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Original Article

Design and Analysis of an Anchoring System for Photovoltaic Facades: Structural Integration and Energy Optimization in Residential Buildings

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Abstract – *This study describes the design and analysis of an anchoring system for photovoltaic facades for buildings. The study proposes a structurally sound and energy-efficient solution to the problem of integrating solar energy into building facades. A detailed structural analysis is performed using Finite Element Analysis (FEA), demonstrating the design's ability to withstand the applied loads with a high Safety Factor (SF) and minimal deformation. The design methodology is based on the German standard VDI 2221, which develops a systematic approach from initial specifications to final design. The selection of materials is based on 6063 aluminum for the structural supports, which optimizes the structural design and contributes to the durability of the system. In addition, the evaluation of photovoltaic performance highlights the system's potential for renewable energy generation. The proposed anchoring system offers a viable way to incorporate photovoltaic systems into residential facades, highlighting the importance of integrating renewable energies into the construction sector.*

Keywords - *Building-Integrated Photovoltaics (BIPV), PV, Renewable energy, Solar energy, Solar facades.*

1. Introduction

Reducing global energy consumption has become a central objective in energy policy and building design, with increasing attention directed toward renewable energy systems as viable alternatives [1, 2]. Among these, Photovoltaic (PV) installations, especially rooftop systems, have shown consistent results in decreasing electricity demand and mitigating greenhouse gas emissions in urban environments [3, 4].

The building sector alone accounts for approximately 28% of global CO_2 emissions and 36% of total final energy consumption, highlighting its strategic role in sustainability efforts [5]. As urban development continues to limit rooftop space, attention has shifted toward vertical surfaces. Integrating PV panels into building facades offers an alternative area for solar capture, particularly in dense cities. However, this vertical approach introduces new engineering challenges, including anchoring design, resistance to wind loads, and compatibility with architectural finishes [6, 7].

Research in the field of Building-Integrated Photovoltaics (BIPV) has mostly focused on optimizing energy efficiency and architectural integration [8, 9]. These systems have shown potential to reduce thermal loads, enhance indoor comfort, and contribute visually to the building envelope [10].

Some recent works propose improvements by combining PV modules with dynamic shading or vegetated systems, which offer environmental and aesthetic benefits [5, 10]. Still, mechanical aspects such as anchoring feasibility, load transmission, and adaptability remain underexplored [11].

Despite growing interest in BIPV systems, much of the existing research prioritises energy performance and visual integration, often overlooking the structural and mechanical requirements of facade-mounted installations. In particular, limited literature addresses the stress distribution in anchoring components, the challenges of installation on diverse wall types, and long-term performance under environmental exposure [11, 7].

Kirimtat et al. [4], for instance, examined PV-integrated shading devices without analyzing mechanical load paths, while Yang et al. [6] proposed a conceptual BIPV platform that omitted physical mounting strategies.

This paper addresses that gap by presenting the design and simulation of a modular anchoring system tailored for residential photovoltaic facades [9]. The proposal emphasizes structural reliability, corrosion resistance, and ease of installation. Both mechanical simulation and energy performance analyses were conducted to evaluate its feasibility.

The remainder of the article is organized as follows: Section 2 outlines the methodology used for design and analysis; Section 3 presents the simulation results; Section 4 discusses the implications of these findings; and Section 5 concludes with final observations and directions for future work.

2. Materials and Methods

The design follows the guidelines set by the German VDI 2221 standard, which is structured in three stages [12]. The first stage covers the specifications and functional structures, while the second stage focuses on the evaluation of the main solutions. Finally, the selected solution is presented in the modular structures dedicated to the development of the final design. For the design and mechanical analysis of the anchorage system, Autodesk Inventor software [13] was used, which allowed for accurately modelling the system components and simulating their structural behavior under various loadings.

2.1. Specification

The list of specifications covers all the requirements that the design must meet without exception. The proposed machine's design, function, energy and control specifications are unambiguously shown in Table 1.

Table 1. List of specifications

Category	Specification
Design	Strong anchoring structure adaptable to residential facades for integrating solar panels into buildings.
Function	Secure and stable support for photovoltaic panels. Solar power generation for self-consumption.
Energy	High-efficiency solar panels. Grid-connected inverter with adequate capacity. Energy storage battery.
Control	Control system for inverter and charge controller operation.

2.2. Function Structures

Figure 1 shows the functional structure of the photovoltaic system for residential facade, where the collection of solar radiation by the panels, which convert it into Direct Current (DC), initiates the process; this energy is regulated by the charge controller in the control box and stored in the battery, and then transformed into Alternating Current (AC) by the inverter and distributed for domestic consumption;

Simultaneously, radiation, temperature and voltage sensors monitor the performance of the system, whose data are processed by an energy management system and visualized by the user through an interface, allowing the control and optimization of the system, even remotely.

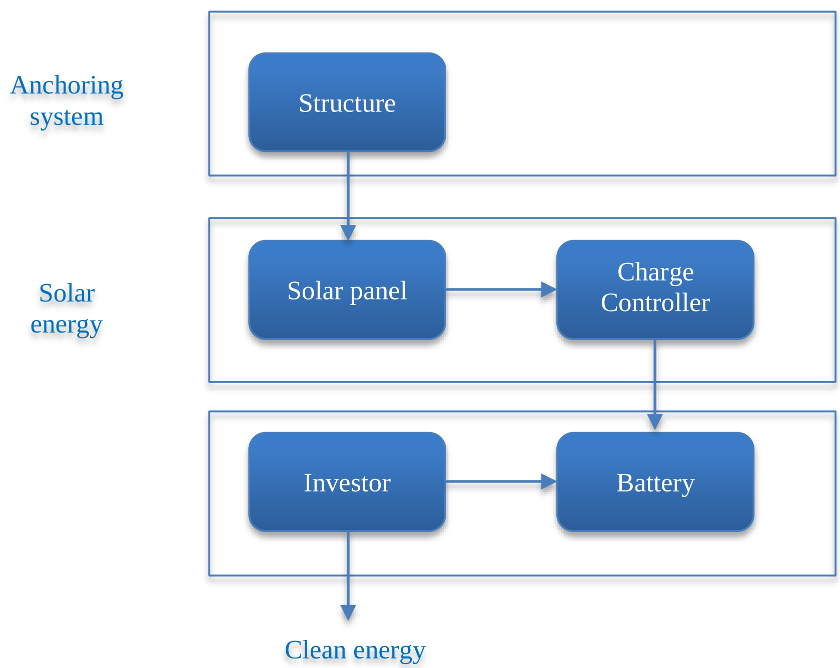

Fig. 1 Function structures

2.3. Principal Solutions

Previous work focused on Building-Integrated Photovoltaic (BIPV) technology which is presented as a promising solution for on-site electricity generation and reduction of building energy consumption [9], furthermore BIPV systems can be integrated into various building elements, such as roofs, facades, shading devices and windows, offering benefits such as electricity generation, CO2 emission reduction and improved building aesthetics [4, 6]. This study considers the photovoltaic system integration on facades to facilitate a safe, efficient and aesthetically pleasing integration in residential buildings.

Kirimtat et al. [4] review Photovoltaic Integrated Shading Device (PVSD) designs and advanced control strategies, highlighting their potential to generate electricity and provide daylighting. Yang et al. [6] propose a framework for BIPV conceptual design that integrates climatic, BIPV product, regulatory, technical, and economic data to create optimal solutions.

Despite the potential of these solutions, there are significant challenges and considerations that need to be addressed. These include technical complexity, aesthetic considerations, the need for supportive policies, and the importance of balancing efficiency with design [8]. Zagorskas and Turskis [8] highlight the importance of supportive policies and innovative solutions to overcome barriers and advance the development of solar facades towards the goals of zero-energy and zero-carbon buildings.

3. Design, Mechanical Analysis and Energy Evaluation

3.1. System Design and Integration

Figure 2 shows a house equipped with 24 solar panels installed on the facade, designed to capture and convert solar energy into electricity. Next to the house is the energy control box, which houses the charge controller, which is responsible for regulating the energy stored in the battery, and the inverter, which transforms the direct current into an alternating current for use in the home.

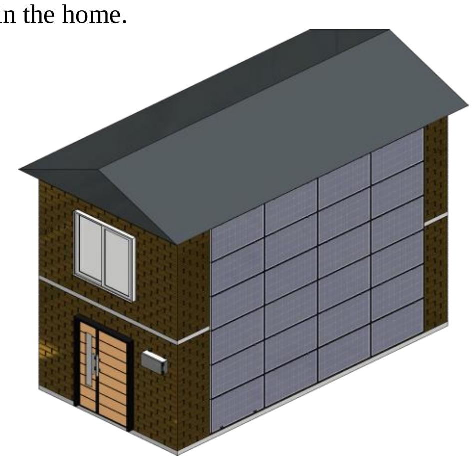

Fig. 2 General isometric view

Figure 3 shows an exploded diagram of the residential solar system, highlighting the distribution and assembly of its parts.

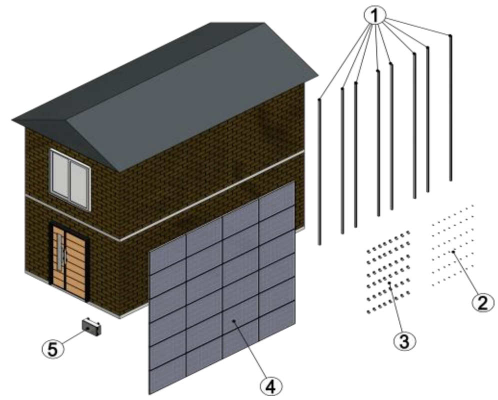

Fig. 3 Disassembly of the anchoring and photovoltaic system

Figure 4 shows an exploded diagram of the power control box, showing the solar inverter, charge controller, battery, support beams and fastening bolts.

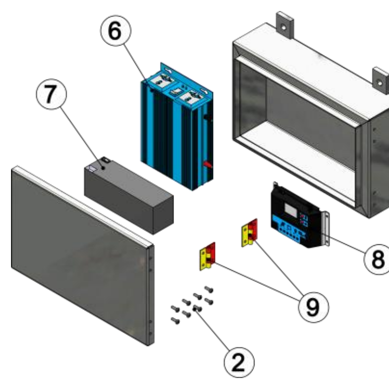

Fig. 4 Control box disassembly

All components are listed and detailed in Table 2.

Table 2. List of parts

N°	Part	Quantity
1	Rectangular steel tube	8
2	Bolts	32
3	Falcat L-shaped frame	32
4	Solar panel	24
5	Power control box	1
6	Solar inverter	1
7	Battery	1
8	Solar controller	1
9	Hinges	2

Figure 5 shows a detailed isometric view of the power control box, showing its internal components, such as the inverter, charge controller and battery, as well as the solar panel mounting system, firmly secured to the structure and the wall to ensure stability and efficiency.

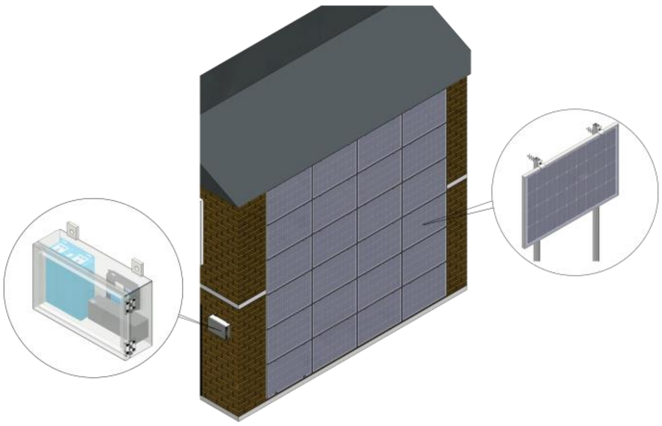

Fig. 5 Detailed view of internal components

Figure 6 shows how the sun's rays interact with the solar panel, converting solar energy into electricity for subsequent management and distribution in the system.

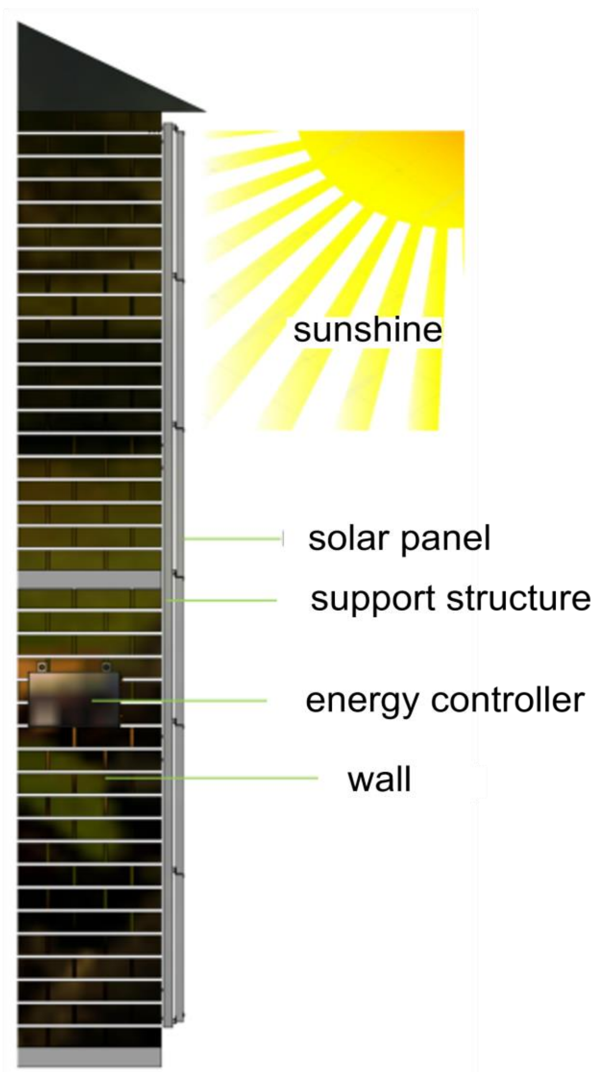

Fig. 6 Cross-sectional view of the anchoring system for photovoltaic facades

3.2. Design and Evaluation of the Energy and Photovoltaic System

A photovoltaic system design was proposed for integration into the facade of a residential building, based on the selection of high-efficiency and high-performance components. Twenty-four polycrystalline/monocrystalline solar panels of 100 Wp each were selected because of their ability to generate power under low irradiation conditions. A 3 kW grid-tie inverter, compatible with the home's single-phase electrical Grid, Was Chosen For Efficient Conversion of The Direct Current (DC) generated by the panels into Alternating Current (AC). The solar cabling design considered the use of 4 mm² photovoltaic cable, resistant to weathering and UV radiation, and MC4 connectors for a secure and durable connection. A mounting structure was designed specifically for vertical facades, using aluminum profiles and stainless steel hardware to resist corrosion. Figure 7 presents the schematic connection diagram of the solar system, detailing the energy flow from the solar panels, connected in parallel to optimize power generation. The energy produced in Direct Current (DC) was regulated by a charge controller, where the connections of the panels were directed to the + and - terminals of the PV. Subsequently, the energy was stored in a battery, connected to the controller's BATT + and BATT - terminals. Finally, the inverter received the power from the battery through its respective + and - connections, converting it from DC to Alternating Current (AC) for distribution and use in the home, ensuring an efficient power supply. Diagram 1 shows the detailed electrical circuit design of the system, including the connection of the panels, the inverter, the protection devices and the bidirectional meter.

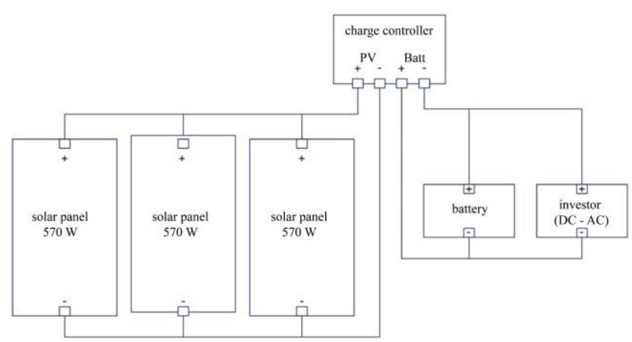

Fig. 7 Schematic connection diagram of the solar system

Equation (1) calculates the power output of the photovoltaic panels [14]:

$$P_{total} = N \times P_{panel} \qquad (1)$$

Where P_{total} = 2400W is the total power of the solar panels, N = 24 is the number of solar panels, and P_{panel} = 100W is the power of each panel.

This calculation corresponds to Standard Test Conditions (STC), i.e. with an irradiance of 1000 W/m² and a cell temperature of 25°C [15].

Equation (2) calculates the amount of energy generated by solar panels in a day. This calculation is based on the total system power and the number of Peak Sun Hours (PSH). Where E_d Is the daily energy generated, P_t Is the total system power, and PSH are the peak sun hours considered by other research [16, 17]

$$E_d = P_t \times PSH \tag{2}$$

From the above calculations and data, it was determined that the energy generated by solar panels in one day is 12 kWh/d.

Equation (3) estimates the real usable energy of the PV system by considering losses associated with the system efficiency and the tilt of the panels; these losses affect the energy production due to the deviation from the optimal orientation. Where E_r is the actual energy generated considering tilt losses, η is the system efficiency, and F_t is the tilt correction factor [17].

$$E_r = E_d \times \eta \times F_t \tag{3}$$

Based on the above calculations, it was determined that the actual energy with losses due to tilt is 6.72 kWh/d.

Figure 8 shows the flow diagram of the photovoltaic system.

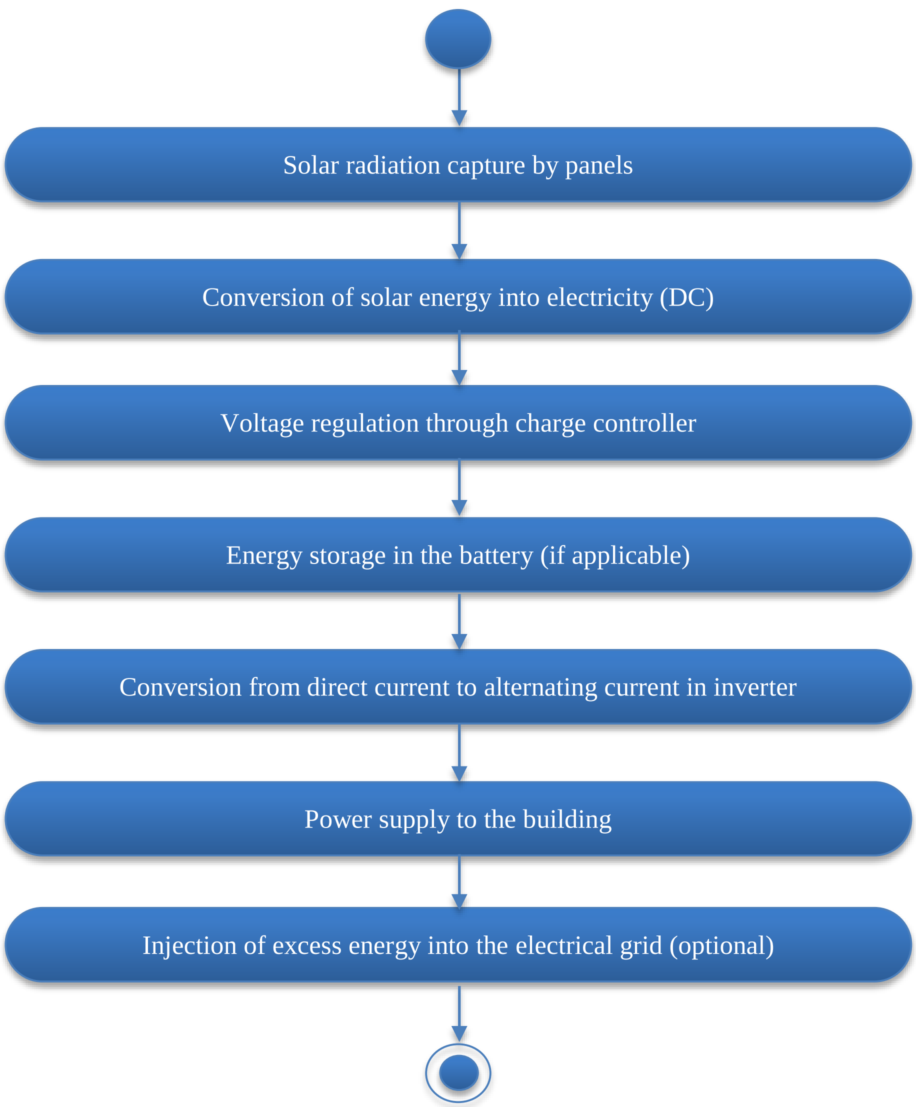

Fig. 8 Photovoltaic system flow diagram

Figure 9 shows a house with 24 solar panels on the facade and a user using the energy control box, where the battery, charge controller and inverter are managed.

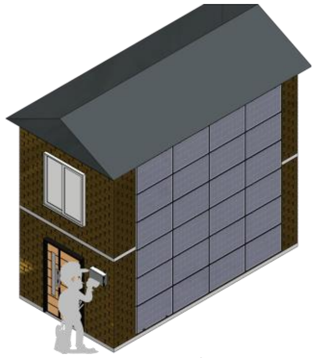

Fig. 9 View of the solar system on the facade and power control box

3.3. Mechanical Design and Evaluation of the Anchoring System

The mechanical design of the anchoring system was conceived with the objective of providing robust and secure support for the photovoltaic panels installed on the facades of residential buildings.

Figure 10 presents the wall mounting, detailing the arrangement of the rectangular steel tubes that are assembled directly on the facade surface. This design sought to evenly distribute the loads and minimize the stresses at the fixing points, guaranteeing the stability of the system under the various mechanical stresses.

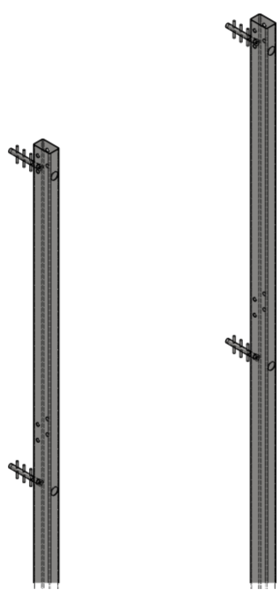

Fig. 10 View of the wall mount

Figure 11 shows a detailed view of the anchorage system, showing the individual components and their interconnection-the design considered optimizing the geometry to reduce the weight of the system without compromising its structural strength. High-strength steel sections and stainless steel hardware were selected to ensure the durability and corrosion resistance of the system in outdoor environments.

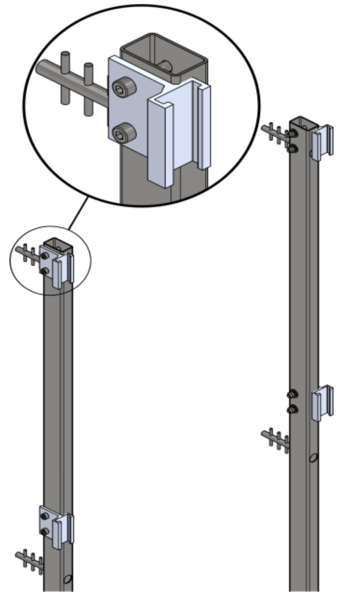

Fig. 11 View of the anchoring system

Figure 12 shows the anchoring system with the photovoltaic panels mounted, highlighting the integration of the photovoltaic system into the facade of the residential structure. The mechanical design of the anchoring system works in conjunction with a fastening system that allows for easy installation and removal of the panels, making maintenance easier. The configuration of the anchoring system was adapted to the dimensions and characteristics of the selected photovoltaic panels, ensuring optimal load distribution and correct orientation of the panels to maximize solar radiation capture.

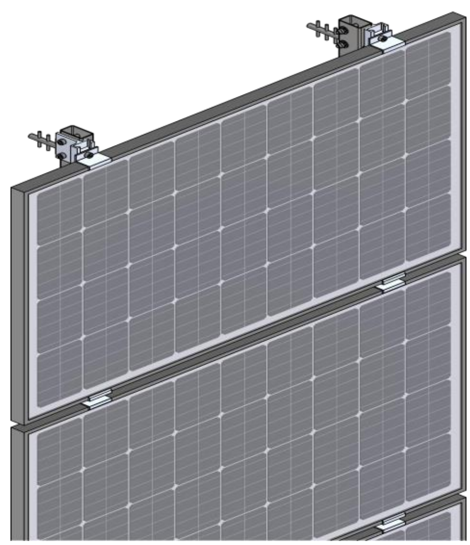

Fig. 12 View of the anchoring system with the solar panels

The mechanical evaluation focused on static loads derived from the weight of the photovoltaic panels. Wind loads, temperature changes, and other environmental factors were not included in this initial simulation phase. These variables may significantly impact structural stress and displacement; therefore, they are proposed for analysis in future research to ensure robustness under real-world environmental conditions.

The boundary conditions in the finite element model assumed that the anchoring system was fully fixed to the wall surface. The rear face of the rectangular steel tubes was defined as a fixed support, with zero displacement in all directions, simulating a rigid embedment into the building facade. This condition reflects the real scenario in which the anchoring system is bolted and embedded directly into the structural wall, without allowance for movement or rotation.

To calculate the total load of the anchoring system for photovoltaic facades. Several factors must be taken into account, including gravity, the mass of the solar panels and the material of the anchoring system.

Equation (4) calculates the weight of the solar panel; it was taken into account that the weight for a 100W 12V polycrystalline solar panel is 7.7kg [18].

$$W = m \times g \tag{4}$$

Solving the equation, we have 75.537N of force that the solar panel exerts on the anchoring system supports. To distribute the load over the entire anchoring system, the number of solar panels is 6, so the total load of the anchoring system is 453,222 N.

In addition, Equation (5) calculates the Von Mises stress to predict the creep of 6063 aluminum under complex loads, which is the material used in the design. Where the normal stresses are σ_x, σ_y and σ_z while the shear stresses are τxy, τyz and τzx at a specific point in the material.

$$\sigma_{vM} = \sqrt{\frac{(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+3(\tau xy^2+\tau yz^2-\tau zx^2)}{2}} \tag{5}$$

Equation (6) calculates the displacement experienced by an object under applied loads. Where δ is the displacement, ε is the deformation, and L is the length of the object.

$$\delta = \int (\varepsilon) d\, L \tag{6}$$

4. Results

The mechanical analysis of the anchorage system was performed with the objective of evaluating its structural integrity under the expected service loads and environmental conditions. Autodesk Inventor software was used to accurately model the system components and simulate their mechanical behavior using Finite Element Analysis FEA [19]. The static stress analysis performed in Autodesk Inventor revealed a maximum Von Mises stress of 12.38 MPa in the 6063 aluminum brackets where the solar panels are attached, shown in Figure 13. This value is well below the 180 MPa yield strength of the material [20], resulting in a safety factor of 14.5. These results confirm that the supports are structurally safe and capable of supporting the weight of the photovoltaic panels.

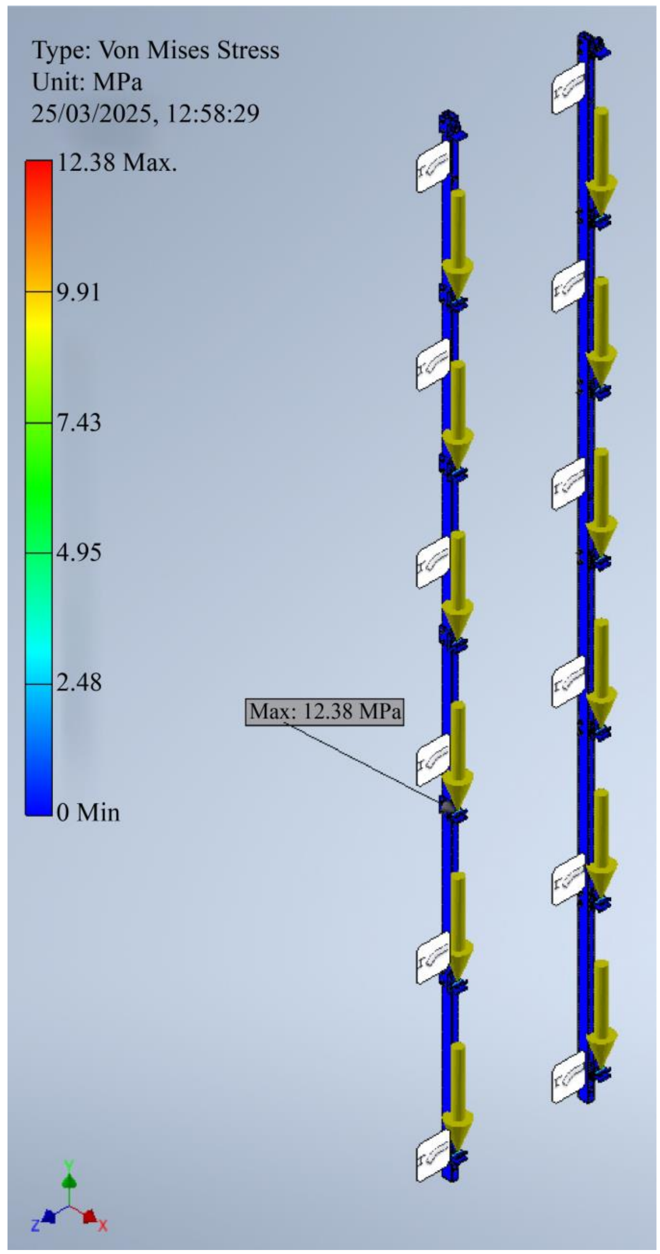

Fig. 13 Static simulation of Von Mises stress

In addition to the Von Mises stress analysis, Figure 14 shows a simulation to evaluate the maximum displacement of the structure under the applied loads. The results revealed a maximum displacement of 0.03215 mm. This extremely low value indicates that the structure exhibits high stiffness and minimal deformation under the design loads.

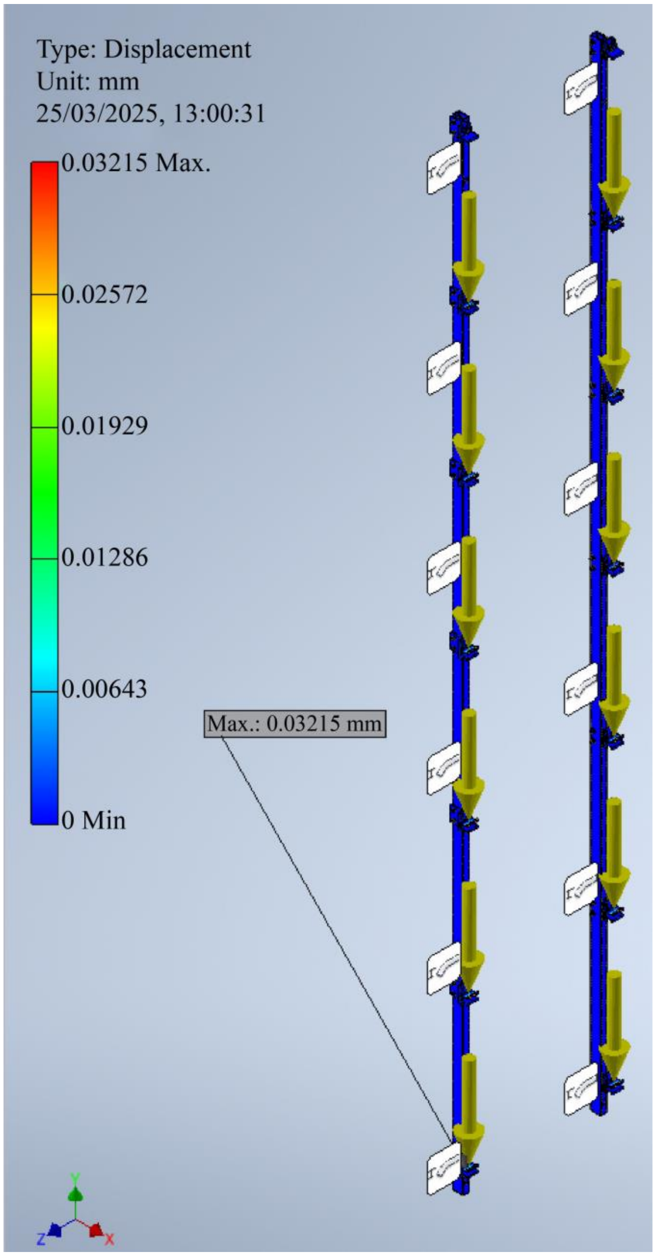

Fig. 14 Simulation of maximum displacement

This study is important to note that it is limited to a digital design and analysis phase. No experimental validation or physical prototyping was performed. However, the results obtained from the finite element simulations provide an initial indication of the system's structural performance. Future work may involve experimental testing or real-scale implementation to validate the design under practical conditions.

5. Discussion

The structural simulation of the proposed anchoring system returned a safety factor of 14.54 and a small deformation of 0.03215 mm. These results are within safe limits and show that the system performs well under expected conditions. The goal of building something reliable and adjustable, as defined in Table 1, was met. Choosing 6063 aluminum, stainless and high-strength steel parts helped create a structure that can resist corrosion and last longer-especially important for installations on building facades.

Compared with standard anchoring methods, this design makes things easier to install without giving up strength or energy output. While earlier studies mainly looked at energy efficiency and visual integration [8, 9], this project focuses on the mechanical part of the system, making sure it is strong enough and still performs well in terms of energy.

Facade-mounted solar systems are tough to get right. You need good anchoring so the panels stay in place, but you also have to consider things like the angle, orientation, and climate in which the system will operate [6, 7]. This design tries to bring all that together, combining structural support with energy production to make the most out of both.

The idea fits into current efforts to use more renewable energy in buildings. As Gielen et al. noted [2], solar systems built into buildings will be more common going forward. This design aims to be part of that shift by offering a strong, easy-to-install system that can work for residential buildings. Most anchoring systems are made for roofs and often need complex installation. This one is modular and lighter, which helps a lot when working on facades. Using aluminum lowers the weight, but still keeps it strong. Plus, the modular parts make transport and assembly more manageable.

Table 3. Comparative analysis of anchoring systems for photovoltaic facades

Criteria	Proposed System	Conventional
Material	Aluminum 6063	Steel or concrete
Weight	Low	Medium to High
Adjustability	High	Low
Installation Complexity	Moderate (preassembled)	High (requires drilling/casting)
Aesthetic Integration	Good	Limited
Corrosion Resistance	High	Medium to Low
Maintenance Access	Easy panel removal	Fixed or semi-permanent mounts

It also allows adjustments based on wall shape, which is not always possible with embedded or rigid systems. The stainless steel parts make it more durable, too. Table 3 gives a quick comparison with traditional systems.

One thing that makes this system stand out is how it fits smaller buildings where the roof might not be available for solar use. The load is spread through a lightweight frame, which avoids putting too much stress on the building itself and doesn't require major installation work.

In short, this anchoring system covers the basics: strong, easy to set up, and supports energy production. The numbers from the simulation suggest it is a good choice for making solar facades more common in homes.

6. Conclusion

The design and analysis of a modular anchoring system for facade-mounted photovoltaic panels has demonstrated positive structural and functional performance. Finite element simulations showed that the system remains stable under expected loads, achieving a high safety factor and very limited deformation. The photovoltaic arrangement, in turn, contributes meaningfully to clean energy generation on residential buildings.

The VDI 2221 methodology provided a clear framework for the design process, from initial requirements to final modeling. Material choices, such as the use of 6063 aluminum and stainless steel fasteners, enhance the system's resistance to corrosion and support its long-term use in exterior applications.

Based on the data obtained, the system appears to be a viable solution for residential buildings seeking to implement facade-integrated solar technology. Its efficient structural behavior and energy output position it as a scalable alternative for sustainable construction practices.

Looking ahead, future work could involve optimizing the geometry of the system for different wall types and exposure conditions. Physical testing, long-term performance monitoring, and an economic/environmental assessment would further strengthen the proposal's practical applicability.

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