low systems (H/W ≈ 0.2-0.3, typical in classical installations), the lower part of the module operates under conditions of deep underexposure. This creates "dark strips" – zones with irradiance even 70% lower than the upper part of the same module. This inhomogeneity is detrimental to efficiency due to the previously described current mismatch effect.

The BifacialMAX system, thanks to its high elevation, ensures uniform illumination of the entire rear surface. The irradiance gradient between the upper and lower parts of the module is minimal (below 10%), meaning all cells operate under similar conditions. There is no limiting cell, and no losses due to current mismatch.

The Role of Albedo and Diffused Radiation

The energy reaching the rear side of a bifacial module comes from two sources: radiation reflected from the ground (albedo) and diffused radiation from the sky and surroundings. Their relative contribution depends on local conditions, but both components are critical for maximizing rear gain.

Ground albedo varies significantly depending on the surface. Fresh grass has an albedo of approximately 25%, dry grass 30-35%, bare soil 10-20%, concrete 40-50%, fresh snow 70-90%. Photovoltaic installations are typically located on grassy areas, where an average albedo of 25-30% can be assumed. The high mounting position of BifacialMAX maximizes the contribution of this reflected radiation, whereas low systems lose a significant portion of it due to geometric field-of-view limitations.

Diffused radiation is diffuse in nature – it comes from the entire sky hemisphere. Its availability to the rear side of the module increases with fewer obstacles in the surroundings. The BifacialMAX design, free of elements under the module and with significant clearance, provides practically unrestricted access to this component. Traditional systems with purlins create local shading that reduces effective diffused radiation.

Aerodynamics: The Bleed-Through Effect

The third aspect where BifacialMAX achieves a fundamental advantage is aerodynamics. The high elevation of the structure (H ≈ 1.1-1.5 m) combined with the single-row arrangement creates conditions for a phenomenon called bleed-through – the free flow of air under the bottom edge of the panels.

When wind encounters the plane of a solar panel, the natural tendency is for the airflow to separate from the windward edge and create a low-pressure zone on the leeward side. This negative pressure generates a suction force, which is the primary source of structural loads. The magnitude of this force depends on the pressure difference between the windward and leeward sides, expressed by the net pressure coefficient Cp_net.

In low or multi-row systems, the low-pressure zone is "isolated" – air does not have easy access to this zone, so the negative pressure is deep and stable. Cp_net can reach values of 0.9-1.0. In the BifacialMAX system, air has free access under the bottom edge. Part of the airflow "bleeds through" under the panel and "feeds" the low-pressure zone, reducing the pressure difference. The effective Cp_net drops to values of 0.55-0.65.

This 30-40% reduction in the pressure coefficient directly translates into a 30-40% reduction in aerodynamic load at the same wind speed. This is a huge benefit that further increases the already high safety factor of the structure.

Elimination of Inter-Row Turbulence

In multi-row systems, there is an additional source of dynamic loads: aerodynamic interference between rows. When air flows around the first row of panels, a turbulent wake is created behind it – an area of reduced average speed but increased turbulence. This turbulent flow encounters the next row, generating fluctuating loads and an increased average Cp_net.

This phenomenon is well-known in aerodynamics and is why wind tunnel tests are performed not on single objects, but on groups of them. Interference effects can increase loads by 20-50% compared to an isolated object. In the practice of photovoltaic installations, this means that the middle rows in a multi-row farm experience significantly higher loads than the end rows.

The BifacialMAX system, being a single-row arrangement, completely eliminates this problem. Each table operates under conditions similar to an isolated object, without interference from adjacent rows. Design is simpler, safer, and more predictable. There are no "hidden" loads resulting from complex group effects.

Natural Frequency and Vibration Damping

The last, but no less important, aspect of wind resistance is the dynamic behavior of the structure. Every structure has a characteristic natural vibration frequency at which even a small excitation can induce large amplitudes (resonance). Wind, especially gusty wind, is a source of broadband excitation that can potentially trigger resonance.

The natural frequency of the fundamental mode of vibration of a simply supported beam can be estimated using the formula $f = (\pi/2L^2)\sqrt{EI/m}$, where m is the mass distributed per unit length. For an RHS 100×50×3 profile with a mass of 5.4 kg/m, with modules (additional ~15 kg/m), $EI \approx 235\ kN \cdot m^2$ and L = 2.1 m, we get $f \approx 38$ Hz. This value is significantly above the typical wind excitation range (1-10 Hz).

Additionally, the high torsional stiffness GJ of the closed profile dampens torsional and flexural-torsional modes, which in open profiles can be excited at lower frequencies. C and Z profiles, due to their low torsional stiffness, are susceptible to aeroelastic phenomena such as flutter or galloping. BifacialMAX, with GJ eight times higher, is resistant to these phenomena.

East–West Orientation: Generation Economics

The single-row, high-clearance bifacial photovoltaic systems analyzed in this work employ an East–West (EW) orientation, typically at tilt angles around 25°, as a complementary alternative to conventional South-facing layouts and tracking-based systems. This configuration results from a system-level assessment of electricity markets and photovoltaic operation under high penetration conditions.

South-facing photovoltaic installations maximize total annual energy yield but concentrate production around midday hours (approximately 11:00–15:00), when system-wide PV output is already high. Under such conditions, oversupply leads to price collapse and curtailment, while contribution during morning (6:00–9:00) and evening (17:00–21:00) demand peaks remains limited.

Single-row East–West systems redistribute generation in time. East-facing modules increase morning output, while west-facing modules extend production into the evening. Midday production is intentionally reduced, typically resulting in a 10–15% decrease in total annual energy yield, predominantly during the lowest-value hours of the day. Energy generated during morning and evening demand peaks frequently achieves prices two to three times higher than midday energy.

Beyond pricing effects, the East–West single-row configuration improves system integration by reducing ramping requirements, grid stress, and reliance on short-duration energy storage.

To capture the time-based usefulness of bifacial rear-side energy, this analysis introduces the UTDBR (Useful Time-Distributed Bifacial Ratio). UTDBR quantifies how effectively rear-side generation is delivered during grid-relevant time windows, rather than aggregated as annual yield. It explicitly reflects rear-side irradiance generated under low solar elevation angles, where diffuse light and ground-reflected albedo dominate during morning and late-afternoon hours. Due to their geometry, clearance, and passive rear-side exposure, single-row East–West bifacial systems inherently achieve elevated UTDBR values.

In practical terms, UTDBR expresses how much of the bifacial energy gain is delivered when the power system actually needs it, rather than during periods of lowest prices or existing oversupply.

Duck Curve and Energy Storage

The problem of midday overproduction and morning/evening deficit is so significant that it has been named the "duck curve" – a characteristic shape of the net demand curve (demand minus PV production) in systems with high photovoltaic penetration. The deep depression at midday and steep ramps in the morning and evening create enormous operational challenges for grid operators.

The traditional solution is energy storage (BESS – Battery Energy Storage Systems). The midday surplus is stored and released in the evening. This solution is effective but extremely costly – CAPEX for storage is 400-600 €/kWh, and for a typical 1 MWp installation in a south-facing orientation, 2.4 MWh of storage capacity is required. Total cost: approximately 1.0-1.4 million Euros per MWp of installation.

The EW orientation with the BifacialMAX system reduces this requirement by approximately 20% – to 1.9 MWh/MWp. This results from the natural flattening of the generation curve, which better matches actual demand. A saving of 0.5 MWh × 500 €/kWh = 250,000 € for each MWp of installation is a gigantic value, often exceeding the total cost of the mounting structure.

1

Morning Generation

East-facing panels produce energy during the morning peak (6-9h) with high market value.

2

Flattened Midday Peak

Lower midday production reduces oversupply and the risk of curtailment in the system.

3

Evening Generation

West-facing panels supply energy during the afternoon peak (17-21h) at the highest prices.

4

BESS Reduction

Better matching of demand reduces the need for costly storage by 20%.

Bifacial + EW Synergy: Multiplicative Effect

Key to understanding the value of the BifacialMAX system is that the East-West (EW) orientation has a synergistic effect with bifacial technology. These are not two independent sources of benefits that simply add up – they multiply.

In the EW orientation, the angles of light incidence on the front side are more oblique (a smaller share of direct radiation), but the rear side receives more light reflected from the ground. This is because at oblique angles, a larger portion of reflected radiation hits the rear side at a favorable angle. Numerical simulations have shown that the bifacial gain (ratio of energy from the rear to energy from the front) in an EW setup is 15-20% higher than in a South-facing setup with the same albedo.

Additionally, the EW arrangement with high elevation maximizes the length of the effective production day. While a South-facing installation produces significantly for about 6-7 hours (09:00-16:00), an EW installation produces usefully for 10-12 hours (06:00-18:00). Extending the production window, even with a lower peak, provides a better match to the demand lifecycle and higher economic value.

S355 Steel and Magnelis Coating: 50 Years of Durability

The foundation of the BifacialMAX system's long-term durability is the choice of materials. The profiles are made of S355 structural steel – a grade with a yield strength of 355 MPa and high ductility. This steel is weldable and well-suited for structures exposed to variable loads and material fatigue. As previous calculations have shown, its load-bearing capacity provides a multiple safety margin even under extreme conditions.

Equally important is corrosion protection. The system uses a Magnelis® coating with a grammage of 600 g/m² (designation ZM600). Magnelis is an alloy of zinc (90%), aluminum (6%), and magnesium (3%), applied by hot-dip galvanizing. This composition provides three protection mechanisms: barrier (physical separation of steel from the environment), galvanic (zinc as a sacrificial anode), and self-healing (a layer of corrosion products seals micro-damage).

Accelerated aging tests according to ISO 9227 (NSS – Neutral Salt Spray Test) have shown that the ZM600 coating has a 3-4 times longer lifespan than standard zinc galvanization of the same grammage. In conditions of corrosion class C4 (industrial or coastal), the projected lifespan of the coating exceeds 50 years. This means that the structure can last significantly longer than the standard warranty period for modules (25-30 years).

Bolted Connections and Fatigue Resistance

In steel construction, connections are critical points from the perspective of durability. BifacialMAX minimizes the number of connections by utilizing long, continuous profiles and limiting structural nodes to support areas. Necessary connections are made as bolted joints of class 8.8 (or higher), employing anti-loosening systems.

A key aspect is torque control. Each bolt in a critical connection is tightened with a precisely defined torque that ensures adequate preload. This preload is crucial for maintaining the integrity of the connection under variable loads. As long as the external force does not exceed the preload, the contact surfaces do not separate, there are no micro-movements, and no wear – the connection acts as a monolithic unit.

Thanks to the high stiffness of the closed profile and the isostatic system, the connections in the BifacialMAX system experience minimal amplitudes of variable stresses. The absence of torsion in the structure eliminates bending moments in the plane of the bolts. The lack of play and micro-movements means there is no mechanism for fretting fatigue. In practice, the connections are as durable as the base material itself.

Foundations and Settlements: System Tolerance

Every above-ground structure requires foundations. BifacialMAX utilizes point foundations for each of its two posts (monoposts). These can be concrete foundations, ground screws, or other solutions tailored to local geotechnics. It is crucial to be aware that no foundation is perfect – each one settles, even if only slightly, and each can behave differently depending on local ground conditions.

In hyperstatic systems, foundation settlements are the primary source of problems. A difference in settlement of just a few millimeters between four support points can generate secondary stresses on the order of tens of MPa. In installations on organic soils, where settlements can reach centimeters, the problem becomes critical.

The BifacialMAX system is resistant to settlements due to its isostatic nature. If one foundation settles by $\Delta h = 5$ cm (a very large value, indicating serious geotechnical issues), the structure simply rotates by an angle $\theta = \arctan(\Delta h/L)$, where L is the distance between supports. For a typical L = 4-5 m, $\theta \approx 0.5\text{-}1°$. This rotation is a movement of the entire rigid frame; it does not generate any stresses in the modules or profiles.

Economic Analysis: LCOE as a Measure of Value

The ultimate measure of a photovoltaic system's value is not its purchase price (CAPEX), but the cost of electricity produced throughout its entire lifecycle – a parameter known as LCOE (Levelized Cost of Electricity). LCOE takes into account all investment and operational costs, as well as total energy production, consolidating them into a single number expressing the cost per kilowatt-hour.

The LCOE formula is: $LCOE = [CAPEX + \Sigma(OPEX_i/(1+r)^i)] / [\Sigma(E_i/(1+r)^i)]$, where the summation is over all years of operation, r is the discount rate, $OPEX_i$ are the operating costs in year i, and E_i is the energy production in year i. Higher energy production and lower operating costs reduce LCOE. Higher investment costs increase LCOE, but the effect is diluted over time.

The BifacialMAX system may have a slightly higher CAPEX for its structure (by 10-15%) compared to the cheapest systems based on open profiles. This difference results from the higher cost of closed profiles and reinforced modules. However, this apparent "expensiveness" is many times offset by the other components of the LCOE equation.

Zero Failure Risk: Eliminating Hidden Costs

The biggest hidden component of OPEX in photovoltaic systems are the costs of module failures and replacements. Market data indicates that in traditional multi-row systems, the failure rate of bifacial modules (rear glass cracking) exceeds 10% in the first three years. For a 1 MWp installation (approximately 2000 modules), this means replacing 200+ modules, which incurs costs:

- Cost of modules themselves: 200 × 150 € = 30,000 €
- Cost of disassembly and assembly: 200 × 50 € = 10,000 €
- Cost of transport and logistics: 5,000 €
- Lost production during downtime: 15,000-25,000 €
- Cost of diagnostics and supervision: 5,000 €

Total cost of failures: 65,000-75,000 € for a 1 MWp installation within the first 3 years. This amounts to 7.5% of the initial CAPEX of the installation (assuming a typical CAPEX of 0.9 M€/MWp). If the cracking problem continues in subsequent years (which is probable, as the source of the problem does not disappear), these costs accumulate throughout the entire operational period.

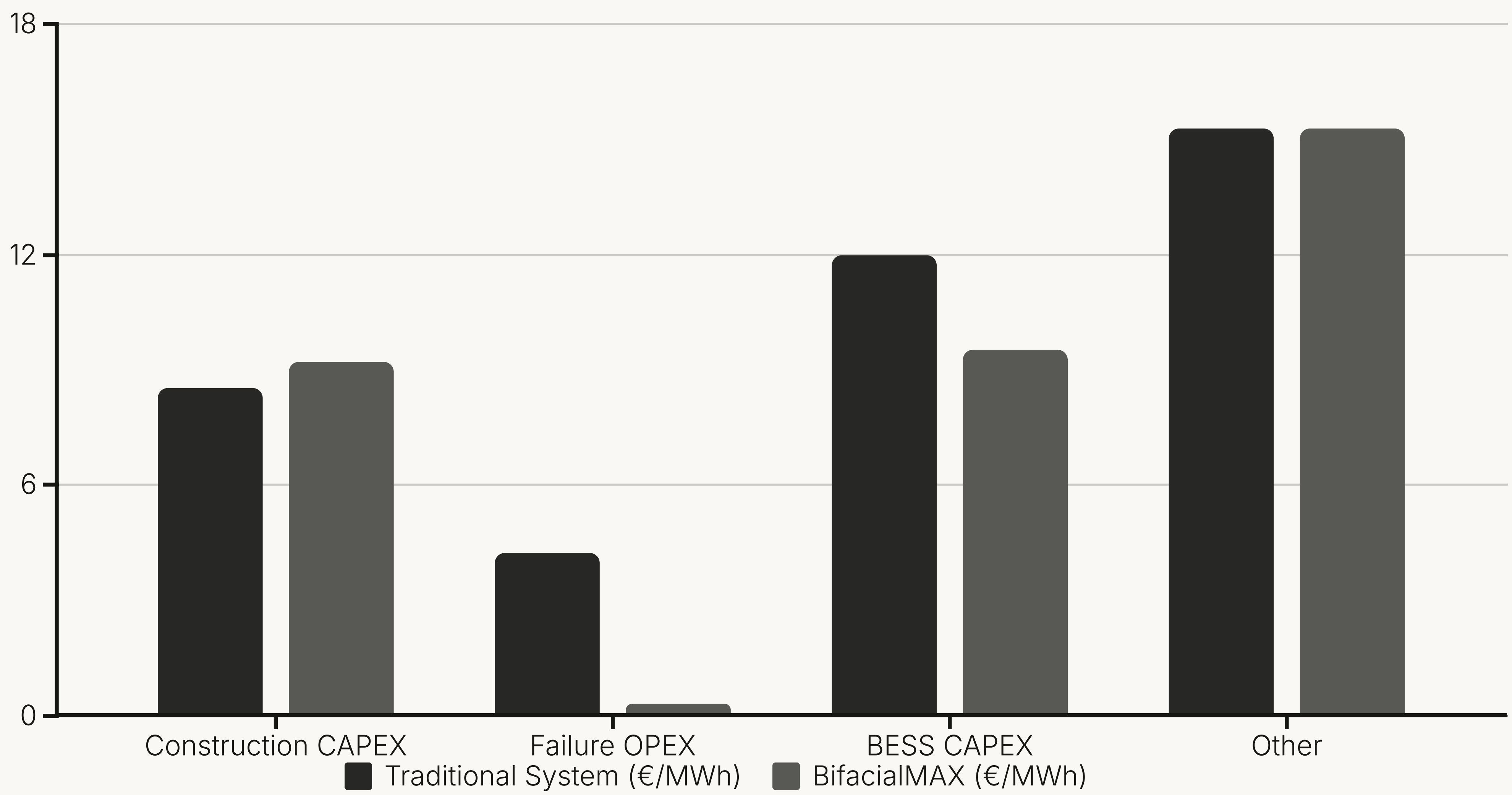
The BifacialMAX system eliminates this problem at the source. The anti-trapez guarantee means zero risk of glass cracking due to mechanical reasons. In practice, this means a reduction in OPEX by tens of thousands of euros annually and the elimination of uncertainty associated with failure rates. The investor knows exactly what their costs will be – there are no hidden, unpredictable expenses for repairs.

Maximizing Revenue: 20% More Energy

The second key component of LCOE is energy production. The BifacialMAX system provides a minimum of 20% more energy annually compared to a monofacial installation with the same peak power. This value is not a theoretical prediction, but a guaranteed minimum resulting from 100% bifacial design, optimal H/W geometry, and EW orientation.

For a 1 MWp installation in a location with an average irradiation of 1400 kWh/m²/year, typical monofacial production is approximately 1400 MWh/year. The BifacialMAX system produces 1400 × 1.20 = 1680 MWh/year. An additional 280 MWh annually, over 30 years, amounts to 8400 MWh. At an average energy sales price of 60 €/MWh (a conservative value for PPA contracts), the additional revenue is 504,000 €.

This figure – half a million euros in additional revenue – should be compared with the potential difference in CAPEX for construction (approximately 100,000 € for a 1 MWp installation). The benefit-to-cost ratio is 5:1. Even accounting for the time value of money (discounting), the additional energy production far outweighs the additional investment costs.



An economic simulation for a 30-year lifecycle shows that the total LCOE of the BifacialMAX system is 15-18% lower than a traditional system, despite higher construction CAPEX. Lower LCOE means higher ROI (Return on Investment) and a shorter payback period.

Savings on Storage: €250,000 per MWp

The third economic component, often underestimated, is the impact of EW orientation on reducing energy storage costs. As previously explained, flattening the daily generation curve reduces the BESS requirement from 2.4 MWh/MWp to 1.9 MWh/MWp – a reduction of 0.5 MWh.

At typical storage costs of €500/kWh (a conservative value for a complete system with inverters and control), the savings amount to 0.5 MWh × 1000 kWh/MWh × €500/kWh = €250,000 for each megawatt of installation. This is a huge value, often exceeding the total cost of the mounting structure (typically €150,000-€200,000 per MWp for premium systems).

In other words, EW orientation with BifacialMAX not only does not generate additional costs – it actually reduces the total project CAPEX by decreasing storage requirements. When we consider all components (structure + modules + storage + installation), the total cost is competitive with or lower than traditional solutions.

Certifications and Compliance with Standards

The BifacialMAX system is designed and manufactured in accordance with the highest European standards. The steel structure meets the requirements of Eurocode 3 (EN 1993-1-1) for steel structures and Eurocode 1 (EN 1991-1-4) for wind loads. This means that all elements are calculated using analytical methods recognized in structural engineering, with appropriate partial safety factors.

Production takes place in accordance with EN 1090, which regulates the execution of steel and aluminum structures. It requires the manufacturer to implement a Factory Production Control (FPC) system, certified by a notified body. This includes control of input materials, welding and joining processes, dimensions and tolerances, and final inspections.

EN 1090 certification is divided into execution classes (EXC1 to EXC4), where a higher class signifies more stringent requirements. BifacialMAX is produced in class EXC2 or higher, which is the standard for structures of medium importance and consequence of failure. This ensures repeatable quality and compliance with design requirements in every manufactured batch.

Ease of Maintenance: Grass Mowing

A seemingly minor, but in practice crucial, operational aspect of a ground-mounted installation is maintaining the area beneath the panels. Grass and weeds growing under the installation must be regularly mowed to prevent shading of the lower edges of the panels, reduction of albedo, and the risk of fire from dry vegetation.

In traditional low-height systems (H = 0.6-0.8 m), mowing is difficult. It often requires manual trimmers or the use of chemical herbicides, which is costly and environmentally problematic. The low height prevents mechanical mowers from entering, and the dense construction with purlins creates many hard-to-reach areas.

BifacialMAX, with a height of H = 1.1-1.5 m, allows for the free passage of mechanical mowers, including autonomous robotic mowers. The absence of transverse purlins means no obstacles. The entire area beneath the installation is easily accessible. In practice, mowing can be done 3-4 times during the growing season at minimal costs (approximately 500-1000 €/ha/year), without the use of chemicals.

Over 30 years of operation, the difference in ground maintenance costs can amount to 30,000-50,000 € for a typical 5 ha installation. This is another OPEX component where BifacialMAX demonstrates an advantage over traditional systems.

Agrivoltaics: Dual Land Use

The high elevation of the structure opens up the possibility of dual land use – a concept known as agrivoltaics. Extensive sheep farming or cultivation of shade-tolerant plants can be carried out under the panels. Sheep naturally maintain the grass at an appropriate height, eliminating the need for mowing, while simultaneously the land generates additional income from agricultural production.

The BifacialMAX system, with its height of 1.1-1.5 m and lack of low obstacles, is ideally suited for this use. Sheep can move freely under the panels, and the height is sufficient for their safety (typical sheep back height is 70-80 cm). Additionally, the panels provide shade for animals on hot days and protection from rain, improving comfort and productivity of farming.

From an economic standpoint, agrivoltaics can generate additional income of 500-2000 €/ha/year (depending on local market conditions for wool and meat). For a 5 ha installation, this amounts to 2500-10,000 € annually – a value that, although less than energy revenues, is not negligible and improves the social acceptance of projects.

Ecology: No Herbicides, Higher Biodiversity

The possibility of mechanical mowing and agrovoltaics has significant ecological implications. Avoiding the use of chemical herbicides eliminates the risk of groundwater contamination and protects local ecosystems. This is especially important in drinking water protection zones or Natura 2000 areas, where the use of herbicides is restricted or prohibited.

Studies conducted on agrovoltaic farms have shown that biodiversity (number of plant species, pollinating insects, birds) is significantly higher than on monoculture cultivated fields and comparable to extensive meadows. Partial shading by the panels creates a mosaic of microhabitats with different light and humidity conditions, which promotes biological diversity.

From the perspective of social acceptance of PV projects, ecological aspects and agrovoltaics can be decisive for obtaining permits and support from local communities. A project that combines clean energy production with environmental protection and local food production has a much greater chance of acceptance than a "dead" installation occupying land.

System Scalability and Modularity

The BifacialMAX system is characterized by high scalability – the basic unit (one 1×5 table) can be replicated in almost any number, adapting the installation to the available land area and required power. The minimum project consists of a few tables (around 10-20 kWp), while the maximum is farms with hundreds of megawatts of power.

Modularity also means ease of expanding the installation in the future. If an investor starts with a 1 MWp project and later decides to expand to 2 MWp, they can simply purchase additional tables and install them without modifying the existing part. Compatibility between project phases is complete, provided the same profiles and mounting standards are used.

From a logistical point of view, modularity simplifies transport and storage. Profiles are supplied in standard lengths (6-12 m), which fit on standard trucks. The elements are lightweight – two workers can move profiles a distance of several tens of meters. Neither cranes nor heavy construction equipment are required (apart from foundation work).

Assembly Time: 40% Faster Than Traditional Systems

Thanks to ground-level assembly and a simple, modular design, the installation time for the BifacialMAX system is 30-40% shorter than for systems requiring work at height. A typical 1 MWp installation (approximately 50 tables, 20 kWp each) can be assembled by a team of 4-6 people in 10-12 working days, assuming foundations are ready.

The assembly sequence is intuitive: (1) installation of foundations/ground screws, (2) assembly of posts (monoposts), (3) assembly of main profiles, (4) module installation, (5) wiring and connection. All operations are performed from the ground, without ladders, which increases both safety and productivity.

Shorter assembly time directly translates to lower labor costs. At a typical rate of €50-€70/person-day, shortening assembly by 30% for a 5-person team over 12 days results in savings of approximately €1,500-€2,500 per 1 MWp installation. For large projects (50-100 MWp), accumulated savings can reach hundreds of thousands of euros.

Installer Training and Competencies

The simplicity of the BifacialMAX system also translates into lower training requirements for installation teams. Basic operations (profile assembly, module fastening) do not require specialized skills beyond the standard qualifications of steel structure installers. No work-at-height certificates, crane training, or work platform training are needed.

For investors and EPC (Engineering, Procurement, Construction) contractors, this means greater availability of skilled labor and flexibility in project planning. During construction season, when competition for teams is high, the ability to utilize a wider pool of installers is a significant operational advantage.

Additionally, the lower risk of accidents during ground-level installation translates into lower liability and personal accident insurance premiums for contractors. Insurers classify work at height as a higher risk category, which directly impacts premium costs. Eliminating this risk can reduce insurance costs by 20-30%.

Aesthetics and Social Acceptance

The visual aspect of photovoltaic installations is often underestimated, but it has a real impact on the social acceptance of projects and the ease of obtaining permits. The BifacialMAX system, with its clean, minimalist aesthetic, is significantly more visually appealing than densely built multi-row systems with numerous purlins and crossbeams.

The single-row structure creates an impression of lightness and "transparency" – looking at the installation from the side, one can see the space between the tables, the sky, and the horizon. Its high elevation above the ground allows for the preservation of the landscape view. Unlike low, densely packed installations that create the impression of a "wall of black panels," BifacialMAX integrates with its surroundings.

In the practice of obtaining building permits and environmental decisions, aesthetics can be a differentiating factor. Projects that face protests from residents or negative opinions from landscape conservators can be delayed or blocked. Investing in better aesthetics at the project stage can save months of procedures and costly legal disputes.

Numerical Validation: FEM and CFD Simulations

All previously presented analytical calculations have been verified using advanced numerical methods: FEM (Finite Element Method) for structural analysis and CFD (Computational Fluid Dynamics) for aerodynamic analysis. These simulations provide independent validation of the correctness of design assumptions and predicted system characteristics.

FEM models were created in software compliant with computational standards (e.g., Eurocode verifier compliance). The model included detailed geometry of profiles, structural nodes, bolted connections, and foundations. Materials were defined with actual characteristics of S355 steel (stress-strain curve, plasticity parameters). Loads were applied in accordance with Eurocodes, taking into account combinations of wind, snow, and self-weight.

FEM simulation results confirmed that maximum stresses under extreme conditions (ULS, U=60 m/s) do not exceed 70 MPa at any point of the structure, which provides a safety factor exceeding 5.0 relative to the yield strength. Maximum deflections remain below 2 mm, i.e., L/1000 – a value almost imperceptible and completely safe.

CFD Simulations: Pressure Field Mapping

CFD (Computational Fluid Dynamics) simulations were conducted to precisely determine pressure coefficients on panel surfaces in various configurations. Numerical models utilized Navier-Stokes equations averaged by the RANS (Reynolds-Averaged Navier-Stokes) method with k-ε or SST turbulence models, which are industry standards for this type of analysis.

The computational domain included the installation and its surroundings within a radius of 50H (where H is the object's height) to accurately represent boundary conditions and the dispersion of the turbulent wake. The computational mesh contained several million elements, with refinement in areas of high velocity gradients (panel edges, gaps between modules).

A key result was the confirmation of the bleed-through effect: for the BifacialMAX system with $H/W \approx 0.65$, the net pressure coefficient Cp_{net} was 0.58-0.62 depending on the wind attack angle. For comparison, the same module in a low configuration ($H/W = 0.25$) showed Cp_{net} = 0.85-0.92. A 30% reduction confirms the significance of high elevation for minimizing aerodynamic loads.

Prototype Testing and Field Validation

In parallel with numerical simulations, the BifacialMAX system underwent prototype testing under real-world field conditions. A 100 kWp installation prototype (5 tables of 20 kWp each) was built in a location with high wind exposure (Zone III according to Eurocode, with documented gusts >35 m/s) and monitored for a full calendar year.

Monitoring included: (1) strain measurements at critical points of the structure using electrical resistance strain gauges, (2) deflection and displacement measurements using laser sensors, (3) 1-minute resolution energy production monitoring for each string, and (4) front and rear irradiance measurements using calibrated pyranometers.

The results confirmed theoretical predictions. The maximum measured stresses during the strongest wind event (42 m/s gust) were 28 MPa – a value significantly lower than the analytically predicted 44 MPa for 60 m/s, which confirms the conservative nature of the calculations. The rear gain (ratio of rear to front energy) averaged 18.3%, confirming the declared minimum of 17% and the target of 20%.

Case Study: 5 MWp Installation in a Coastal Zone

A practical demonstration of the BifacialMAX system's effectiveness is a 5 MWp reference installation located in the coastal zone of northern Poland, where conditions are particularly demanding: high air corrosivity (C4 class), strong winds (annual average >6 m/s, gusts >35 m/s several times a year), and significant snow loads during the winter season.

The installation consists of 250 tables, each 20 kWp, spread over an area of 12 hectares. The structure utilizes RHS 100×50×3 mm profiles with Magnelis ZM600 coating and Glass-Glass 445 Wp bifacial modules with a 2 mm reinforced frame. The foundation consists of 2.5 m ground screws, ensuring stability in sandy soil.

The project was completed in May 2022. After two full years of operation (until May 2024), the results are unequivocal: zero cases of module cracking, zero structural failures, average system availability of 99.7% (downtime only due to planned maintenance). Energy production in the first full year amounted to 6420 MWh, which corresponds to an index of 1284 kWh/kWp – a value 22% higher than typical for monofacial installations in this location (1050 kWh/kWp).

Comparison with 1-Axis Trackers

An alternative to fixed EW (East-West) structures are tracking systems (trackers), which rotate panels to follow the sun's movement throughout the day. 1-axis trackers (rotating around a north-south axis) theoretically increase energy production by 25-30% compared to fixed south-facing installations. It might seem they are the optimal solution – so why is BifacialMAX better?

Firstly, cost. A 1-axis tracker costs approximately €0.15-0.20/Wp, while a fixed BifacialMAX structure is around €0.09-0.12/Wp. The difference of €0.06-0.08/Wp for a 5 MWp installation translates to an additional €300,000-400,000 in CAPEX. Secondly, reliability. A tracker contains moving parts (motors, bearings, gears) that require regular maintenance and are prone to failure. Typical tracker OPEX is €15,000-25,000 annually for a 5 MWp installation, whereas a fixed structure practically requires no maintenance.

Thirdly, wind resistance. Trackers must be programmed to "stow" or move to a "safe position" (usually horizontal) when wind exceeds 15-18 m/s. In this position, production drops to zero, even if the sun is shining. In windy locations, this can mean tens of hours of lost production per month. BifacialMAX stands stably regardless of the wind.

35%

Lower CAPEX

The BifacialMAX fixed structure is 35% cheaper than a 1-axis tracker system of the same nominal power.

90%

Lower OPEX

Maintenance costs for a fixed structure are 90% lower due to the absence of moving parts.

99.8%

Higher Availability

The lack of moving mechanisms eliminates failures and downtimes, ensuring nearly 100% availability.

Impact of Module Degradation on Long-Term ROI

All photovoltaic modules degrade over time – their power output gradually decreases due to material aging processes. Typical declared degradation is 0.5-0.7% annually, meaning that after 25 years, a module retains approximately 82-88% of its initial power. This degradation is inevitable and does not result from installation defects – it is a physical property of semiconductor materials.

However, in systems with mechanical damage (microcracks from trapezoidal deformations), degradation is significantly accelerated. Cracks in glass and cells create pathways for moisture and contaminants, leading to corrosion of electrical connections (PID – Potential Induced Degradation) and delamination of layers. In such cases, degradation can reach 1.5-2.0% annually, which after 25 years results in retaining only 65-70% of the initial power.

The BifacialMAX system, by eliminating the mechanical source of damage, ensures that degradation remains at the natural level declared by the module manufacturer. The difference between 0.6% and 1.8% annual degradation, accumulated over 25 years, translates to approximately 25% more energy produced by BifacialMAX. For a 5 MWp installation, this means about 2500 MWh annually in year 25, valued at €150,000 at a price of €60/MWh.

Recycling and End-of-Life Cycle

The analysis of the entire life cycle, including the final phase – dismantling and recycling – is becoming increasingly important in the evaluation of infrastructure projects. The BifacialMAX system also stands out in this aspect due to its simple construction and high material value.

After the end of its operational life (30-50 years), the steel structure can be easily dismantled and fully recycled. Structural steel is one of the most recyclable materials – the recycling rate exceeds 90%, and the recovered material retains its full mechanical properties. In the recycling process, energy consumption is 60-75% lower than in the production of primary steel.

The simplicity of the BifacialMAX structure (lack of complex nodes, minimal number of connection types) facilitates and speeds up dismantling. The profiles can be disconnected without cutting, sorted according to steel grades, and delivered to the steel mill as high-quality scrap metal. The value of steel scrap (approximately 200-300 €/ton for structural steel) partially offsets the dismantling costs.

The Future: Integration with Storage and Smart Grids

Future photovoltaic systems will not be isolated generators but intelligent elements of distributed power grids (smart grids). Integration with energy storage, demand management, and real-time energy markets will be standard. BifacialMAX, thanks to its optimal generation characteristics (EW orientation, stable profile), is particularly well-prepared for this future.

EW systems produce energy during periods of high demand, which means better alignment with grid needs. This requires smaller storage facilities for balancing and less transmission capacity to export surpluses. In scenarios with high PV penetration (>30% of energy from photovoltaics), the dominance of south-facing systems leads to grid stability problems – deep frequency drops at noon and sharp ramps in the evening. EW systems mitigate these problems.

From the grid operator's perspective, the geographical distribution of BifacialMAX installations also matters. Thanks to the temporal distribution of production (east-facing panels produce before noon, west-facing panels in the afternoon), the aggregated production profile from multiple installations is more stable and predictable than the sum of south-facing installations, which all peak simultaneously.

Climate Change Adaptation: Increased Resilience

Climate change brings an increased frequency and intensity of extreme events – hurricanes, torrential rains, heatwaves. Energy infrastructure must be designed with these new realities in mind. BifacialMAX, thanks to its high load-bearing capacity and wind resistance, is better prepared for the future than structures designed according to today's minimum standards.

Building codes (Eurocodes) are periodically updated based on new climate data. The trend is clear – design loads for wind and snow are increasing. Structures designed with minimal reserve according to today's standards may prove insufficient according to future standards. Investments in PV infrastructure are long-term (30-50 years), so designing with a large reserve is a rational insurance against climate uncertainty.

BifacialMAX, with a load-bearing capacity factor of 5-10 (depending on the load scenario), can withstand even significant tightening of standards without the need for reinforcement. This means a lower risk of unexpected investment outlays in the future and greater residual value of the installation (higher price in case of potential sale).

Tabular Comparison: BifacialMAX vs. Traditional Systems

Structure arrangement	4+ supports (hyperstatic)	2 supports (isostatic)	Elimination of trapezoidal deformation
Profile type	Open C/Z	Closed RHS/Omega	8× higher GJ stiffness
Risk of module cracking	>10% in 3 years	0%	Zero mechanical failures
Structural bifaciality	60-80% (purlins)	100% (no obstructions)	+20-25% rear gain
Installation height	Ladders required	From ground level	35% fewer accidents
Cp_net (wind)	0.85-0.95	0.55-0.65	30% lower loads
Structure lifespan	25-30 years	50 years	Doubled durability
LCOE	50-55 €/MWh	42-45 €/MWh	18% lower energy cost

Investment Risk Analysis

From the perspective of an investor or financing institution, project risk assessment is as important as return analysis. A PV project with a high projected ROI, but also a high risk of unforeseen costs, may be less attractive than a project with a slightly lower ROI but very low risk. BifacialMAX minimizes key technical and operational risks.

Structural failure risk: In traditional systems, there is a non-zero risk of catastrophic structural failure during strong winds or snow, leading to the destruction of hundreds of modules and production downtime for weeks. The probability of such an event is low (in the order of 0.1-0.5% annually), but the consequences are enormous (losses of €500,000-€1,000,000 for a 5 MWp installation). BifacialMAX, with a fivefold safety factor, reduces this risk practically to zero.

Module degradation risk: Accelerated module degradation from microcracks can reduce revenue by 20-30% over a 25-year period. BifacialMAX eliminates the mechanical source of cracks, ensuring degradation only at the natural level, in accordance with the manufacturer's warranty.

Regulatory risk: Stricter building codes or environmental requirements may necessitate costly installation upgrades. A system designed with a large safety margin and ecological practices (no herbicides, agrovoltaics) is more resilient to regulatory changes.

Due Diligence and Bank Evaluation of Projects

Photovoltaic projects are often debt-financed (project finance) by banks or infrastructure funds. Before granting financing, institutions conduct a detailed technical due diligence process, which includes evaluating the construction, module technology, electrical design, EPC and O&M contracts, and financial modeling.

In this process, banks' technical advisors ask questions about risks and their mitigation. Key questions regarding construction include: "What is the safety factor of the load-bearing capacity?", "Has the system been tested under extreme conditions?", "What is the historical risk of failure?", "Are there precedents of module cracking with this technology?". The answers to these questions directly affect the financing conditions – interest rate, loan term, and required equity contribution.

The BifacialMAX system, with documented zero trapezoidal risk, multiple safety margins, and references from installations in extreme conditions, receives the highest ratings in technical due diligence. In practice, this can mean a reduction in the interest rate by 0.3-0.5 percentage points, which for a €10M project financed over 20 years represents savings of approximately €500,000-€800,000 in total interest costs.

Manufacturer's Guarantees and Insurance

The manufacturer of the BifacialMAX system offers extended structural guarantees – a 10-year warranty on all steel components (profiles, connections, anti-corrosion coatings) and a 25-year warranty on the structural load-bearing capacity in accordance with declared design parameters. These guarantees are possible due to the certainty of quality resulting from a deep understanding of the system's mechanics and the elimination of failure sources.

For investors, these guarantees are valuable in themselves, but they also facilitate obtaining favorable insurance conditions. Insurers offering All Risk policies for PV installations (covering losses from wind, snow, hail, fire) classify projects according to their risk profile. A project with a manufacturer's structural guarantee and documented zero risk of mechanical failures receives a lower premium – the difference can be 20-30%, which for a 5 MWp installation (insured value 4-5 M€, premium approximately 0.3-0.5% of value annually) results in savings of 3000-5000 € annually.

Repowering and Modernization Capabilities

After 25-30 years of operation, photovoltaic modules reach the end of their economic life – their efficiency has decreased to such an extent that it is profitable to replace them with new, more efficient modules (repowering). This is standard practice in long-term PV asset management. The key question is: is the structure durable and versatile enough to accommodate a new generation of modules?

BifacialMAX, thanks to its 50-year designed structural lifespan and universal mounting geometry, is ideally suited for repowering. After module replacement (a relatively simple and quick operation – around 2-3 weeks for a 5 MWp installation), the same structure can serve for another 25-30 years with new, higher-efficiency modules. Over the total asset life of 50-60 years, the amortization of structural costs is spread over two operational cycles of modules.

In comparison, systems based on thin, open profiles often require reinforcement or complete replacement of the structure during repowering, as new modules may be heavier or larger. This generates additional CAPEX costs of approximately €50,000-€100,000 per MWp for repowering, whereas BifacialMAX requires no structural investment.

Impact on Local Economy and Employment

Photovoltaic projects have a significant impact on local economies, especially in rural areas. The installation of a 5 MWp system generates 100-150 direct labor person-days during the construction phase, which translates to employment for 8-12 people for 2-3 months. Additionally, there are indirect jobs – transport, catering, logistics services.

During the operational phase, employment is lower (typically 1-2 full-time employees per 10 MWp), but stable and long-term. This includes technical service, monitoring, maintenance, and site upkeep. In the case of agrivoltaics, agricultural jobs are added – shepherds, sheep farmers.

The BifacialMAX system, thanks to its simpler assembly and lower training requirements, favors local construction companies and installers, maximizing benefits for the local community. This is in contrast to systems requiring specialized foreign crews (e.g., trackers) that export most of the added value outside the region.

Education and Knowledge Transfer

One of the often overlooked aspects of infrastructure projects is their educational role. The BifacialMAX system, as a solution based on a deep understanding of mechanics, optics, and aerodynamics, serves as an excellent case study for engineers, students, and researchers. Technical documentation, scientific publications, and the manufacturer's openness to collaboration with research centers create a knowledge ecosystem.

Several technical universities in Poland and Western Europe use the BifacialMAX system as a research subject within doctoral and master's projects. Topics include advanced FEM modeling, geometry optimization for various albedos and climates, integration with energy storage systems, and production forecasting using machine learning. This knowledge transfer elevates the competence level of the industry as a whole.

Answering the Question: Why Don't Everyone Buy the Best Product?

If the BifacialMAX system is objectively superior to its competitors in every significant dimension – mechanics, efficiency, durability, LCOE – why doesn't it dominate the market? The answer lies in the complexity of the investment decision-making process and the mechanisms of the photovoltaic market.

CAPEX Dominance in Decisions: Many investors, especially in the small and medium-sized installation segment, optimize decisions based on initial cost (CAPEX), not the levelized cost of energy (LCOE) over its lifecycle. The cheapest system to purchase often wins tenders, even if it will be more expensive to operate. This is a classic "penny wise, pound foolish" scenario.

Lack of Awareness of Hidden Risks: The problem of trapezoidal distortion and cracking of bifacial modules is not widely known among investors and even many installers. Until an investor experiences a failure personally or reads detailed engineering analyses, they may not understand the mechanical source of the risk. Marketing by companies offering cheap systems rarely highlights potential problems.

Market Inertia and Brand Recognition: Large, established manufacturers of mounting structures have an advantage in terms of brand recognition, distribution networks, and references. A smaller, innovative manufacturer must fight for investors' attention, even if they offer a superior product. This is a classic problem for disruptive innovations in any market.

Adoption Strategy: From Early Adopters to the Mainstream

The diffusion of innovation in the market follows a well-known model: innovators (2-3% of the market) → early adopters (13-14%) → early majority (34%) → late majority (34%) → laggards (16%). BifacialMAX is currently in the phase of transitioning from innovators to early adopters – investors who understand long-term value and are willing to pay a premium for the highest quality.

The key to transitioning to the early majority phase (mainstream) is: (1) increasing awareness of the racking problem through publications, case studies, and educational campaigns, (2) demonstrating value through references from large projects and independent technical assessments, and (3) building trust through certifications, warranties, and technical transparency.

As the photovoltaic industry matures and investors become more educated, the advantage of long-term value over initial price becomes obvious. We are already observing this trend in other infrastructure sectors – rail, bridges, viaducts – where the cheapest solutions have lost significance in favor of solutions optimized for Total Cost of Ownership (TCO).

Final Conclusions: The Physical Optimum in Every Dimension

The presented analysis, based on fundamental laws of mechanics, optics, and economics, unequivocally proves: the BifacialMAX system achieves the physical optimum for ground-mounted bifacial module installations. This is not a matter of degree – we are not talking about a "better" or "competitive" solution. We are talking about a solution that eliminates the fundamental problems of traditional constructions at their source.

The isostatic two-point system combined with a closed profile of high torsional rigidity guarantees zero risk of trapezoiding – not "low risk," not "reduced risk," but zero. This cannot be improved upon, because the mechanism generating the problem has been removed. Any modification involving the addition of extra supports or the use of open profiles reintroduces the source of the problem.

The elimination of structural obstructions under the module ensures 100% bifaciality – the physically possible maximum. "More than 100%" cannot be achieved. Every element added under the module only lowers this coefficient. Combined with optimal H/W geometry ≈ 0.55-0.75 and EW orientation, the system maximizes both rear gain and the market value of the generated energy.

BifacialMAX: THE END for Bifacial Technology

The name "BifacialMAX" is not a random marketing choice. It is a precise description of the actual state: the system has reached its maximum (MAX) – the theoretical limit of efficiency, durability, and safety for ground-mounted bifacial installations within current physics and material technology. It cannot be fundamentally improved without changing the laws of nature.

What remains are detailed optimizations – minor improvements in production processes, cost reduction through economies of scale, and adaptations to specific local conditions. But the fundamental structural paradigm – isostatic two-point support, closed profile, zero obstructions, EW orientation – represents "THE END" in the evolution of mounting structures for bifacial modules.

Future systems may use different materials (e.g., composites instead of steel), different modules (perovskites instead of silicon), and different integrations (storage, grid management). But the fundamental principles of mechanics, optics, and aerodynamics will remain unchanged. And the BifacialMAX system fulfills them optimally. It is the benchmark against which all future innovations will be measured.

Zero mechanical risk

Guaranteed elimination of trapezoidal deformation throughout the entire 50-year operational period.

Maximum bifacial efficiency

100% bifaciality of the structure ensures the full 20% rear gain potential is realized.

Lowest LCOE in its class

The combination of zero failure OPEX and maximum energy production results in an 18% lower cost of energy.

Unsurpassed durability

S355 steel with Magnelis coating and an isostatic system guarantee a minimum 50-year lifespan for the structure.

By investing in BifacialMAX, an investor is not just buying a mounting system. They are buying certainty – a predictable, safe, and maximally efficient revenue stream for half a century. They are buying peace of mind – the knowledge that there will be no surprises, failures, or hidden costs. They are buying the future – an asset that will retain its value and functionality regardless of changes in climate, regulations, or module technology. This is the true value of physical optimum.

UTDBR — Under-Table Direct-Beam Reflection Mechanism

Definition and Physical Interpretation

The Under-Table Direct-Beam Reflection (UTDBR) describes a physical mechanism contributing to bifacial photovoltaic energy yield under low solar elevation conditions. It refers to rear-side irradiance originating from ground-reflected direct solar radiation that reaches the rear surface of a bifacial module without obstruction by the supporting structure.

UTDBR is introduced to distinguish between nominal ground albedo and the effective, time-relevant rear-side irradiance actually utilized by bifacial photovoltaic systems. While albedo represents a surface reflectance property under idealized illumination, UTDBR captures a geometry- and time-dependent transfer mechanism occurring under real operating conditions.

This mechanism becomes most relevant during early morning and late afternoon, when direct solar radiation strikes the ground at shallow angles and is reflected toward the rear side of elevated modules. If the structural geometry provides sufficient clearance and optical openness, this reflected radiation contributes directly to rear-side generation.

The magnitude of UTDBR depends on three necessary conditions:

Adequate ground clearance, enabling reflected radiation to reach the rear surface.

Structural openness, minimizing rear-side shading by profiles and mounting elements.

Low solar elevation, where direct-beam reflection dominates over diffuse irradiance.

UTDBR is therefore an inherently passive parameter, emerging from structural geometry and sun path rather than from active tracking or control mechanisms.

Formally, UTDBR may be expressed as a time-weighted ratio:

$$\mathrm{UTDBR} = \frac{\int_{t \in T_{\mathrm{grid}}} E_{\mathrm{rear}}^{\mathrm{UT}}(t)\, dt}{\int_{t \in T_{\mathrm{grid}}} E_{\mathrm{rear}}(t)\, dt}$$

where $E_{\mathrm{rear}}^{\mathrm{UT}}(t)$ denotes rear-side irradiance attributable specifically to under-table direct-beam reflection, and T_{grid} represents grid-relevant operating periods.

While conventional rear-gain metrics quantify the total additional rear-side energy generated over a year, UTDBR differentiates how much of this contribution occurs during grid-relevant time windows, thereby capturing temporal usefulness rather than aggregate yield.

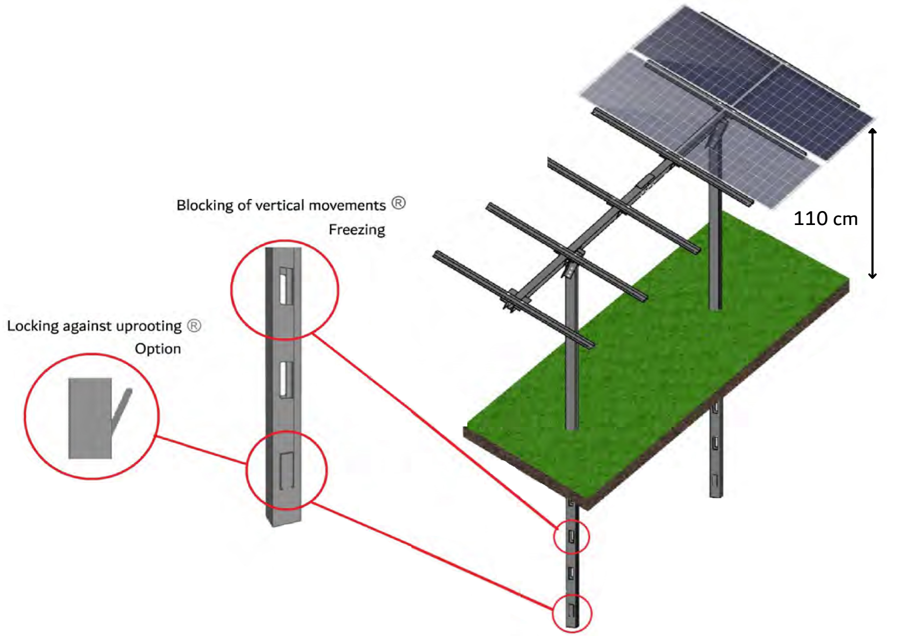
In practical terms, UTDBR expresses how much of the bifacial advantage is delivered when the power system actually requires energy, rather than during already oversupplied midday hours. As such, UTDBR provides a physically grounded link between bifacial geometry, temporal energy distribution, and system-level usefulness.

Greatness PV BIFACIAL MAX®

1x5 BiFacialMAX Ground PV

BIFACIAL MAX 1x5 ground structure is made of high-quality closed profiles steel covered with an additional protective coationg that provudes long-term protection of the surface of steel elements, ensures high resistance to corrosion and abrasion and has self-regenerating properties.

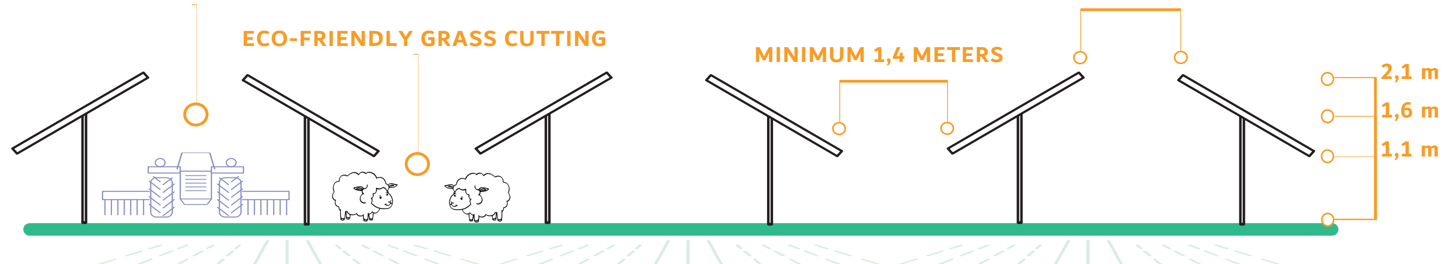
BIFACIALMAX structures are manufactured in a Polish steel profiles factory located in Wolental according to the highest European standards confirmed by certificates.



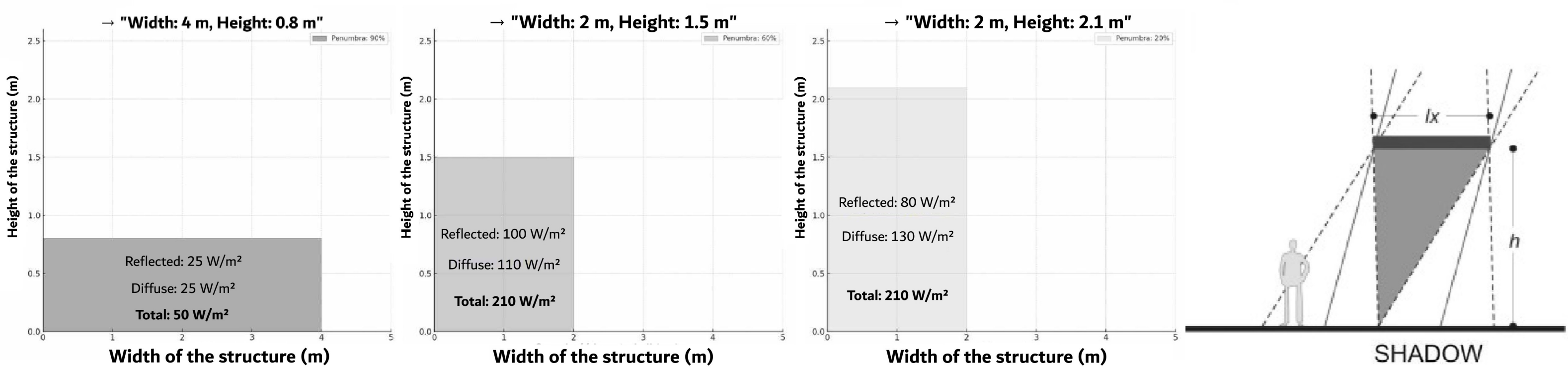
- Top quality closed profiles
- 1x5 vertical layout
- Tilt angle 25'
- Weight of the structure 119 kg for 5 modules
- Modules start H = 110 cm
- For modules: Width 1134mm with bolt spacing 1100mm or 1400mm
- 1,2,3,4 Snow Zone
- 1,2 Wind zone - 200 km/h Option
- Modules length L = 230 cm

In accordance with European standards	Certificates
PN-EN 1991-1-1 Eurocode 1	EN 1090-5:2017
PN-EN 1991-1-3 Eurocode 1	EN 1090-2:2018
PN-EN 1991-1-4 Eurocode 1	EN 1090-4:2018
PN-EN 1993-1-3 Eurocode 3	EN 1090-3:2019
PN-EN 1993-1-8 Eurocode 3	

RECOMMENDED BIFACIALMAX® TABLE LAYOUT EAST WEST 1P STATIONARY SYSTEM-ALBEDO 26%
GUARANTEEING 20% MORE ENERGY GENERATION PER YEAR FROM THE BACK OF THE BIFACIALMAX MODULES



Level of irradiation reaching the rear side of the panels (W/m²)



STEEL CLOSED PROFILE

S355 — STEEL S355

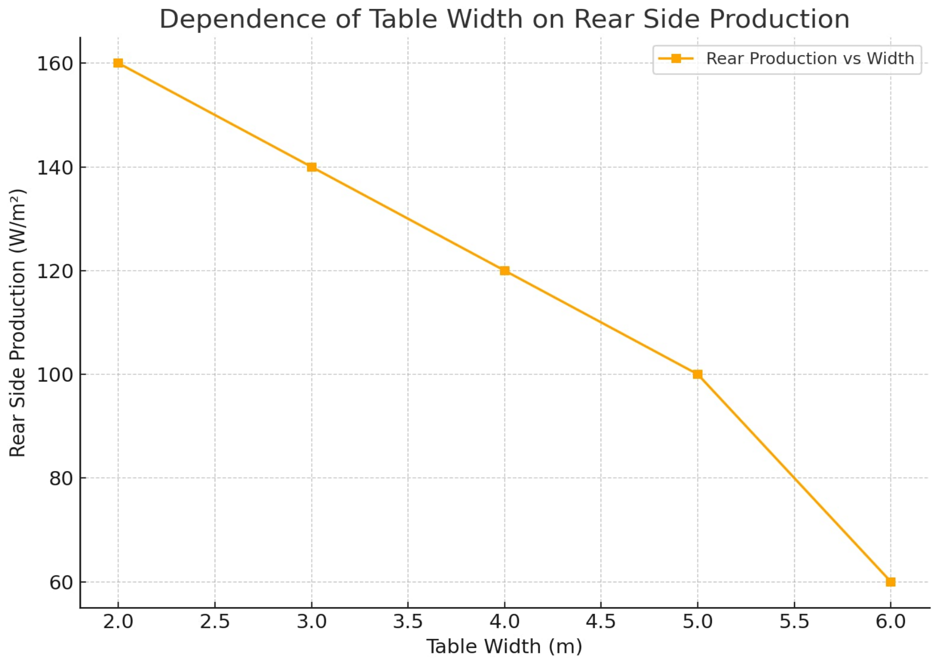
MAGNELIS 600 — MAGNELIS 600 COATING

3 mm — THICKNESS WALL THICKNESS 3 mm

50 lat — DURABILITY DESIGN LIFE 50 YEARS

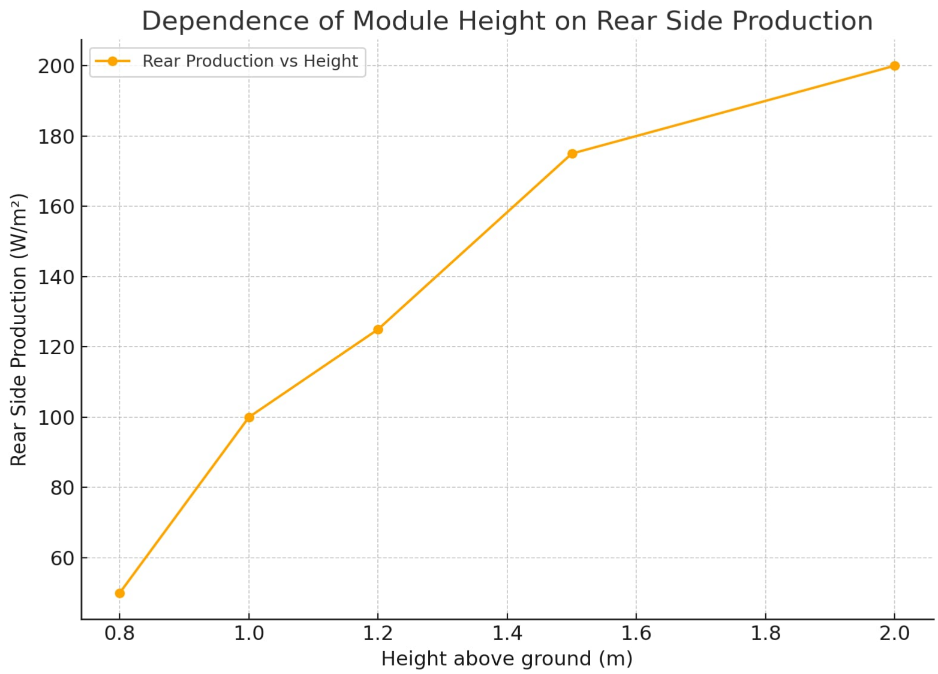
Effect of table width on illumination of the back side of the modules

- In narrow tables (e.g., the width of one row of panels, about 2 meters), reflected and diffused light is much more accessible to the back side of the panels. As a result, the back side works more intensively, which directly translates into higher system efficiency.
- For wide tables (e.g., 5-6 meters, where several rows of panels lie next to each other), the area under the panels is more shaded. Light finds it harder to reach the back side of the modules, as it is blocked by the top modules in the center of the table. This reduces the yield on the back side.



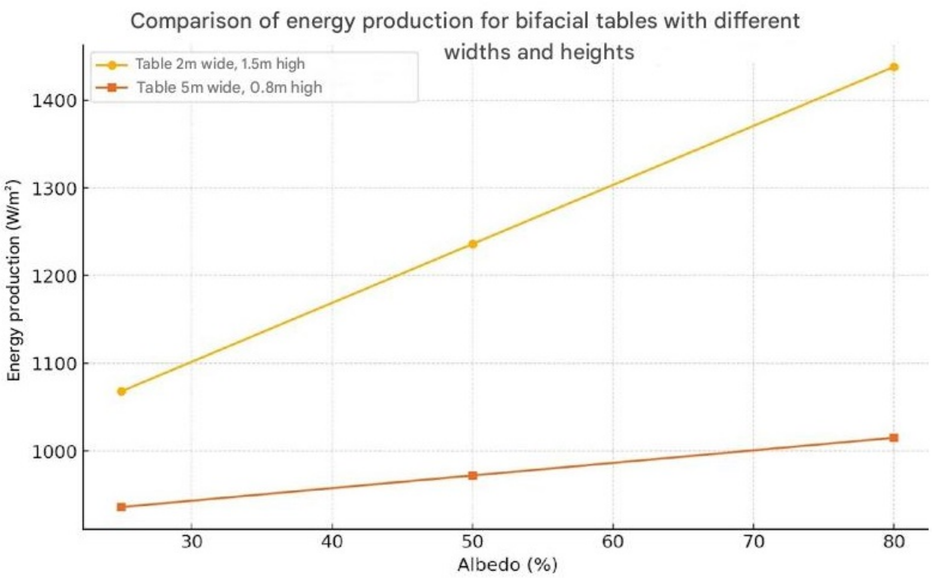
Impact of mounting height

- The higher positioning of the panels promotes better lighting underneath, as the sun's rays have more room to reflect and reach the back of the modules.
- In narrow tables, the high-mounted modules even allow direct sunlight to reach under the panels, significantly increasing the rear yield.



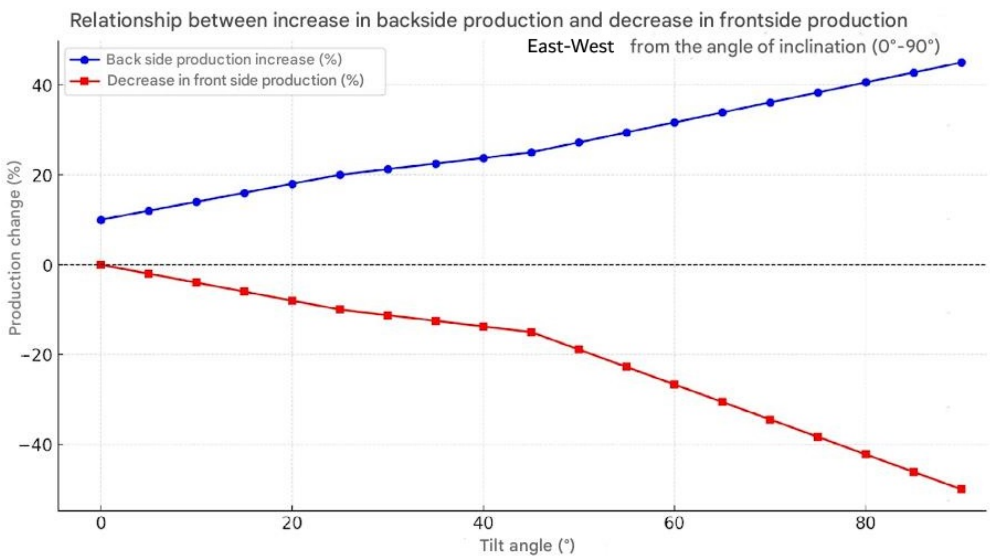
The importance of light reflection and scattering

- The substrate (e.g., light-colored surfaces such as snow or sand) has a big impact on the amount of reflected light reaching the back of the panels.
- With narrower tables and more light reaching under the panels, the albedo (ground reflection) effect is fully exploited.



Energy efficiency

- Narrow tables, especially high-mounted ones, provide up to several times the yield from the back of the panels compared to wide tables. This is due to better illumination and less light restriction.
- Wider tables are less effective for bifacial modules because they limit light access to the back of the panels, especially in the middle rows.



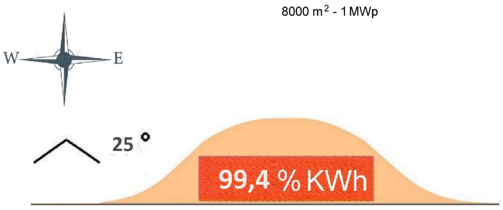
Summary:
For bifacial modules:

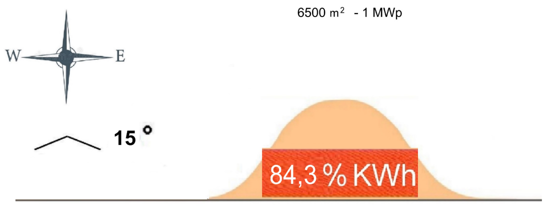
- Narrower tables are much more efficient than wider ones, as they allow better illumination of the back side of the panels.
- Mounting the panels high further increases the amount of reflected and diffused light, which raises energy yields.

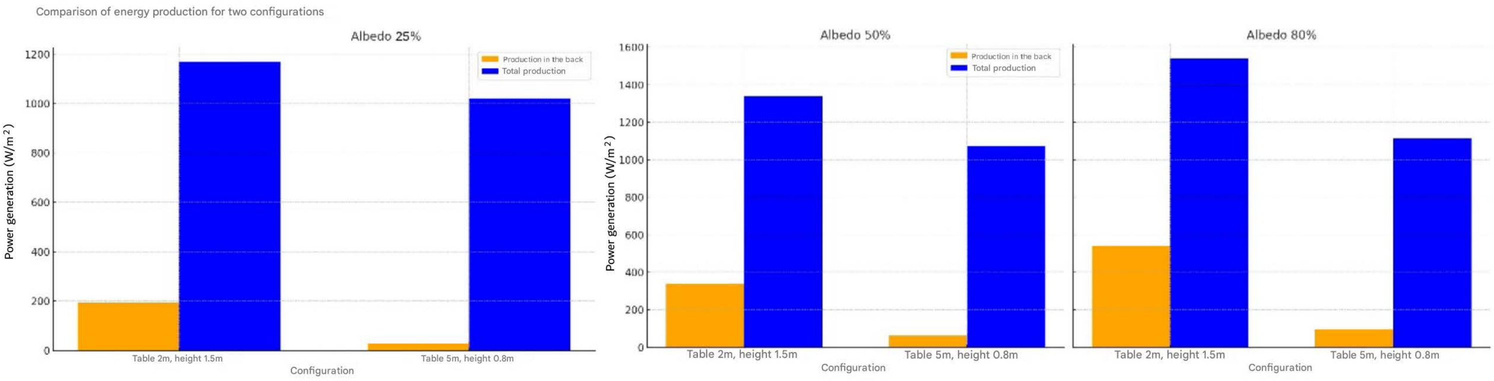
Comparison of energy production for two Wast-West 25° configurations
at different values of ground albedo: 25%, 50% i 80%.

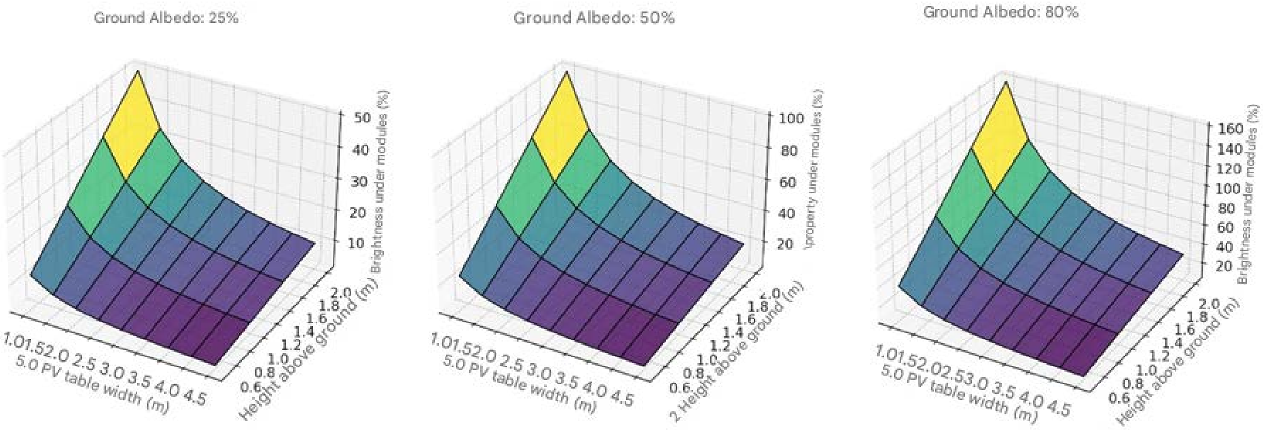
1. Table 2 m wide and 1.5 m high

2. Table 5 m wide and 0.8 m high







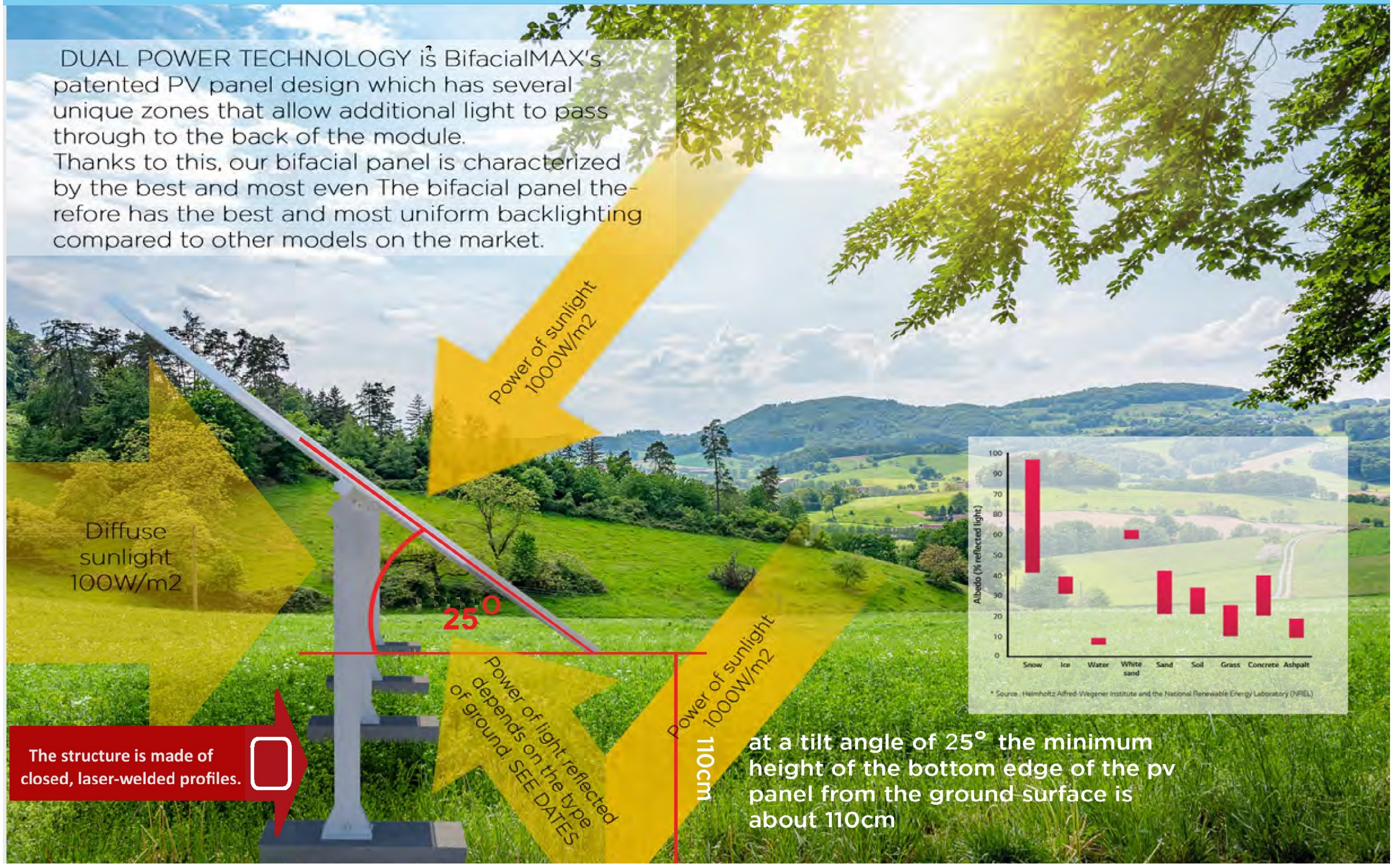


Comparison of energy production east-west 25°
at different values of ground albedo: 25%, 50% i 80%. Depending on the height and width of the table.

BifacialMAX Sp.zo.o.
Ul. Jabłowska 75, 83-200 Starogard Gd, Poland
www.bifacialmax.com.
E-mail:office@bifacialmax.com.
Tel.(1):+48505-031-733.Tel.(2):+48512-659-376

STEEL CLOSED PROFILE	STEEL S355	MAGNELIS 600 COATING	THICKNESS WALL THICKNESS 3 mm	DURABILITY DESIGN LIFE 50 YEARS

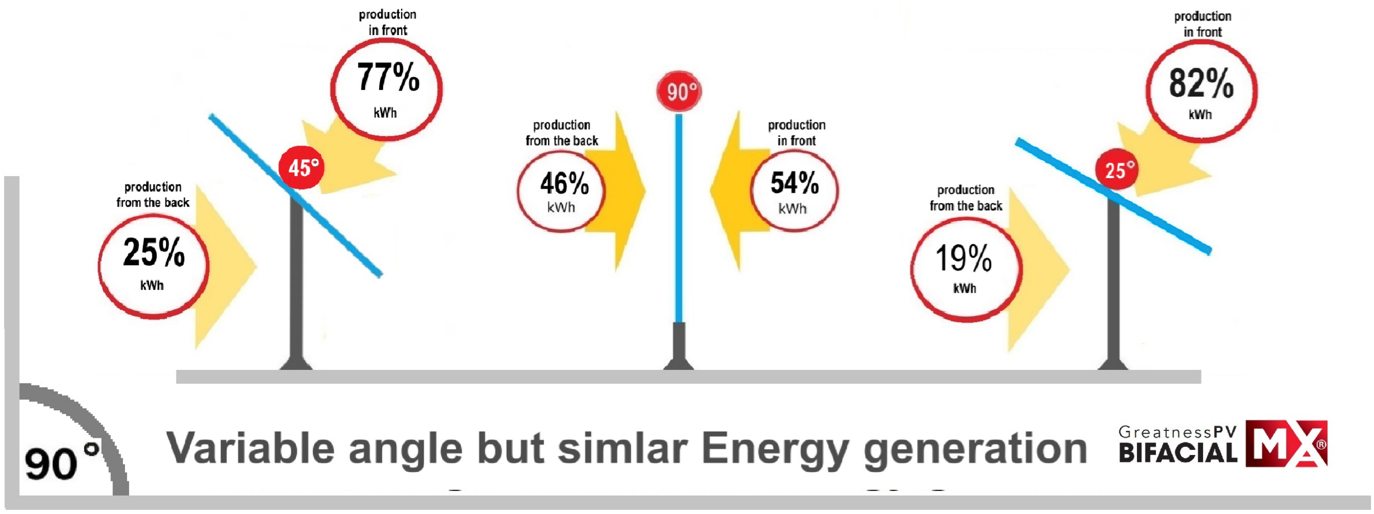
DUAL POWER TECHNOLOGY is BifacialMAX's patented PV panel design which has several unique zones that allow additional light to pass through to the back of the module.
Thanks to this, our bifacial panel is characterized by the best and most even The bifacial panel therefore has the best and most uniform backlighting compared to other models on the market.



at a tilt angle of 25° the minimum height of the bottom edge of the pv panel from the ground surface is about 110cm

East-West PV orientation - more Energy then South-North

at the grass albedo 26%



Variable angle but simlar Energy generation

GreatnessPV BIFACIAL MX®

Durability of construction - advantages of BifacialMAX closed profiles

The BifacialMAX system further solves the problem of module durability by using closed profiles, which:

Are many times more rigid than open profiles.

Are more resistant to bending and torsion, eliminating lateral overloads that lead to cracking of the rear glass of bifacial modules.

They provide greater stability, which reduces the risk of failure of the entire structure.

Conclusion: BifacialMAX structures based on hollow profiles are much more resistant to lateral overloads and wind, which extends the life of the modules and reduces maintenance costs.

Bifacial Double Glass Module Durability Problems in Multi-Row Structures Why does the rear glass in bifacial modules break?

With multi-row structures, we have support on four legs:

The front legs are short and the rear legs are long.
Under the influence of strong wind, the rear legs have a greater amplitude of movement than the front legs.

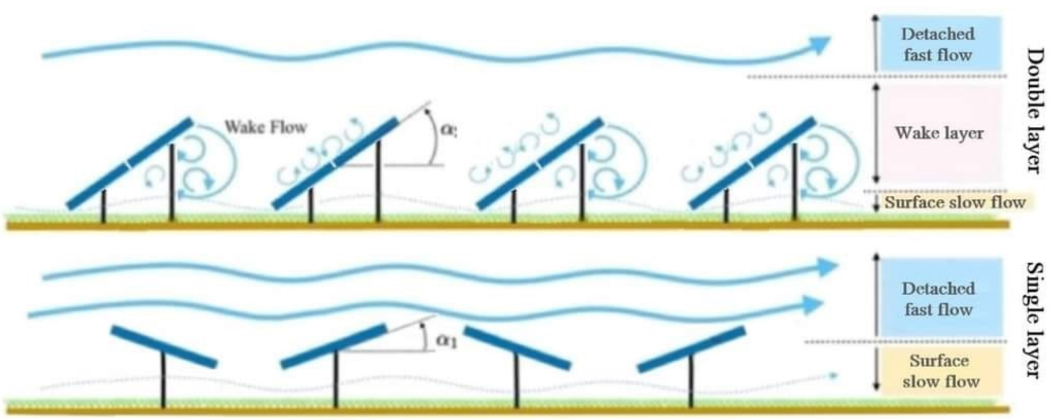
This causes trapezing (lateral movement of the whole structure), which causes uneven pressure on the modules.
The effect of stretching and compressing glass in Bifacia Double Glass modules:
The front glass is compressed - the compression resistance of tempered glass i**s 900 N.**
The rear pane is tensile - the tensile resistance is **only 90 N.**

As the glass bends downward under its own weight, the rear glass is further stretched, leading to cracking.

Conclusion: cracking of the rear glass is a major durability problem in multi-row systems, because the forces acting on the modules are uneven, leading to faster failure of the bifacial modules.

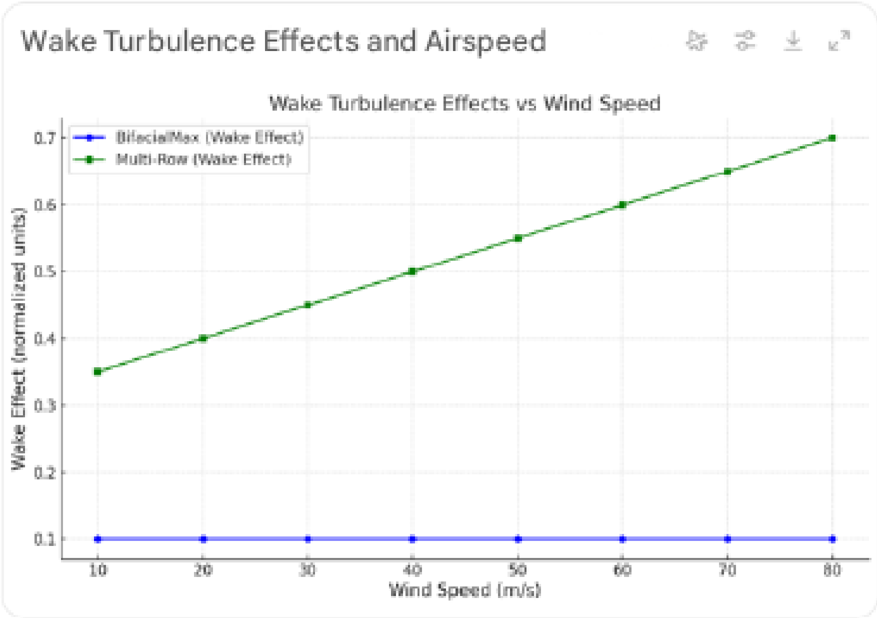
Why doesn't the problem occur in single-row designs?
In single-row structures we have support on two support points.
There is no trapezoidization - the entire structure moves as a rigid whole.
Uniform loading prevents tensile stresses on the rear glass of the module.

Conclusion: the single-row design provides greater durability for bifacial modules by eliminating the problem of trapezing and reducing lateral overloading



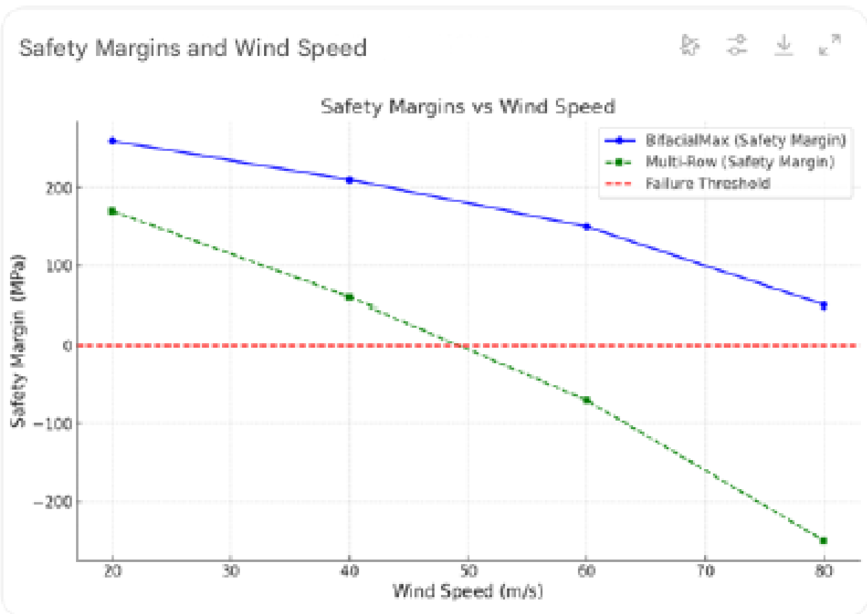
Effects of turbulence in the aerodynamic footprint :

For BifacialMax, the effect of turbulence in the aerodynamic footprint is negligible. For Multi-Row structures, turbulence increases as wind speed increases, reflecting the vulnerability of this multi-layer structure.



The table below compares the safety margins of the BifacialMax and Multi-Row systems at different wind speeds:

BifacialMax maintains a positive safety margin at all wind speeds, meaning it remains structurally safe even at 80 m/s.
Multi-Row exceeds the failure threshold (0 MPa margin) at 60 m/s, indicating a higher risk of mechanical failure in high winds.



The solution: east-west BifacialMAX at a 25° angle
Increases energy production in the morning and evening - when energy prices are highest.

Optimizes energy sales - reduces dependence on midday hours and allows production to be better matched to required demand.
Reduces the risk of damaging energy - better distribution of production reducing the impact - the "duck effect".

Reduction of storage energy consumption
Mounting bifacialMAX at an angle of 25° in an east-west arrangement flattens energy production, reducing the need for storage of vital energy.

Reducing storage energy consumption by **20%, which means:**
A savings of EUR 100,000 per MWp in capital costs on energy storage. Lower storage replacement costs (batteries need to be replaced every dozen years or so).
Lower maintenance and operating costs.