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A comprehensive review on architectural design and development of flexible photovoltaic solar panel

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Abstract This review article aims to investigate the potential of flexible solar panels to revolutionize building and vehicle roofing design. The study explores the technology, its advantages over conventional panels, and architectural design considerations for seamless integration into curved surfaces. Flexible solar panels represent an emerging technology with the potential to transform the aesthetics and functionality of buildings and vehicles. Unlike rigid panels, flexible solar cells can conform to curved surfaces, offering new possibilities for architectural design and energy generation. This review comprehensively explores the technology behind flexible solar panels, comparing their characteristics to conventional flat panels. It delves into architectural design considerations, examining various methods and tools employed for optimizing panel shape, arrangement, and integration within the built environment. The findings of this review highlight the significant advantages of flexible solar panels in terms of aesthetic appeal and design flexibility. The ability to seamlessly integrate these panels into curved surfaces opens up new possibilities for architectural innovation. Flexible solar panels have the potential to become an integral component of future building and vehicle design. By overcoming the limitations of traditional solar technology, these panels can contribute to sustainable energy generation while enhancing the visual appeal of structures. Further research and development are necessary to optimize the efficiency and durability of flexible solar panels for extensive adoption.

Keywords: aesthetic architecture, curvature, flexible solar panel, photovoltaic

1. Introduction

The demand for energy, which is supplied mostly by fossil fuels such as coal, oil, and natural gas, has been steadily increasing due to industrialization and increasing population density. The 1973 oil crisis led to a volatile global energy market, causing nations to seek alternative energy sources. The danger of pollution is further increased by the use of fossil fuels (Shahbaz et al., 2023). A comprehensive review of studies conducted in 2022 on the topic of renewable energy systems revealed that the majority of researchers believe that such systems are technically and economically feasible and that solar energy may constitute the backbone of such systems in the future. There is increasing agreement on the core concept's general practicality, but there are still many operational barriers to overcome, including technological, economic, resource, and environmental concerns (Østergaard et al., 2022).

There is a growing desire for solar renewable energy sources to address climate change and provide a reliable electricity supply; however, traditional, conventional solar panels have certain drawbacks. Owing to their substantial dimensions and limited adaptability, it is challenging to position them on curved surfaces or integrate them into buildings. This restricts their effectiveness in some situations, prompting research into solar alternatives that offer greater versatility (Dallaev et al., 2023).

Flexible solar panels, on the other hand, are versatile and practical alternatives to rigid panels because of their ability to bend to curved and uneven surfaces, maximizing the useable area for solar energy collection on nonplanar structures such as RV roofs and boats. Their high efficiency and bending durability make them excellent for building integrated photovoltaics (BIPV) systems (Jung et al., 2019). Rounded geometric shapes, such as cylinders, domes, arches, and curved roofs, are not suitable for traditional flat solar panels because of their curved architectural components. The amount of solar radiation and module curvature influence the system's potential electrical power output. Most photovoltaic modules are flat plane, but semiflexible and flexible thin-film modules are becoming more accessible, offering new opportunities for unevenly shaped surfaces. Slender, lightweight, sturdy, and flexible photovoltaic modules offer extensive solar power generation systems, but studies on their performance are limited (Badi et al., 2022).

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Photovoltaics are the process of directly converting sunlight into electricity without the use of a heat engine. Solar cells in a photovoltaic system need a light-absorbing substance within their structure to collect photons and produce free electrons through the photovoltaic effect. The photovoltaic effect is the fundamental process by which light is converted into energy in photovoltaic or solar cells. When sunlight hits a photovoltaic cell, it provides sufficient energy to certain electrons to increase their energy level and release it. An inherent potential barrier within the cell influences the electrons to generate a voltage, which is then utilized to propel a current across a circuit. Photovoltaic devices are durable and straightforward in design, requiring minimal maintenance. Their key benefit is their ability to function as independent systems, providing power outputs ranging from microwatts to megawatts. A solar power generating system comprises cells, mechanical and electrical connections, mountings, and mechanisms for controlling and adjusting the electrical output. The systems are rated in peak kilowatts (kWp), representing the amount of electrical power a system is predicted to produce under optimal conditions when the sun is directly above it on a clear day (Parida et al., 2011).

The primary component of a solar photovoltaic power system is the solar PV module. Figure 1 displays an assembled image of a crystalline silicon solar module built on a glass-back sheet, highlighting its key components. The solar cells are linked in series to create a circuit. The solar cell circuit is enclosed between a glass layer and a back sheet made of a polymer, using an encapsulant such a thin sheet of ethyl vinyl acetate (EVA), and then the entire structure is laminated. An aluminum frame is attached to all four edges of the lamination, and a junction box containing wires and connectors is attached to the back of the module (Satpathy & Pamuru, 2022).

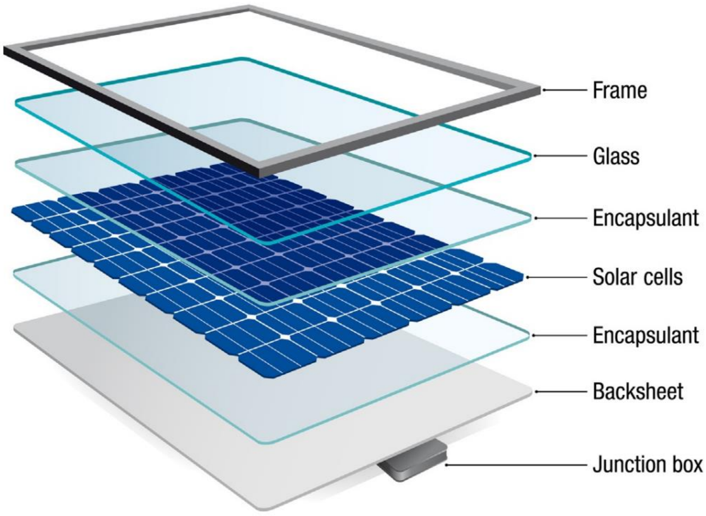


Figure 1 Assembly of a solar PV module.
Source: Satpathy & Pamuru (2022)

Advanced photovoltaic modules, or flexible solar panels, are renowned for their flexibility and versatility in a range of applications. These panels can adapt to curved surfaces and unusual installations since they are lightweight and flexible. This feature creates numerous opportunities for its use in various industries, including building integrated photovoltaics (BIPV), automotive, and aerospace. Flexible photovoltaic systems are appropriate for structures with intricate envelope shapes, such as grain silos, traditional Islamic architecture, and petrochemical tanks. This crucial stage can generate some electrical energy while maintaining geometric and aerodynamic features (Esmaeili Shayan et al.,2022). Flexible solar panels are an innovative technology that provides distinct benefits, such as flexibility, a lightweight structure, and versatility. Owing to their ability to facilitate novel applications and installations that were previously difficult with typical rigid solar panels, they have the potential to completely transform the solar energy sector.

1.1. Traditional flat solar panels vs. *flexible solar panels*

There are a few important considerations when comparing flexible and flat solar panels. The comparison is visually presented in Figure 2 and was taken from one of Sunpower's high-efficiency products, the Maxeon 6 AC flat panel, in addition to a flexible solar panel (Sunpower Corporation,2018; Maxeon Solar Technologies, 2024). Flat solar panels, as the traditional choice, have been widely used for solar energy harvesting. Typically, they are inflexible and composed of silicon, providing high efficiency but restricted flexibility (Carvalhaes-Dias et al., 2018). Conversely, flexible solar panels provide the benefit of being lightweight and capable of conforming to different surfaces. This makes them well suited for situations where flexibility is of utmost importance (Oku et al., 2015). The panels' flexibility enables creative designs and uses, particularly in space conditions where flexibility is crucial (Carr, 2023).

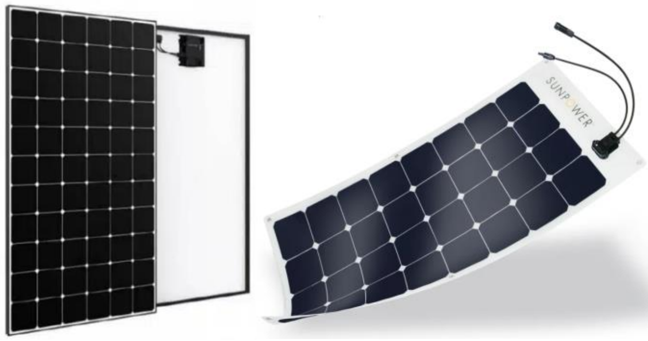


Figure 2 Maxeon 6 AC flat panel and flexible solar panel produced by Sunpower.
Source: Sunpower Corporation (2018); Maxeon Solar Technologies (2024)

An important factor to consider is the efficacy of energy acquisition between planar and pliable photovoltaic panels. Research has shown that the ability of flat solar panels to collect energy may be improved by the use of thermoelectric generators (TEGs) (Carvalhaes-Dias et al., 2018). In recent studies, Cho et al. (2021) investigated the use of ferroelectric effects in flat panel solar cells to increase the regulation of charge carrier transport. These efforts are aimed at improving the efficiency of flat solar panels. On the other hand, researchers have studied flexible solar panels to explore their ability to collect energy from both wind and solar sources at the same time. This demonstrates the panels' adaptability in catching various types of energy (Silva-Leon et al., 2019).

Flat solar panels are often placed in stationary locations or with single-axis solar tracking systems to maximize energy absorption, with a focus on design and construction aspects (Rosyadah et al., 2022). Research has assessed the efficiency of stationary solar panels in comparison with vertically inclined single-axis solar trackers, emphasizing the importance of tracking systems in optimizing energy production (-, 2024). On the other hand, there has been a significant research effort to study the use of flexible solar panels for controlling vibrations in flexible satellites. This research highlights the need to consider the structural dynamics of these panels to achieve the best performance (Ji & Liu, 2019).

The installation and maintenance of solar panels can have a pivotal impact on their efficiency. Studies have shown that using solar panels as shading devices may effectively control interior temperatures, highlighting the dual functions of solar panels (Kindangen et al., 2021). Furthermore, the use of IoT technology has been suggested as a means to maintain the effectiveness of solar panels, signaling a shift toward intelligent solutions for maximizing solar energy production (Vinoth et al., 2022). In addition, research has investigated the influence of orbital motion on the dynamic characteristics of solar panels in space vehicles, emphasizing the difficulties of managing vibrations under these conditions (Li et al., 2011). Moreover, the choice of materials and technology used in solar panels has a crucial role in determining their overall performance. Traditional flat solar panels have been widely used, but recent progress in materials science has allowed for the creation of flexible photovoltaic panels that are very efficient (Bukovnik et al., 2011). These panels, which are both lightweight and flexible, are particularly beneficial in specialized industries such as aerospace and military, where weight and flexibility are crucial considerations (Bukovnik et al., 2011). Furthermore, researchers have suggested the use of microcells in flexible solar panels as a means to generate superior power outputs, signifying a transition toward solar panel designs that are both more efficient and lighter in weight (Bukovnik et al., 2011).

To summarize, the comparison of flat solar panels with flexible solar panels demonstrates a rapidly evolving field of technical progress and practical use. Although flat solar panels are still widely used because of their efficiency and dependability, flexible solar panels provide flexibility and adaptation in different environments. The selection between the two options is contingent upon particular criteria, including but not limited to flexibility, weight, efficiency, and application situations. With ongoing advancements in solar panel technology, both flat and flexible solar panels are expected to play specific roles in the renewable energy industry, meeting various energy collection requirements.

2. Architectural Development of Flexible Solar Panels

Flexible solar panels represent a notable breakthrough in solar technology, providing flexibility and adaptability for a range of uses, such as integrating into buildings and using them in vehicles. The historical development of flexible solar panels for architectural applications has significantly advanced over time, with breakthroughs in materials science, engineering, and design playing crucial roles in their growth. In 2012, Ureña-Sánchez et al. (2012) provided evidence of the practicality of using roof-mounted flexible solar panels for greenhouse tomato production. This study highlights the potential for integrating flexible solar panels into building structures for energy generation. The research demonstrated several roof mounting configurations, emphasizing the adaptability of flexible solar panels for architectural purposes. Early research on flexible solar panels focused on increasing the flexibility and efficiency of solar cells for use in architecture.

Research conducted by Wang et al. (2016) highlighted the importance of using high-efficiency flexible solar cells made from organometallic halide perovskites. These solar cells are crucial for providing power to wearable devices and decreasing expenses associated with shipping and installation. Flexible solar panels are essential for generating energy for spacecraft in space applications. Research on the impact of copper diffusion in gallium arsenide solar cells has emphasized the promise of thin-film epitaxial ft-off (ELO) III-V solar cells for use in space. These solar cells offer outstanding qualities that make them suitable for flexible solar panels (Van Leest et al., 2015). In their study conducted in 2016, Groenewolt et al. investigated techniques for modeling and assessing the behavior of flexible solar panels on curved surfaces with irregular shapes. Their research aimed to broaden the range of applications for bendable photovoltaic modules by enabling their use in curved architectural features. This study facilitated the incorporation of adaptable solar panels on unconventional building surfaces, improving both power production and visual attractiveness. The incorporation of flexible solar panels into architectural environments has become easier because of progress in materials science and design optimization. The application of superhydrophobic and antireflective coatings to flexible surfaces has broadened the applicability of flexible solar panels to architectural and automotive glasses, improving their utility and visual attractiveness (Ren & He, 2017). In addition, the development of adaptable methods for durable coatings that reduce reflection and repel water has opened up possibilities for integrating flexible solar panels into different settings, such as buildings and electrical devices (Ren & He, 2017). The incorporation of few-layered transition metal dichalcogenides into Schottky solar cells has facilitated the development of semitransparent and flexible power generators. This advancement has expanded the possibilities for widespread use in architectural contexts (Akama et al., 2017).

The advancement of flexible solar panels for architectural applications was further enhanced by the introduction of unique energy-harvesting devices, such as the inverted flag idea developed by Silva-Leon et al. in 2019. The inverted flag design, which incorporates flexible piezoelectric strips and flexible solar panels, allows for the simultaneous gathering of wind and solar energy. This innovative approach provides a sustainable option for integrating renewable energy systems into buildings. The use of flexible solar panels on building surfaces has been investigated in architectural simulations as a means to capture renewable energy effectively. By affixing solar panels in a three-dimensional manner onto building surfaces, it is possible to create renewable energy not only from sunlight but also from the fluid vibrations produced by the panels (Choi, 2021). This method harnesses renewable energy not only from solar radiation but also from the fluid vibration caused by solar panels. Advancements in materials science and manufacturing processes have recently resulted in the creation of lightweight and efficient flexible solar panels that are suitable for incorporation into architectural structures. Research conducted by Carr (2023) has focused mostly on robotic methods for producing and assembling thin-film space solar arrays.

These studies have shown the ability of automated procedures to manufacture flexible solar panels suitable for space conditions, with possible applications in architecture as well. In addition, the use of mirror-assisted and concave pyramid-shaped architectures in solar-thermal steam generators has shown promise in achieving efficient water evaporation and saltwater desalination. This highlights the adaptability of flexible solar panels in meeting various energy requirements (Sun et al.,2023). The development of flexible solar panels for architectural applications may be seen as a continuum, starting with early studies on highly efficient solar cells and ending with actual installations on building surfaces. The incorporation of flexible solar panels into architectural design has been propelled by progress in materials, manufacturing techniques, and energy-capturing technologies, emphasizing the possibility of incorporating sustainable and visually appealing solar solutions into buildings.

2.1. Development of solar in building integrated photovoltaics (BIPVs)

Extensive research and inventions have focused on the historical advancement of flexible solar panels in Building-Integrated Photovoltaics (BIPVs). Giacomo et al. (2016) analyzed the advancements, difficulties, and future prospects of flexible perovskite solar cells, with a focus on producing these cells on flexible surfaces such as see-through plastics and metal foils. This method allows for efficient energy collection in several fields, such as building integrated photovoltaic (BIPV) applications, where the ability to adapt to curved or uneven surfaces is crucial for seamless integration into architectural designs. Research conducted by Jung et al. (2019) has focused on the potential of flexible perovskite solar cells to be mounted on curved surfaces, which makes them suitable for building-integrated photovoltaic (BIPV) applications. This study highlights the importance of including flexibility in the design of solar cells, specifically to accommodate nonplanar surfaces typically seen in architectural projects. In addition, Um et al. (2021) highlighted the remarkable efficiency of organometallic trihalide perovskite-based light absorbers in flexible crystalline-silicon photovoltaics. These light absorbers have attracted significant interest because of their exceptional photovoltaic qualities. The progress made in perovskite solar cells has played a significant role in the creation of flexible and highly efficient solar panels that are well suited for building integrated photovoltaic (BIPV) applications. Ni Niu et al. (2022) explored methods for transforming physically nonstretchy photovoltaic devices into stretchable devices by using chemical thinning and stress-releasing adhesives.

This study focuses on the creation of flexible solar cells for commercial use. These solar cells are made from materials such as copper indium gallium selenide (CIGS), amorphous silicon germanium (A-SiGe), and cadmium telluride (CdTe). The energy conversion efficiencies of these solar cells range from 10.2% to 23.35%. The evolution of flexible solar panels in building-integrated photovoltaics (BIPVs) has been influenced by progress in materials research, engineering, and design optimization. The capacity of solar panels to adjust to nonplanar surfaces, along with their exceptional efficiency and flexibility, has rendered them essential elements of sustainable and energy-efficient architecture designs.

2.2. Development of solar-in-vehicle integrated photovoltaics (VIPVs)

In an effort to improve the sustainability and energy efficiency of the automobile sector, many studies and inventions have focused on the creation of flexible solar panels for rooftops. The research conducted by López-Covarrubias et al. (2019) underscores the use of dye-sensitized solar cells (DSSCs) in many sectors, such as the automobile industry, with a particular focus on their viability for solar roofing and smart sensors. This study highlights the adaptability of DSSC technology in automotive contexts, namely, the use of flexible solar panels on car roofs to generate electricity. Giacomo et al. (2016) address the advancements and difficulties encountered in the production of flexible perovskite solar cells, with a focus on their use with flexible substrates such as metallic foils and transparent polymers. This method allows for efficient energy collection in several fields, such as automotive roofs, where flexible solar panels may adapt to the curved surfaces of vehicles, offering a sustainable energy alternative for cars.

Amrillah et al. (2023) investigated methods for creating photovoltaic devices that can stretch, with a specific focus on the advancement of flexible solar cells that may be used commercially. These solar cells are made from materials such as copper indium gallium selenide (CIGS) and cadmium telluride (CdTe). These adaptable solar cells exhibit excellent energy conversion efficiencies and are well suited for automotive applications, such as seamlessly integrated into car roofs to generate electricity while on the go.

In addition, Masuda et al. (2018) conducted research on solar modules that are visually appealing and have high power retention. These modules are colored via automotive paints and aim to overcome the challenges related to weight and design that arise when traditional vehicle roofs are replaced with solar modules. This study highlights the importance of preserving the visual attractiveness and practicality of automobiles while integrating solar technology with car roofs.

2.3. Development of solar in wearable textile technology

The development of flexible solar panels for wearable textile jackets has made great progress in recent years, owing to advancements in materials science, solar cell technology, and wearable electronics. Park (2014) showcased the incorporation of pliable solar films into the sleeves of clothing and the visors of hoods, highlighting the importance of achieving a harmonious equilibrium between weight and design in solar-powered garments for emergency communications and outdoor pursuits. In their study, Lv et al. (2023) examined the properties and applications of fiber-shaped organic solar cells with inherent stretchability. The authors emphasized the promising prospects of incorporating these solar cells into wearable textiles. These solar cells, which are fashioned like fibers, are flexible and wearable, which makes them well suited for the purpose of gathering energy in clothes. The research highlighted the seamless integration of these devices into fabrics, demonstrating their adaptability for wearable technology. With the introduction of a stretchable triboelectric textile for wearable device power supplies, Hou et al. (2018) revealed a creative method for energy harvesting in apparel. This study demonstrated the use of flexible fabrics to collect various forms of human motion energy, offering a renewable energy supply for wearable electronic devices incorporated into garments.

A study conducted by Athauda & Ozer (2013) concentrated on the cultivation of metal–oxide semiconductor nanowires on flexible substrates such as textiles. This research emphasized the importance of creating wearable electronics that have both sensing and protective capabilities. Lee et al. (2013) focused on the use of wearable textile batteries rechargeable with solar energy in the field of wearable energy solutions. This work demonstrates the incorporation of solar energy harvesting into wearable electronics. This study focuses on integrating solar energy harvesting directly into wearable clothes, with the aim of eliminating the need for separate equipment. This aligns with the objective of developing self-sustaining wearable technology. This study contributes to the progress of smart textiles by integrating solar technology, which allows for the development of portable and flexible photovoltaic systems for wearable purposes. Research conducted by Lee et al. (2019) has focused on the development of stretchable electrodes and devices for textile and wearable electronics. This paper offers valuable information on the materials used, manufacturing techniques, and potential applications in the field of wearable technology. In addition, the research conducted by Zhao et al. (2021) highlights the ability of incorporating MnO2 nanosheet-based zinc-ion batteries with perovskite solar cells into a secure and flexible wristband system. This study highlights the possibility of using flexible perovskite solar cells in lightweight wearable devices.

The integration of energy collection capabilities into clothes has been explored in research on solar energy harvesting electronic textiles by Satharasinghe et al. (2020), with an emphasis on solar energy harvesting. This study highlights the capacity of solar energy collection to produce self-sustaining wearable devices, in line with the idea of incorporating flexible solar panels into the material of a jacket to generate energy while on the go. Ultimately, the incorporation of solar technology into wearable textiles has resulted in the creation of cutting-edge and environmentally friendly wearable technologies that use solar power to improve the performance and energy efficiency of clothes.

3. Aesthetics in the Field of Solar Technology

Aesthetics is a philosophical field that focuses on the nature, expression, and perception of beauty in the fine arts, as well as the study of psychological responses to beauty and creative experiences. According to Alexander Gottlieb Baumgarten's "Aestheica," aesthetics is information acquired via senses that are unique from knowledge acquired through intellectual means but do not imply inferiority. Evaluations of aesthetics might have a moral, ethical, socioeconomic, or even political foundation. In a context of poverty, a grand residence may be seen as a sign of prestige or an ostentatious demonstration of affluence and influence. For example, Roman architecture was driven by power, whereas Greek architecture was driven by elegance, which is reflected in their aesthetics (Chokshi, 2018). Aesthetic buildings encompass the design, shape, and visual attractiveness of a structure, extending beyond its surface appearance. The design involves the careful incorporation of architectural components, including proportion, symmetry, and material quality, to create a balanced and aesthetically beautiful space. Aesthetic construction also takes into account the cultural and historical context of a structure, as well as its emotional and psychological influence on residents and the community. The visual characteristics of a structure may elicit emotions such as admiration, calmness, or nostalgia, enhancing the entire atmosphere of a place (Uzunoğlu, 2012). The visual appeal of buildings significantly influences how we perceive and value the constructed surroundings (Jennath & Nidhish, 2016). Specific architectural features are deliberately or instinctively used to design structures that attract a large audience (Uzunoğlu, 2012). The criteria include the form, shape, style, and layout of structures.

These factors impact the overall visual evaluation of a building's exterior appearance. Architectural aesthetic issues, such as unattractive forms, shapes, and styles that result in a chaotic environment, have enduring effects on urban residents both visually and mentally. It is essential to include the study of aesthetics in architecture education curricula to address these challenges (Ghonim & Eweda, 2018). Architects may design visually appealing and harmonious structures that enhance the urban environment by using aesthetic principles (Uzunoğlu, 2012). The visual appeal of structures is a key element in architectural design that greatly impacts how we see the constructed surroundings. Architects may design visually harmonious and pleasant structures that enrich the entire urban fabric by using the principles of aesthetics. Architectural education curricula must include the study of aesthetics to help in designing structures that have beneficial visual and psychological influences on urban residents. Highlighting the importance of aesthetic elements such as form, shape, style, and layout in architectural design is crucial for improving our built environment (Lavdas & Salingaros, 2022).

3.1. Aesthetic curvature

Curvature is a crucial factor in aesthetics, especially in regard to the impression of beauty and the desire for certain forms and patterns. Research has shown that people from many cultures generally prefer curved shapes rather than sharp ones, suggesting a global inclination toward curved contours in aesthetic perception. Gómez-Puerto et al. (2018). The aesthetic sensitivity of items and designs is influenced by their curvature, as shown by research that emphasizes the significance of curvature in both tangible objects and conceptual ideas (Corradi et al., 2019). Moreover, much research has been conducted on the connection between curvature and beauty, and the results show that curvature is nonlinearly connected to beauty and may account for a sizable percentage of aesthetic judgments (Hübner &Ufken,2022).

Curvature in an aesthetic curve refers to the level of smoothness or the extent of variation from a straight line in a visual or artistic curve (Chojecki et al., 2021). This characteristic is crucial in aesthetic design, as it enhances the overall visual attractiveness and agreeable look of a curve (Crăciun et al., 2020). An attractive curve is defined as a curve with a linear logarithmic curvature gradient (Miura et al., 2020). The curvature of an artistic curve indicates the degree to which it diverges gently from a straight line, influencing its visual appeal and beauty (Corradi et al., 2019). Examining the radius of curvature at various places is a method for observing the curvature of an aesthetic curve. The radius of curvature is the radius of the circle that most closely fits the curve at a certain location. A lower radius of curvature signifies a sharper curve, whereas a greater radius of curvature implies a more gradual or smoother curve. Comprehending and controlling the curvature of curves is crucial in aesthetic design to produce visually pleasing shapes and forms. This pertains to a range of industries, including graphic design, architecture, industrial design, and art. Designers may create balance, harmony, and beauty in their work by precisely managing the curvature. The curvature of a curve can also impact how light interacts with the surface, affecting highlights, shadows, and reflections. This comprehension is essential in disciplines such as product design and visual arts, where the interaction between light and shape plays a key role in the overall aesthetic impact. Understanding the curvature of aesthetic curves is crucial for designers who want to create visually appealing and harmonious compositions (Crăciun et al., 2020).

Researchers have investigated the idea of aesthetic curves in the fields of design and geometry. They have suggested criteria for determining aesthetic curves by analyzing their curvature qualities (Crăciun et al., 2020). Log-aesthetic curves emphasize the importance of curvature in creating aesthetic preferences and have been created for industrial design applications to generate visually pleasant designs (Arslan et al., 2014). In addition, researchers have explored the use of mathematical approaches, such as adaptive Runge–Kutta methods, to generate log-aesthetic curves. The goal of this investigation was to improve the visual appeal of curves and surfaces (Gobithaasan et al.,2014). The role of curvature has been examined in terms of visual aspects and aesthetic appreciation in many situations, such as node-link diagrams. In these diagrams, the curvature of forms affects aesthetic judgments and the level of attention (Carbon et al., 2018). In addition, researchers have investigated the interaction between objective and subjective aspects in empirical aesthetics. They have shown that low-level stimulus qualities such as curvature, symmetry, and contour are important in influencing aesthetic perceptions (Chamberlain, 2022). Researchers have also examined the assessment of intentional grins, emphasizing the importance of aligning the shape of teeth with facial characteristics to achieve visually pleasant smiles (Zhong,2024).

Curvature is a crucial factor in computer-aided design and geometric modeling since it directly impacts the construction of visually appealing curves and surfaces. Designers may use flexible curve types such as Bézier, B-spline, and NURBS to alter curvature and generate visually attractive forms for different design purposes (Miura & Gobithaasan, 2014). The use of log-aesthetic curves in transition curve modeling has been investigated for the purpose of achieving seamless and visually appealing form transitions in industrial design applications (Arslan et al., 2014). Researchers have also devised interactive methods for Hermite interpolation utilizing extended log-aesthetic curves. These approaches are aimed at simplifying the process of creating curves with desired curvature attributes for design purposes (Nagy et al., 2021). In general, curvature influences preferences for forms, contours, and surfaces and is a significant factor in aesthetic perception, design, and geometric modeling. Comprehending the correlation between curvature and aesthetics is crucial for crafting visually pleasing designs and augmenting the overall aesthetic experience in several domains.

3.2. Aesthetic curvature in solar applications

The study of aesthetic curvature in solar applications is becoming more important in the area of photovoltaics. Researchers are investigating many factors concerning the design, efficiency, and performance of solar panels on curved surfaces. An important consideration is the influence of curvature on the performance of solar panels, specifically in terms of optimizing power output and efficiency. Researchers have shown that by integrating curved reflectors between arrays of solar panels, they can efficiently use all incoming sunlight, resulting in a substantial increase in power output (Choi et al., 2019). This technique emphasizes the potential advantages of incorporating curvature into solar panel systems to optimize total energy generation.

In addition, the use of flexible thin-film photovoltaic (PV) panels has enabled the application of solar modules on surfaces with irregular curves, thereby increasing the potential for solar panel installations (Groenewolt et al., 2016). It is essential to understand the behavior of curved photovoltaic panels under various conditions, including temperature fluctuations, to maximize their efficiency. Studies have demonstrated that, compared with flat panels, curved photovoltaic (PV) modules experience a slightly greater change in power with temperature. This highlights the importance of taking thermal effects into account when curved solar applications are used (Badi et al., 2022).

Mathematical models have been created to define aesthetic curves in the field of aesthetic curvature. These models are based on curvature gradients, and their purpose is to generate visually appealing and efficient designs for solar panels (Crăciun et al., 2020). These models offer a structure for creating solar panel arrangements that not only exhibit excellent performance but also possess an aesthetically appealing curvature. By incorporating the curvature profile as a crucial factor in the design process, researchers can develop solar panel configurations that are not only highly efficient but also aesthetically pleasing.

Moreover, when designing curved photovoltaic modules for particular purposes, such as car roofs, careful analysis of the shape and curvature of the surface is crucial to maximize the interception of solar radiation (Ota et al., 2018). Researchers can improve the efficiency of solar energy capture in different environments by creating curve-correction factors that describe the output of three-dimensional curved PV modules. This approach emphasizes the importance of customizing the design of solar panels to match the exact curvature of the surface where they are installed to optimize energy generation.

Furthermore, researchers have focused on enhancing the overall efficiency of photovoltaic systems by investigating and developing maximum power point tracking (MPPT) algorithms specifically designed for partial shading conditions (Guo & Abdul, 2021; Wirateruna & Millenia, 2022). Partial shading can result in the presence of multiple peaks in the characteristic curve of the photovoltaic system, which requires the implementation of sophisticated tracking algorithms to ensure that the system operates at its highest power output. Researchers have aimed to improve the performance of solar panel systems and increase energy production by optimizing maximum power point tracking (MPPT) strategies in the presence of changing shading conditions.

Researchers have investigated innovative methods that utilize inexpensive sensors and communication technologies to monitor the efficiency of solar panels in the fields of solar panel diagnostics and fault detection (García et al., 2022). By employing fault diagnosis techniques and predictive maintenance strategies, the dependability and durability of solar panel systems can be guaranteed. Progress in sensor technology and data analysis has aided in the effective functioning of solar energy systems by facilitating real-time monitoring and identification of potential problems.

In addition, the use of analytical formulations and equivalent circuit parameters to model the behavior of solar panels has yielded valuable information about the performance characteristics of photovoltaic devices (Alvarez et al., 2021; Cubas et al., 2014). Through precise modeling of the current–voltage characteristics of solar panels, researchers are able to forecast and enhance their efficiency in various operational scenarios. These analytical methodologies provide a methodical means of comprehending and enhancing the performance of solar panels, thereby contributing to the progress of solar energy technology. To summarize, the incorporation of aesthetic curvature in solar applications is a complex field of study that involves the design, efficiency, modeling, and optimization of solar panel systems. Researchers can improve the performance and aesthetic appeal of solar panels on curved surfaces by using mathematical models, advanced tracking algorithms, and innovative design strategies. The complex and significant task of developing next-generation solar energy technologies requires the consideration of curvature, which is a crucial aspect of this interdisciplinary research field that encompasses physics, mathematics, engineering, and environmental science.

3.3. Aesthetic application of the solar panel

Examining the interface between practicality and aesthetics is crucial when considering the aesthetic uses of flexible and conventional solar panels in building integrated photovoltaics (BIPVs) and automotive environments. Historically, traditional solar panels have prioritized functionality, with a greater emphasis on energy output rather than visual appeal. Recent progress has emphasized the importance of incorporating aesthetics into the design of solar panels to improve their acceptability and integration into urban settings (Jiang et al., 2023). Conversely, flexible solar panels provide distinct design opportunities because of their lightweight and adjustable characteristics, making them well suited for applications where aesthetics are important, such as in building-integrated photovoltaics (BIPV) and automotive design (Mumyatov & Troshin, 2023). The visual attractiveness of solar panels is essential for their effective incorporation into building structures within the framework of BIPV systems. Integrated photovoltaic (BIPV) technology seeks to develop visually attractive solar structures that not only provide energy but also increase the aesthetic appeal of buildings (Thampi et al., 2014). Research has highlighted the capacity of building integrated photovoltaics (BIPVs) to fulfill two functions: generating energy and enhancing the visual appeal of urban landscapes (Heo et al., 2021). BIPV systems may achieve energy efficiency and aesthetic appeal by integrating colored silicon heterojunction solar cells or bifacial-colortunable perovskite solar cells. This makes them well suited for architectural applications (Taylor, 2021; Heo et al., 2021). Furthermore, the use of flexible solar panels has been suggested to enhance both the visual appeal and electrical efficiency of solar panels in urban settings. Fractal patterns can increase the surface area of solar panels, expanding their energy production capability and improving their aesthetic appeal (Roe et al., 2020). Biophilic fractal designs integrate beauty and functions, allowing solar panels to not only produce but also enhance health and performance in building settings (Yun et al., 2016). These novel methods have the capacity to incorporate aesthetics into the design of solar panels, resulting in visually attractive and efficient building integrated photovoltaic (BIPV) systems.

The aesthetic incorporation of solar panels is becoming more crucial in the automobile sector, particularly with the increasing popularity of electric cars. Flexible solar panels provide a viable approach for incorporating solar energy production into vehicle design while maintaining aesthetic appeal (Mumyatov & Troshin, 2023). Researchers are investigating methods to improve the aesthetic appeal of solar panels in automotive applications by creating monolithic structured textile-based dye-sensitized solar cells or high-agility satellites with composite solar panels (Kim et al., 2016; Sayem et al., 2022). These technological improvements not only enhance the environmental friendliness of automobiles but also provide a futuristic and aesthetically pleasing aspect of automotive design.

4. Architectural Design Development of a Flexible Solar Panel

The development of flexible curved solar panel design in architecture has been greatly impacted by the use of mathematical modeling, triangulation, parametric modeling, and computer-aided design (CAD) software for geometric design. The use of these methods and approaches has been vital in enhancing the design, effectiveness, and incorporation of pliable curved solar panels in architectural constructions. Mathematical modeling has played a crucial role in predicting the performance and behavior of flexible curved solar panels over uneven surfaces. Researchers and designers can forecast the energy production and efficiency of these panels in architectural contexts by using mathematical models that consider the curvature of the panels and the influence of sunlight at various angles (Groenewolt et al., 2016). The use of mathematical modeling, triangulation, parametric modeling, and geometric design software has fundamentally transformed the design procedure of pliable curved solar panels in the field of architecture. Designers may use these tools and approaches to develop cutting-edge, energy-saving, and aesthetically pleasing solar panel systems that seamlessly integrate with architectural components while optimizing energy production capacity.

4.1. Geometric design

Zhang & Balog (2013) explored planar and nonplanar photovoltaic surfaces by using monocrystalline solar modules 1STH-245 and three monocrystalline modules arranged at a 60° tilt to create a trapezoidal shape. The study demonstrated that the suggested trapezoidal nonplanar photovoltaic surface captures approximately 20% more solar energy than does a flat roof surface of the same size. The experiment was confirmed by practical experimentation utilizing a test environment and measurements conducted over several days throughout the year.

Figure 3 illustrates the typical installation arrangement of a flexible photovoltaic (PV) module when subjected to bending circumstances. The slope of the PV module is determined by the angle β(◦) between the horizontal plane and the chord of the arc created by the curved PV module. In addition, the PV module is mounted at an azimuth angle of α(◦) relative to the north–south axis. Each point of the flexible PV module receives a varying quantity of solar irradiation due to the constant variation in the angle of incidence of the solar irradiation over the surface of the module. When subjected to bending, the flexible PV module assumes a curved shape in the form of an arc. The extent of curvature of the flexible PV module is represented by the central angle θ (in degrees, 0◦ ≤ θ ≤ 180◦), with its vertex located at the center of the circle and its sides running through the borders of the flexible PV module. The length of the chord created between the two edges of the bent PV module may be determined via geometrical calculations (Konstantopoulos & Koutroulis, 2013).

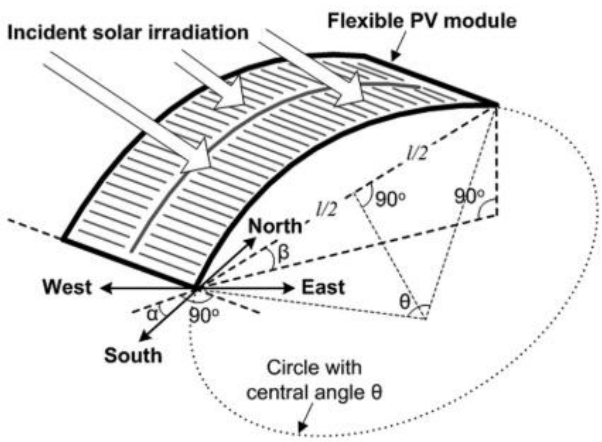


Figure 3 Geometric representation of a flexible photovoltaic (PV) model subjected to bending conditions.
Source: Konstantopoulos & Koutroulis (2013)

Shibasaki & Yachi (2014) presented a method for calculating the power output of a cylindrical flexible photovoltaic cell, considering nonuniform sunlight exposure on a curved surface. The technique uses the average insolation throughout the cell's full area, considering the directional sensitivity of solar radiation and the photovoltaic cell's design. The power production is directly related to the average insolation throughout the cell area. A cylindrical flexible photovoltaic cell is used to calculate the amount of sunlight spread over its surface area. The flexible photovoltaic cell is attached to the outside of a cylindrical pole. Modifying the cylindrical flexible PV cell's form involves adjusting the angle e, the pole diameter r, and the cell height H. Figure 4 displays a schematic illustration of a cylindrical-shaped PV cell. The amount of sunlight received in the cell changes on the basis of the orientation around the pole.

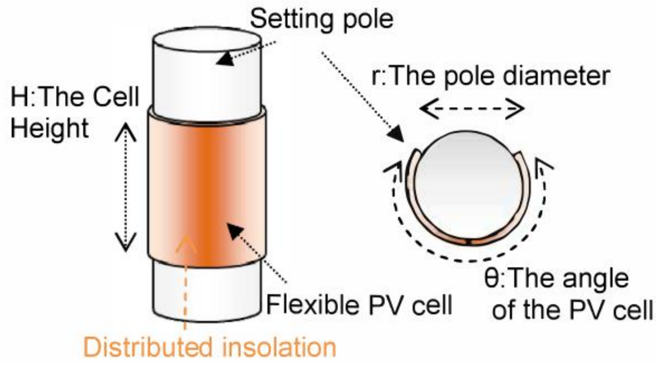


Figure 4 A flexible PV cell is installed on the outside surface of a cylindrical pole.
Source: Shibasaki & Yachi (2014)

Sharma et al. (2014) presented a good example of a real scenario for a common curve form of an FPV module. FPV modules with a generalized curved form were used in outdoor situations and studied for different curve angles, as shown in Figure 5(c), where the angle θ_p, the angle between the plane of the sun's trajectory and the PV module's plane of curvature, is considered to be zero. Figures 5(a) and (b) show a curved FPV module and the angle of curvature (θ_c) in three-dimensional and two-dimensional space. The FPV module is mounted on a curved surface represented by an arc $\widehat{CAD}$. The arc $\widehat{CAD}$ might belong to either a circle or an ellipse. The chord $\overline{CD}$ forms the base of this arc and is inclined at an angle θ_i with respect to the horizontal plane of the Earth. The perpendicular bisector of $\overline{CD}$ intersects arc $\widehat{CAD}$ at point A. The angle ∠ACB, denoted as θ_c, is referred to as the curve angle in this study and indicates the degree of curvature or bending of the module. The curve angle is determined analytically via the following formula:

$$\theta_c = tan^{-1}\left(\frac{AB}{BC}\right) \quad (1)$$

θ_i is considered to be zero to simplify the analysis.

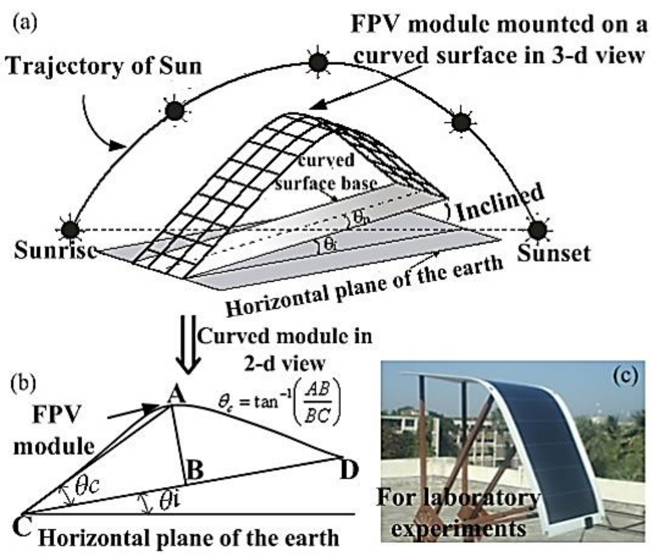


Figure 5 Diagram of a standard FPV module arrangement, showing the curve angle and inclination angle. (a) 3D perspective (b) 2D perspective (c) Experimental setup designed to analyze the performance of FPV modules at different curve angles.
Source: Sharma et al. (2014)

Park et al. (2017) studied the geometry of a flexible PV-cell in two states: flat (dashed line) and bent with a radius of curvature R (solid line). The first parameter of concern is the angle of incidence between the PV-cell surface and the light beams from the source. The angle is divided into two components, elevation angle α and inclination angle β, where 0 ≤ α and β ≤ π, for a precise description of the flat cell. The first component represents the angle of the light source from the ground surface, labeled 1 in Figure 6, whereas the second term, labeled 2, represents the inclination angle of the PV-cell from the ground surface. Figure 3 shows the flat PV-cell positioned parallel to the ground with an inclination angle of β = 0 for clarity.

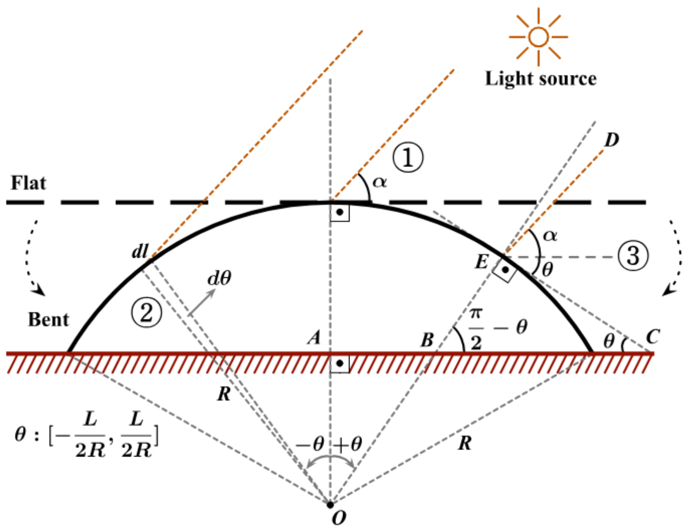


Figure 6 Flat and curved illustration with key parameters.
Source: Park et al. (2017)

A dome-shaped solar form is a vertically oriented cutoff ellipsoid divided into 16 vertical sections. In the simulations, the modules were horizontally divided into two sections of the same length (295 mm). The form of the modules in the system is depicted in Figure 7. Each of the components symbolizes one solar module curved along the horizontal axis. The top piece has an average tilt angle of 54°, and the bottom portion has an average tilt angle of 76° (Bednar et al., 2018).

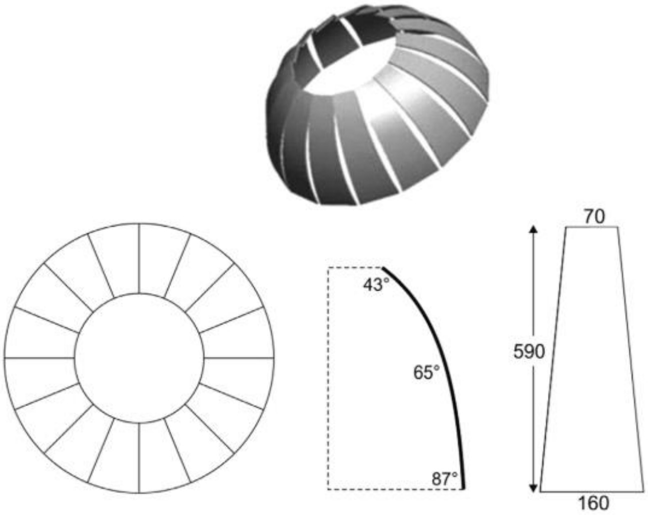


Figure 7 Dome shape, curved angles and dimensions of the curved module.
Source: Bednar et al. (2018)

Prototype two has a curved shade component for a skylight, as shown in Figure 8. The shade has a conical shape and faces south. The intended use is for roof windows and skylights with a combination of passive shading. The active photovoltaic shade obstructs direct sunlight and the window facing North, enabling mostly diffuse light. This leads to a decreased chance of overheating. The curvature is determined by two angles, as shown in Figure 12b. Two curvatures were analyzed: curvature A with angles of α = 60° and β = 32.36° and curvature B with angles of α = 75° and β = 23.74° (Bednar et al., 2018).

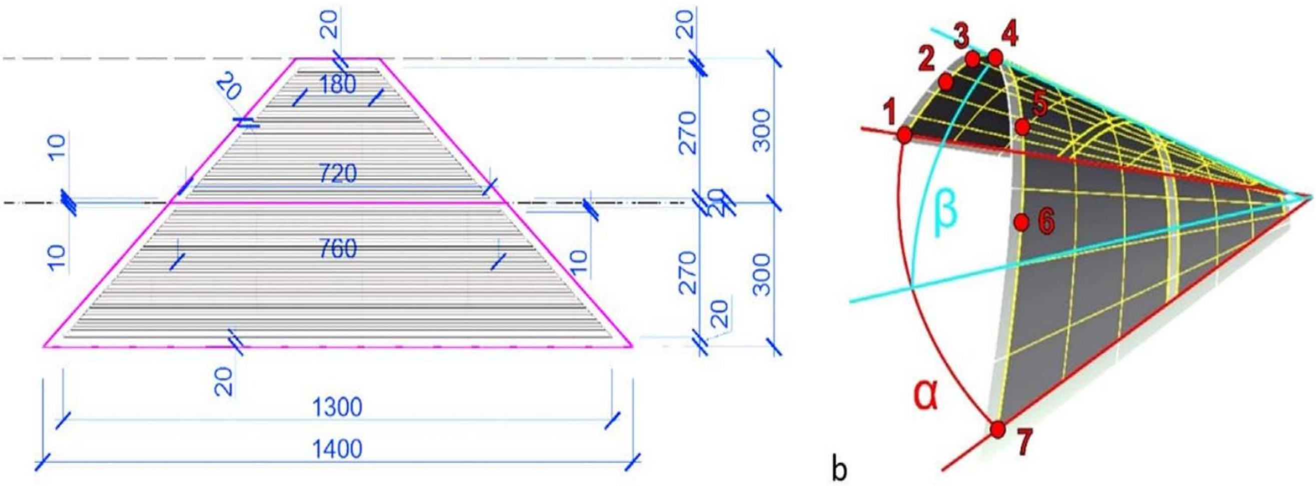


Figure 8 Conical shape module with a 7-point calculation.
Source: Bednar et al. (2018)

The performance of curved thin-film modules for product-integrated solar applications was simulated and studied by Bednar et al. (2018). Two study cases are presented: dome-shaped solar street lighting and a conic-shaped active rooftop shade for skylight. Kurz et al. (2018) analyzed the performance of a tested structure in actual settings, specifically examining variations in factors related to the inclination angle and surface shape. Research has revealed that altering the module inclination angle results in a decrease of approximately 25% in the produced current, voltage, and output power. When the module was bent at a 90° angle to the ground, it resulted in uneven solar radiation levels and increased energy losses.

Chen et al. (2019) developed an autonomous deployment system that uses parametric modeling to enhance the self-assembly process of a solar panel array via elastic origami and shape-memory-polymer actuators. This technique involves the examination of several geometric characteristics, including the form, size, and arrangement of the origami structure shown in Figure 9; the design of the scissor mechanism; and the positioning of the actuator. In addition, the lengths and arrangement of the edges of the polygon are essential for determining the overall size and form of the system in both its collapsed and deployed stages. By meticulously regulating these variables, the system may be designed to achieve efficient and dependable self-deployment.

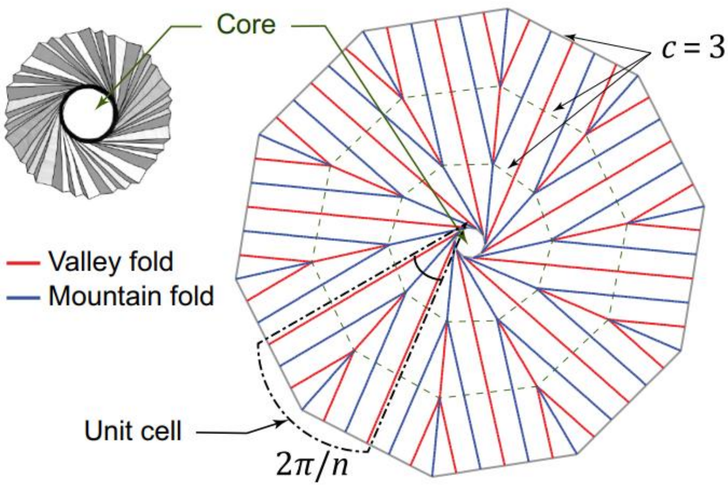


Figure 9 A flexible origami design that can transition between collapsed and extended states. The rotational angle of 2π/n determines the unit cell of the origami.
Source: Chen et al. (2019)

Arissetyadhi et al. (2020) arranged panels in an arch configuration to increase power generation and efficiency by using semiflexible monocrystalline solar panels. This research examines how the collected power and efficiency may be increased by positioning the solar panel in the concave, convex, and flat configurations shown in Figure 10. The data were collected in Palembang's dry and rainy seasons. A peak power output of 20.27 Watts and an efficiency of 13.14% were attained in a concave configuration in the dry season. Compared with the flat configuration, which generated 10.24 Watts and 9.71% efficiency, the convex configuration yielded more power and efficiency at 13.26 Watts and 9.30%, respectively. The results indicate that arches are more efficient for harvesting solar electricity and have broader applications, such as powering a mobile robot used in agriculture.

(a) Plane Setting (b) Concave Setting (c) Convex Setting

Figure 10 Incidents recorded by a solar panel with various surface configurations.
Source: Arissetyadhi et al. (2020)

Parametric modeling allows designers to construct versatile curved solar panel designs that can be adjusted to different architectural arrangements. Parametric models enable the creation of dynamic designs that adapt to environmental circumstances and energy needs by specifying factors such as curvature, size, and orientation (González-Acevedo et al., 2021). Geometric design software, such as computer-aided design (CAD) tools, has given architects and engineers the ability to visually represent, examine, and improve the design of curved solar panels that may be adjusted in architectural settings. These software tools facilitate the development of intricate 3D models, simulations of solar exposure, and structural analysis to guarantee that the panels are both operational and visually appealing within the architectural environment. Segarra Balaguer (2021) used a geometric approach to examine the efficiency of CIGS flexible solar panels in different configurations. The semicircular forms shown in Figure 11 are among the configurations in which the panels may be tested according to the flexible support structure design. This research sought to examine variations in performance depending on the geometry of the panels. The flexible support system enabled the panels to undergo testing in various arrangements, yielding vital insights into the impact of geometry on energy generation. The geometric technique is being utilized to evaluate the influence of geometry on the efficiency of CIGS flexible solar panels in selecting the practical and optimal design.

Badi et al. (2022) conducted measurements on flexible flat plane and semicylinder PV panels in direct sunlight. The semicylindrical shape ensures that the width of the circular arc is twice the height by utilizing three-dimensional adjustable mechanical support. This support allowed the side lengths of the semicylinder to be attached along the supporting bars, forming a closely fitting semicylindrical shape. The two identical PV panels were positioned in an east–west orientation at a latitude of 28.38° in Tabuk city, with their absorbing surfaces directly facing the sun's rays. The two identical PV panels were aligned in an east–west orientation and placed at a latitude of 28.38° in Tabuk city, with their absorbing surfaces directly facing the sun's rays. Global horizontal irradiance (GHI), which includes both direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), strikes flat and semicylindrical photovoltaic panels at the same angle along a direction parallel to the central axis and is considered when developing PV systems. The GHI is the sum of the DNI and DHI components on a flat surface. Thus, the GHI is anticipated to decrease on the basis of the radius of the semicylindrical form. The decrease in solar power density between the semicylindrical surface and the tangential plane N–N must be assessed on the basis of the inclination of direct sunlight, as shown in Figure 12.

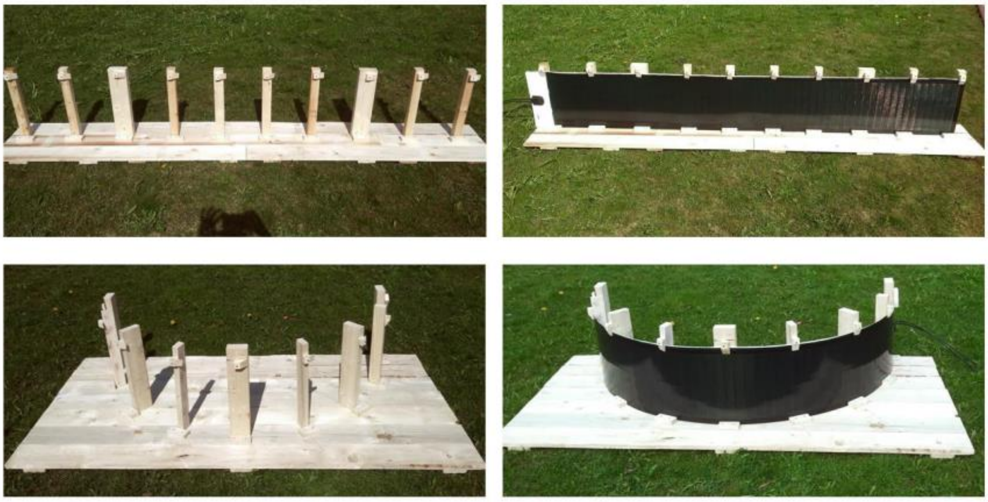


Figure 11 Flat and curved panel conditions.
Source: Segarra (2020)

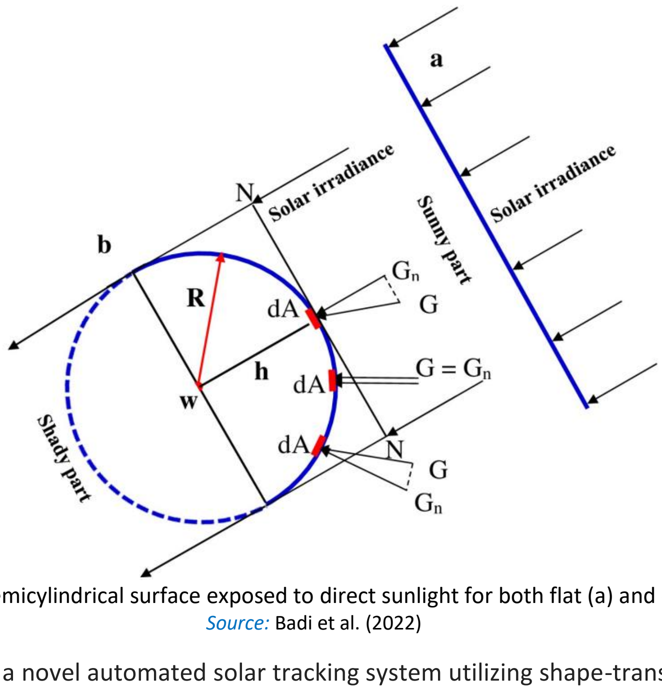


Figure 12 Tangential plane and semicylindrical surface exposed to direct sunlight for both flat (a) and curved (b) photovoltaic panels.
Source: Badi et al. (2022)

Yun et al. (2022) proposed a novel automated solar tracking system utilizing shape-transformable 3D tessellated solar-cell arrays, as shown in Figure 13. The system operates by utilizing tessellated solar-cell units and shape-memory alloys to facilitate movement in response to sunlight-induced heat on the array surface. The array changes its form to increase its cross-sectional area exposed to sunlight by using shape-memory-alloy actuation in combination with an arch-shaped array with fixed displacement and freely rotating ends. Compared with perfectly tracking photovoltaic modules, arch-structured transformable tessellated solar-cell arrays have better sun-tracking performance. Additionally, they function as bifacial solar modules in self-shaded areas. Compared with traditional solar-tracking systems or fixed solar cells, their greater sun-tracking capabilities led to increased power generation. This technology generates 60% more power by tracking the movement of the sun throughout the day.

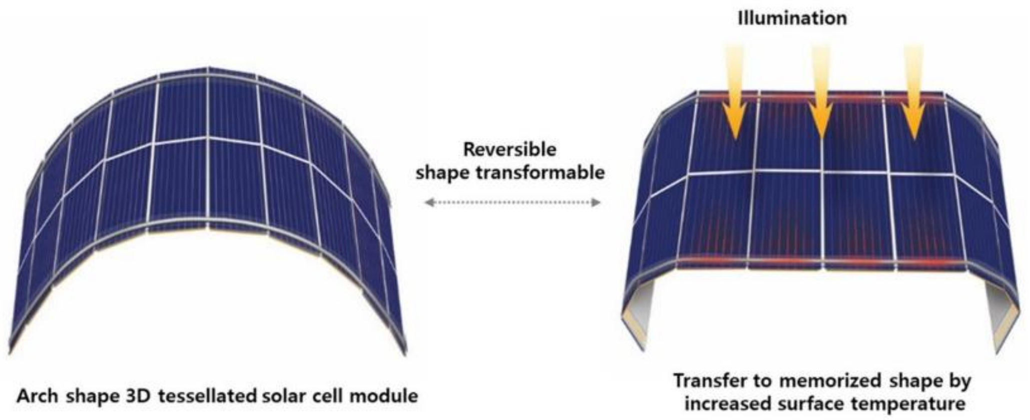


Figure 13 Reversible shape transformation from an arch shape to a memorized shape.
Source: Yun et al. (2022)

Attia (2024) utilized an integrated 1D/3D model to thoroughly examine the behavior and efficiency of flexible and curved solar panels. The 1D model investigates the processes occurring at the material level inside solar cells, with a specific emphasis on phenomena such as carrier production, transport, and recombination. The 3D model accurately depicts the whole geometry and bending form of the module, allowing for the study of the generation of power by considering its physical structure and interaction with sunlight. The study uses a vertically oriented cutoff ellipsoid, split into 16 vertical sections, as the geometric form of the "Solar Hub". Figure 14 illustrates the configuration of the modules in the system. Additionally, the simulations from these models are executed in a sequential manner, where the output of the 1D model (such as the J-V curve) is used as input for the 3D model. This comprehensive method offers a thorough and precise examination of the complete solar module, taking into account both the operations at the material level and the overall geometry of the module. Specialized tools such as COMSOL Multiphysics and SCAPS-1D are used to carry out simulations aimed at analyzing and enhancing the performance of flexible thin-film modules utilized in solar energy applications.

Figure 14 Solar street lights are referred to as "solar hubs".
Source: Attia (2024)

4.2. Triangulation

Triangulation methods have been used to precisely map and measure uneven surfaces where flexible curved solar panels are to be placed. Designers may use triangulation to determine the exact positions of points on a surface. This allows them to produce accurate digital models that help them decide where and how to install solar panels to maximize energy collection and ensure that they blend well with the overall design. Fabbri et al. (2012) utilized software to simulate the triangulation concept on surfaces that are not uniform, using both flat and inclined components on automotive solar roofing, as shown in Figure 3. The system utilizes inputs, including geographical coordinates, irradiance data, photovoltaic cell characteristics, dimensions, and surface structures, for setup. A GUI streamlines program input and parameter entry. The tool employs three models: geometry, PV cell, and solar radiation models. The configuration and simulation of the surface photovoltaic cell are created via 3D computer-aided design drawings. The geometry is transformed into an STL file format, which is often used for rapid prototyping and computer-aided manufacturing. The surface consists of a mesh of triangles defined by vertex coordinates. The software computes the normal vector for each center to identify surface areas with similar inclinations. The application uses three matrices to graphically represent the mesh. The GUI allows users to specify the geometrical and electrical characteristics of a PV cell. The algorithm calculates the maximum number of PV cells that may be positioned on the surface on the basis of inclinations to fill the area. The curved surface is composed of many flat triangular portions, each of which may be seen as distinct surfaces with different slopes. The software optimizes electrical and mechanical connections and arranges the cells on chosen surfaces. A model for calculating solar radiation was developed to determine the power output of photovoltaic cells.

Groenewolt et al. (2016) presented a technique for creating geometric shapes for flexible solar panels on curved surfaces and organizing many panels on a surface. This approach assists in determining how different geometric factors affect the possible surface area of photovoltaic panels on a double-curved roof and the anticipated solar irradiation of these panels. Geometric techniques are utilized to estimate complex double-curved shapes by employing triangulated strips and effectively arranging them on a surface. As illustrated in Figure 15, a model is designed to evaluate how well triangulation methods such as congruent triangles and adaptive triangles represent the real bending behavior of sheet metal and the impact of altering the diagonal direction via the congruent triangles method, and the geometric disparities between methods are compared. The solar insolation potential of different roof shapes is assessed by integrating these methodologies with solar insolation analysis software. The solar insolation is closely correlated with the panel surface area in a roughly linear manner. Placing short and broad panels perpendicular to the longest edge of the roof maximizes the effective PV area and solar insolation.

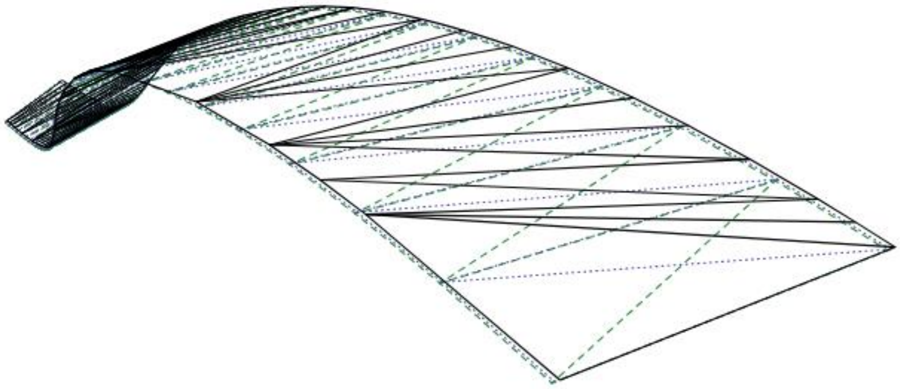


Figure 15 Triangulation methods comparison.
Source: Groenewolt et al. (2016)

The approaches demonstrated reliability and effectiveness in the case study conducted for designing the NEST Hilo building at EMPA Düsseldorf, which serves as a platform for innovative building technologies. The building has a double-curved roof with solar cells attached to flexible metal plates organized in parallel strips, as illustrated in Figure 16 (Groenewolt et al., 2016).

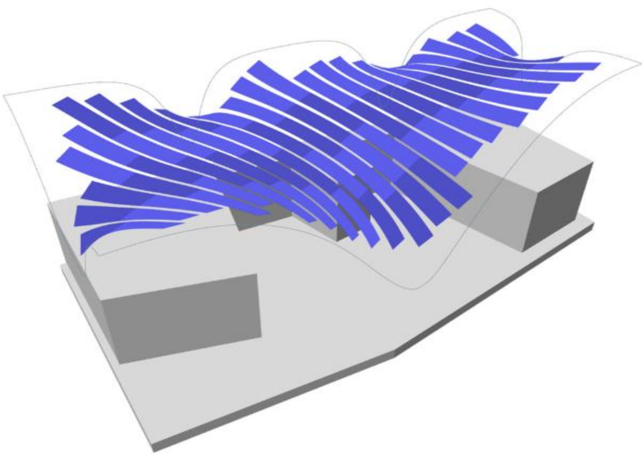


Figure 16 Design featuring a sequence of curved solar panels installed on the roof of the Hilo building.
Source: Groenewolt et al. (2016)

Other geometric triangulations were designed by Hofer & Schlueter (2016) via geometry curved flexible thin-film photovoltaic (FPV) modules simulated within the Rhinoceros 3D/Grasshopper environment to improve the design and arrangement of FPV modules on a doubly curved roof shell structure. This allows one to model the placement of FPV modules on arbitrarily curved surfaces and to assess module curvature, twisting, and other structural integration parameters.

Assoa & Levrard (2020) designed a unique building-integrated photovoltaic module for complex exterior shapes, particularly geodesic domes. Experimental and numerical investigations were conducted to verify the system installation technique and integration settings. An experimental investigation of the thermal behavior and electrical output of a south–oriented triangular solar module pasted on a polymer textile was performed in the cold season considering four slopes between 0° and 90° to approximate the principal tilt of the dome facets. The study revealed that the thermal behavior and electrical output of the south-oriented triangular solar module on a polymer textile were consistent, with an electrical efficiency ranging from 6.5% to 8.5% and an array yield of up to 8.8 Wh/Wp. All the slopes considered provided good thermal and electrical performance, with the PV module heating below 50°C.

4.3. Curve correction factor

Ota et al. (2018) defined the curve-correction factor as a distinct value determined by the three-dimensional curved geometry of the PV module. The curve-correction factor was determined via a ray-trace simulator. The form of the curved surface influences the curve-correction factor, as illustrated in Figure 17. To estimate the energy output of three-dimensional vehicle roof photovoltaic panels accurately, providing a scientifically precise approach for modeling the solar irradiation received by the panel is crucial. Furthermore, it is necessary to assess the average yearly irradiance that falls on vehicle roofs since the PV module is often shaded when driving and while parked.

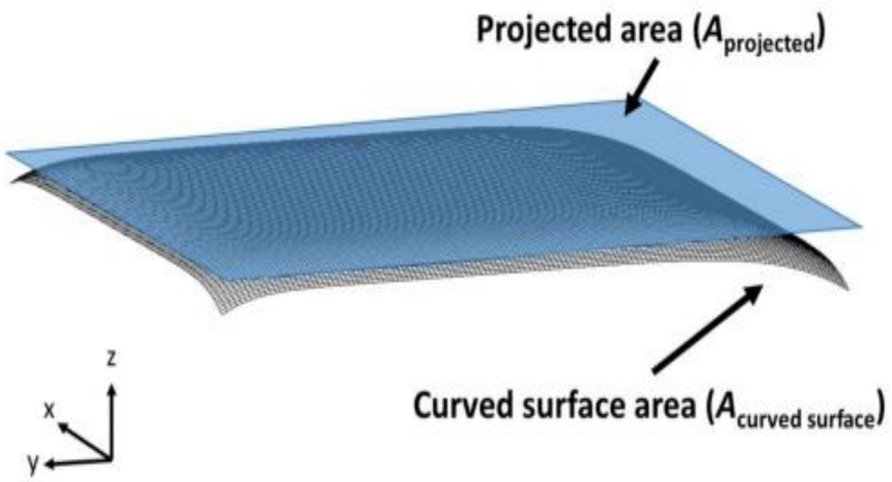


Figure 17 Curved surface model.
Source: Ota et al. (2018)

Park & Chakraborty (2018) introduced a design-time approach to address the nonuniform solar irradiation received by a PV array on a curved surface. Our solution takes into account the serial–parallel connections of a photovoltaic array as a control variable and develops an algorithm using the k-means clustering method. The average power output is enhanced by up to 84%. The suggested methodology utilizes the correlation of solar irradiance values among each cell, which can be derived from the curvature. Araki et al. (2019) used a curve-correction factor through numerical ray-tracing simulations where the incidence angle of sunlight was computed on the basis of direction, shadowing, climatic patterns, and direct and diffuse sunlight. The absorbed flux on the curved module surface is determined by randomly tracing rays. The energy output of a curved photovoltaic system decreases significantly when the curvature and incidence angle distributions are influenced by latitude, climatic patterns, and shading conditions.

Tayagaki et al. (2019) used the curve correction factor technique to evaluate the power production of nonplanar solar panels on cars in comparison with flat reference panels. This approach computes the curve correction factor, which represents the comparative power production of nonplanar panels on the basis of their surface properties and alignment. The analysis focuses on the absorption of sunlight by slanted panels on surfaces that are not flat, providing valuable information on the shape and orientation of the panels' effectiveness in converting sunlight into energy. The approach examines the proportion of nonplanar panels to reference flat panels and the tilt angle, establishing a direct correlation between the curve correction factor and surface ratio. Figure 18 presents a simplified model of a vehicle and its potential deformation or movement under certain conditions, such as loading or structural dynamics. The vertical lines labeled X_0 denote precise reference points or places along the framework of the vehicle. The vehicle's potential form or position in reaction to certain pressures or motions is shown by the thick blue line. The presence of the distance l and the angle ϑ indicates that rotational or curvilinear motion occurs in the vehicle's frame or body as a result of the applied force or load.

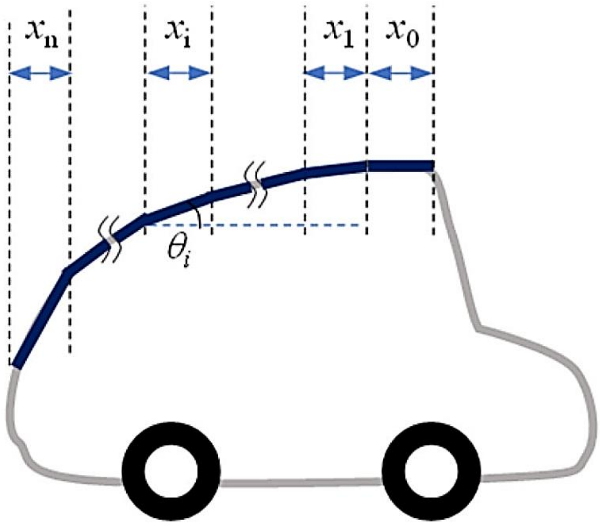


Figure 18 Curved surface consisting of several inclined panels.
Source: Tayagaki et al. (2019)

Ray-tracing simulations of the distribution of irradiance on a three-dimensional photovoltaic module were conducted by Yamada (2020). The research compares two distinct modules, A and B, as illustrated in Figure 19, by analyzing their distribution of irradiance under various levels of diffuse fractions (k_d). The diagram depicts the outcomes, emphasizing the influence of curved surfaces, which are determined by the radii of curves in the x- and y-axes (R_x, R_y). Module A results in more pronounced curved surfaces than does Module B, leading to discernible variations in the distribution of irradiance. At a zenith point of 60° and an azimuth of 45°, the distribution of irradiance exhibits substantial variation. The degree of variance is more noticeable when the radii of the curves are small, suggesting a significant lack of homogeneity in the distribution of Module A. The color chart illustrates the variations in three distinct diffuse fractions, namely, 0.9, 0.6, and 0.3. The diffuse fraction k_d decreases from left to right on the chart, aiding in the comprehension of the proportion of irradiance that consists of global components.

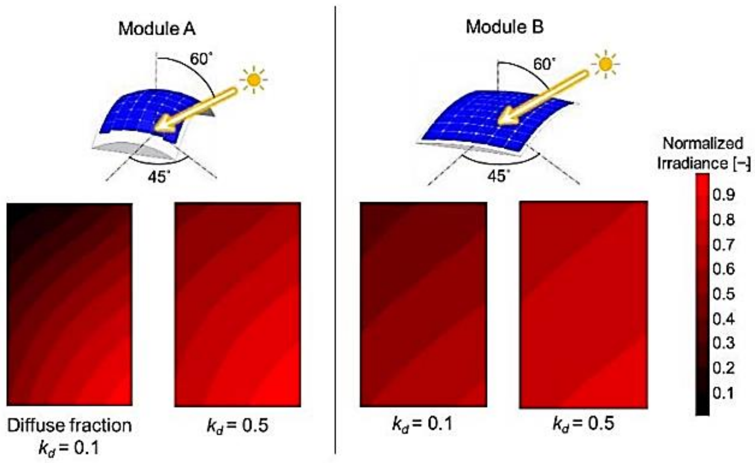


Figure 19 The simulated distributions of irradiance on 3D-PV modules with various curved surfaces. Module A has a curvature radius of 1 m in both the x and y directions, whereas Module B has a curvature radius of 3 m in both directions. The analysis is conducted for two values of k_d, namely, 0.1 and 0.5. k_d represents the ratio of the diffuse component to the global component of irradiance.
Source: Yamada (2020)

Araki et al. (2020) introduced an innovative approach to measure and analyze the changing solar energy levels around a moving vehicle. The technique employs five pyranometers labeled as *Qx+*, *Qx−*, *Qy+*, *Qy−*, and *Qz* illustrated in Figure 20, positioned on top of a vehicle in different orientations to collect real-time sun irradiance data while the vehicle is in motion. This extensive data gathering enables the creation of an advanced shading model that integrates direct sunshine, diffuse sunlight, and reflections from nearby objects. To confirm the correctness and dependability of the simulation, researchers compare the measured data with the modeled data. This approach offers significant knowledge on the practical solar energy capacity for automobiles, therefore enabling the enhancement of solar energy collection and usage in automotive contexts.

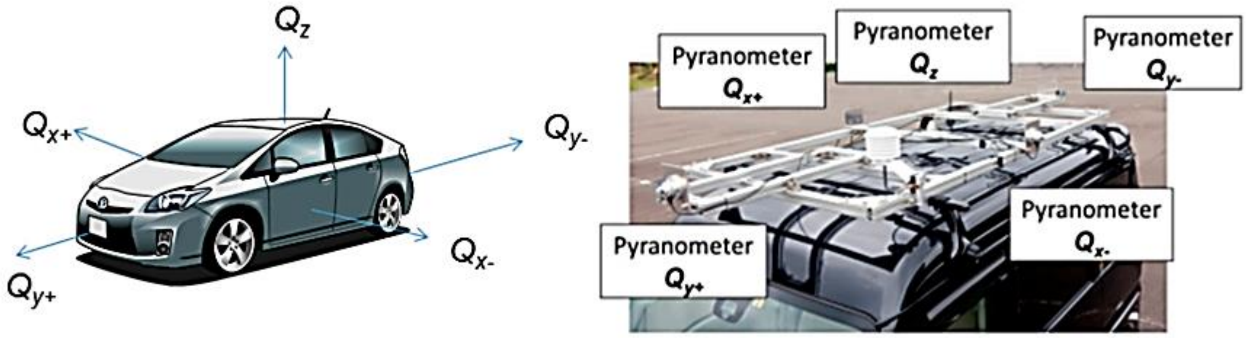


Figure 20 Five pyranometers positioned on an automobile along the orthogonal axis.
Source: Araki et al. (2020)

Figure 21 depicts the procedure of creating a curved surface, especially an automobile roof PV, via the use of random integers. The figure uses a bicubic spline interpolation technique, which is a method used to generate a seamless and uninterrupted surface from a grid of points. Interpolated surfaces are capable of accommodating intricate forms that cannot be readily created via basic geometric techniques. This allows for precise and seamless representations, which are crucial for a variety of simulations and analyses. The picture has many important components, such as an "impact line" denoted as $\varphi= x^2$, and specific parameters such as θ max, which represent the highest possible values for angles related to the surface's form or sites of impact. The presence of random numbers is indicative of the use of stochastic techniques to simulate or evaluate the distribution of effects or data points on the surface, hence improving the model's resilience and dependability. The automobile is equipped with a measurement system consisting of five pyranometers positioned along the orthogonal axis (Araki et al.,2020).

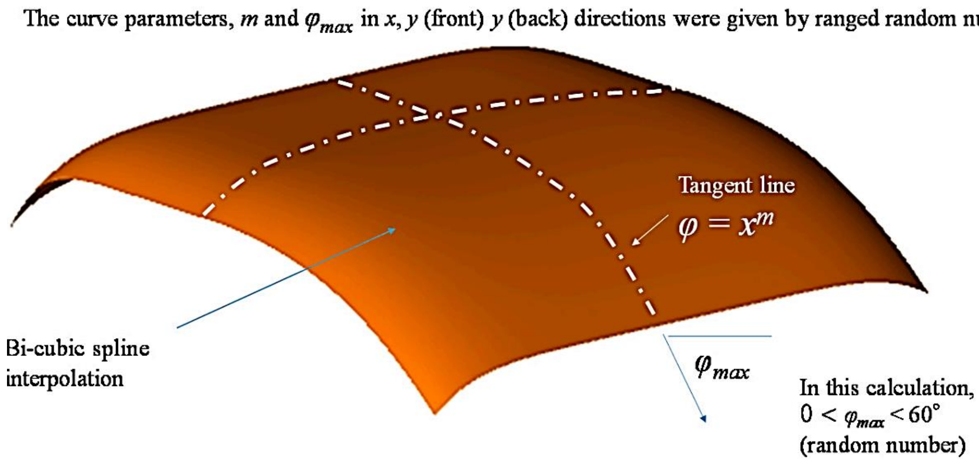
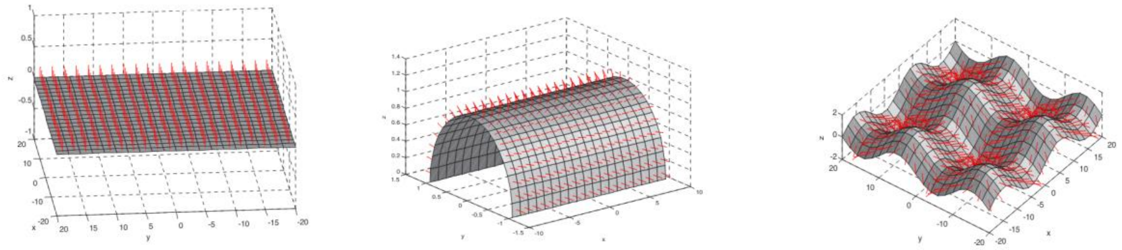


Figure 21 Curved surface modeling of vehicle roof PV.
Source: Araki et al. (2020)

4.4. Mathematical modeling

Karavadi and Balog (2011) reported findings that used view factor and ray-tracing methods to measure the amount of sunlight received on a nonflat photovoltaic surface. The method is first tested on a flat panel to confirm its precision and then on other surfaces, such as semicylinders, cylinders, and hemispheres, which exhibit a uniform pattern. It is then applied to a wavy geometry resembling a fabric-like surface.

A three-dimensional surface is generated in MATLAB to depict the PV panel and the meshed solar cells. Normal vectors are generated for each cell, and a line is drawn across the center of these cells to display the different orientations at which they are positioned relative to the sun's location in the sky. The flat plate shown in Figure 22(a) consists of individual pixel components. The normal vectors of each pixel are aligned. Each row of pixels in the semicylinder illustrated in Figure 22(b) has consistent surface-normal vectors, although there are fluctuations across rows. The wavy surface in Figure 22(c) may exhibit irregularity in adjacent or proximal pixels with random fluctuations. There is not a singular view factor that applies to the full PV surface. Research has shown that semicylindrical surfaces collect 20.88% more energy than flat plates do and 41.63% more energy than flat plates do on a particular day. Compared with flat plates, cylindrical surfaces are more efficient at capturing energy throughout the day, with a surface area increase of 214%. Compared with flat plates, semicylindrical surfaces have a 57% greater surface area, resulting in a 20.88% increase in energy harvested (Karavadi and Balog, 2011).



(a) (b) (c)

Figure 22 (a) Flat panel surface. (b) Semicylindrical mesh surface. (c) Wavy mesh surface.
Source: Karavadi and Balog (2011)

The research of Walker et al. (2019) introduces a method for creating and optimizing 3D models of solar systems in urban settings. The system uses a high-resolution ray-tracing irradiance simulation and an electrical model based on a single-diode model. The technique enhances electrical connections to obtain the highest output by using a genetic algorithm. The approach is used on flat and curved thin-film CIGS modules as well as two interconnected thin-film modules under varying irradiance and partial shade circumstances. Using evolutionary algorithms, the layout may be adjusted to reduce string mismatch losses for BIPV networks with different modules, as indicated by the findings. The comprehensive electrical simulation assesses the impact of the module design and inverter approach on system performance. Tanwar et al. (2019) examined the power generation of pliable photovoltaic modules on curved surfaces. This research uses evolutionary algorithms in MATLAB to improve the design of flexible curve panels by considering aspects such as panel efficiency, curve angles, and field area. Research has sought to optimize the power output from flexible solar panels through a thorough examination of these aspects. The findings demonstrate the efficacy of this strategy in improving power generation from flexible curved panels via improved design configurations. The objective function for the solar field model is formulated in (2)–(4):

$$\text{Minimum } A = \frac{Sin\theta}{\theta} \times L \times W \tag{2}$$

subject to the condition

$$W \geq H \times K \times \cos\beta + (K-1) \times D \tag{3}$$

However, the bounds are

$$\begin{gathered} 40 < L < 100 \\ 6 < K < 11 \\ 1 < D < 3 \\ 0° < \beta < 90° \end{gathered} \tag{4}$$

where:

A Solar panel installation area;
L Length of the field;
W Width of the field;
H Width of the collector;
β Tilt angle;
K Number of rows;
D Distance of rows;
θ Curve angle of the panel.

The formulation for determining the maximum power of a solar field area is as follows:

$$\text{Max.} P = \mu \times A \times I \tag{5}$$

Bound

$$0.15 < \mu < 0.21 \tag{6}$$

where:

P Power generation;
H Efficiency of panel;
I Irradiation of the sun per day.

Alpuerto (2021) conducted a study to maximize system performance by analyzing the impact of solar radiation on specific surfaces via mathematical models. The assessment of the morphology employs semicylinder, ellipse, and sinusoidal curvatures, which quantify the instantaneous rate of change in the unit tangent direction. Depending on the information provided, equations that determine curvature may be employed interchangeably.

$$\kappa = \left|\frac{d\vec{T}}{ds}\right| = \frac{\|\vec{T}'(t)\|}{\|\vec{r}'(t)\|} + \frac{|f''(x)|}{(1+[f'(x)]^2)^{\frac{3}{2}}} \quad (7)$$

Variables $\vec{T}$ and *s* indicate the unit tangent and arc length, respectively. Curvature is quantified in units of inverse length, which is an abstract notion when considered without context. The rate of curvature change may be defined as the ratio of the radians to the arc length, which is theoretically equal since the radians are dimensionless. Curvature is a measure of the rate at which the direction of a curve changes in relation to its length (Alpuerto, 2021). A standardized set of curved surfaces was developed by Ota et al. (2022) to statistically examine the roof forms of commercial vehicles and determine the photovoltaic (PV) coverage for different curved surfaces. The distribution of coverage on car roofs is shown in Figure 23, and the impacts of curvature on both surface coverage and power output are measured. The fundamental principles derived suggest that a hemispherical surface with a radius of curvature of 1000 mm may achieve a coverage ratio of 96%. The mathematical representation of the curved surface of a car roof is shown in Equation 8.

$$S(u,v) = (x(u,v), y(u,v), z\,(u,v))^T \quad (8)$$

where the vector S represents the curved surface with parameters u and v. It has a size of 3 × 1, where the zeroth column corresponds to the x component, the first column corresponds to the y component, and the second column corresponds to the z component. The index is initialized to 0. The grid points on the curved surface are represented by coordinates that are determined locally on the basis of the lowest degree polynomial that guarantees continuity in the second-order derivative. This ensures that a cubic polynomial may be used to seamlessly link the grid points, a technique known as bicubic spline interpolation. The coordinates are provided in a two-dimensional computer-aided design (CAD) format (Ota et al., 2022).

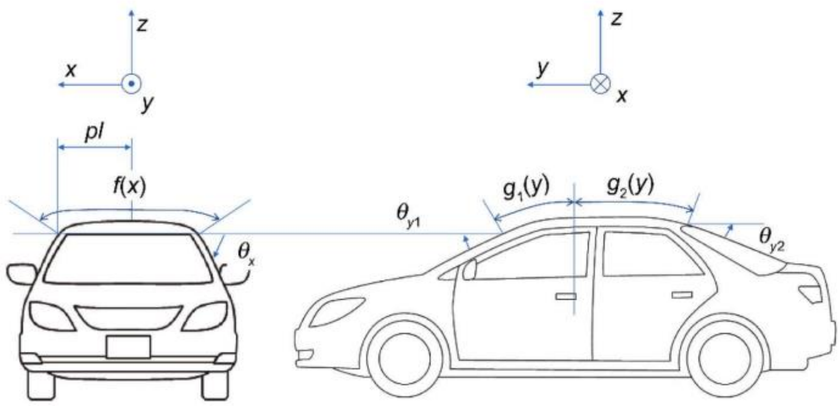


Figure 23 Curved surface characteristics from 2D computer-aided design (CAD) drawings of a vehicle body.
Source: Ota et al. (2022)

The amount of solar radiation on a curved roof surface of a greenhouse was calculated by creating a model via Rhinoceros/Grasshopper CAD software and the open-source solar modeling tool pvlib-python©. In the mathematical modeling procedure, the curved surface is divided into smaller planar subsections to calculate the angles of incidence and tilt for each subsection. The curved surface of the OPV array was divided into 320 flat portions, which matched the size and location of the 320 OPV cells in the array. This method included dividing the curved surface into smaller parts that are considered to be locally flat to calculate the changing angles of β and γs for each section. The curved OPV arrays on the greenhouse were modeled via Rhinoceros CAD/Grasshopper software. The modeling was based on scaled drawings of the greenhouse construction provided by the manufacturer. Figure 24 shows a three-dimensional representation of a greenhouse fitted with eight organic photovoltaic (OPV) arrays installed on its roof (Waller et al., 2022).

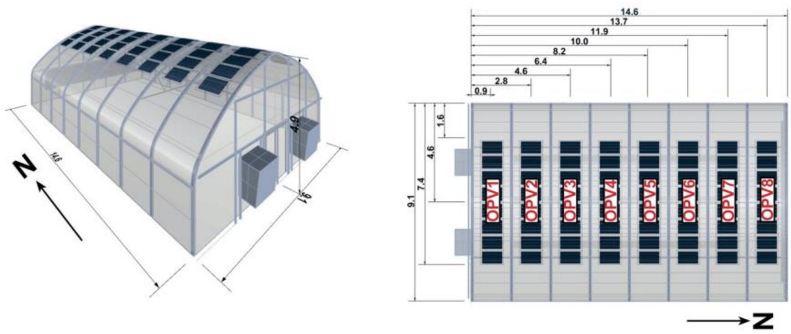


Figure 24 3D model of the greenhouse showing 8 OPV arrays that have been constructed. The model provides a southwest perspective on the (left) and a top view on the (right), with clear labeling of the OPV array IDs.
Source: Waller et al. (2022)

Espitia-Mesa et al. (2024) developed curved photovoltaic surfaces that optimize solar exposure and enhance radiation collection while maintaining the same occupied area as standard PV modules. To assess the amount of radiation collected by a series of surfaces with a projected flat area of $1m2$ on a terrace in Medellín, Colombia, a genetic algorithm (GA) is included in a computational ray tracing tool. This integration allows for the evaluation of radiation based on historical irradiance data. Mathematical models are created to analyze the performance of a photovoltaic (PV) module's geometric design and its ability to capture radiation. These models use the principle of curvature to precisely define the geometric properties of a photovoltaic (PV) surface with curvature S that is formed by four points arranged in a straight line. To ascertain the curvature of a surface, including the maximum permissible radius of curvature, it is essential to provide the definition of curvature defined in Equation 9. Furthermore, an irradiance study modeled in Equation (10) is used to ascertain the solar resources available at a certain site. A numerical ray tracing tool was created to clarify the correlation between the radiation collected and the geometric configuration of the surface, as shown in Figure 25.

$$\vec{r} = \left(x, (u, v), y(u, v)\right); u, v \in R \tag{9}$$

$$P_{capt} = \frac{1}{t_f - t_0} \iint G(t) r(t) dS dt \tag{10}$$

Equation (10) defines the mean power captured P_{capt} by a PV surface as the sum of the irradiance $G(t)$ in a specific direction $r(t)$ over a differential surface dS within a time interval dt. This expression will be utilized in future analyses to assess various PV surfaces.

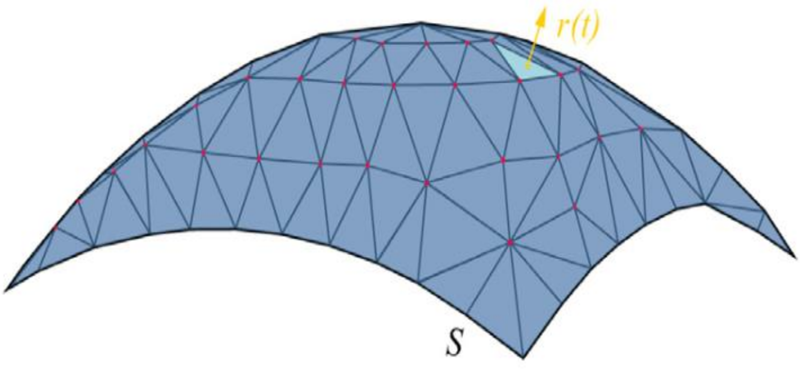


Figure 25 Delaunay triangulation mesh.
Source: Espitia-Mesa et al. (2024)

Current research on flexible solar panel integration in architecture focuses on broader aspects, such as general geometric optimization, material property determination, simulation and modeling methods. However, there is a notable gap in investigations of the use of precise control points in cubic Bézier curves (S-shaped and C-shaped) for this purpose. S-shaped shapes offer smooth transitions, whereas C-shaped shapes provide greater control over curvature. The lack of research on S-shaped and C-shaped architectures in flexible architectural designs offers distinct potential. Designers might strike a balance between visually attractive designs and effective solar energy collection by effectively integrating these shapes. This research gap has the potential to revolutionize the aesthetics and functionality of future buildings by creating new design methodologies and tools for integrating flexible solar panels. Table 1 shows the summary of the design studies.

Table 1 Summary of design studies on flexible solar PV panels.

Author	Design Method	Objective of the Study	Methodology	Result/Conclusion
Karavadi & Balog (2011)	Geometric Design	Analyze energy harvest from nonflat PV geometries for power optimization.	Modeling approach to determine energy variations in nonflat PV geometries. View factors calculated for energy captured by various surface geometries. Pixelization concept to maximize energy harvest and minimize power devices.	Novel nonflat PV geometries capture more energy than flat plates. Power electronics design should adapt to optimize energy harvest.
Fabbri et al (2012)	Triangulation	Simulate PV generator behavior on nonhomogeneous surfaces with optimal angles.	Tool simulates PV generator behavior on various surfaces using three models. User defines PV cell characteristics to calculate cell allocation on surface. Model validated with commercial solar panels and ENECOM HF40 cell.	Curved PV cells enhance product quality without affecting aerodynamics or aesthetics. Software tool models PV generator behavior on nonplanar surfaces effectively.
Zhang & Balog (2013)	Geometric Design	To compare energy harvest of planar vs. nonplanar PV surfaces.	Modeling approach to determine view factor of arbitrary geometry. Experimental circuit with PV module, NI MyDaq, and DC load. Validation of modeling through comparison of planar and nonplanar surfaces.	Nonplanar PV surface harvests 20% more solar energy than planar. Nonplanar PV captures more solar energy than planar.
Konstantopoulos & Koutroulis (2014)	Geometric Design	Develop global MPPT system for flexible PV modules.	Experimentally investigates geometrical parameters' impact on PV module characteristics. Proposes a new method for tracking global MPP of flexible PV modules.	New global MPPT method for flexible PV modules with superior performance. Proposed HCPSO algorithm minimizes power loss and maximizes energy production. Boost converter based design applicable to distributed MPPT architectures.
Sharma et al (2014)	Geometric Design	To develop a novel MPPT approach for curved FPV modules.	Empirical models relate FPV parameters with environmental factors and layout design. Proposed 'scanning window' technique maximizes power yield of curved FPV modules.	Proposed SWT technique enhances power tracking for curved FPV modules. Optimum layout designs for BIPV and standalone PV systems facilitated.
Shibasaki & Yachi (2014)	Geometric Design	Estimate power output of cylindrically shaped flexible PV cell systems accurately. Develop a design tool for flexible PV cells to optimize power.	Single flexible PV cell model mounted on cylindrical pole. New method estimating power output of flexible PV cell.	Proposed method estimates power output of cylindrically shaped flexible PV cell. Linear relationship between power output and average insolation observed. Estimated power output 2.7 times higher than actual measured value.
Groenewolt et al (2016)	Triangulation	To design and analyze photovoltaic systems using flexible panels effectively. To assess solar insolation potential and panel arrangement on curved surfaces.	Generate flexible panel geometry using congruent triangles on curved surfaces. Analyze strip behavior with elements perpendicular or along the curvature.	Methods analyze solar insolation, panel geometry, and surface approximation effectively. Efficiently cover irregular surfaces with strip geometry for photovoltaic panels. Automated system can inform electrical design of photovoltaic systems.
Hofer & Schlueter (2016)	Triangulation	To optimize FPV module design for performance in partial shading. Investigate how design parameters influence	Simulation in Rhinoceros 3DGrasshopper for curved FPV modules. Calculation of electricity yield in partial shading and under curvature	Novel simulation methodology for FPV module electricity yield calculation. Design parameters impact energy yield on doubly curved roof shell

		energy yield on curved surfaces.		
Park & Joshi (2017)	Geometric Design	To model bending impact on harvested energy in flexible PV-cells. Validate analytical model with empirical data for energy harvesting efficiency.	Analytical modeling of flexible PV cells considering bending effects. Validation of the proposed model through extensive experiments. Derivation of an analytical radiation model with bending.	Energy harvesting is crucial for low power IoT devices. Flexible PV cells ensure uninterrupted operation of wearable IoT devices.
Bednar et al (2018)	Geometric Design	To simulate performance of curved thin-film modules for PV applications.	Combined 1D3D model of photovoltaic module used for simulations. SCAPS1D simulation software utilized for 1D material model simulations. Baseline parameters based on Cu (In,Ga)Se2 technology for simulations.	Hybrid approach for simulating thin film modules with flexibility and efficiency. Demonstrated use in BIPV applications with arbitrary shapes and orientations.
Kurz et al (2018)	Geometric Design	Analyze impact of flexible PV tile shape on performance parameters.	Testing involved a flexible CIGS module with 70 W output capacity. Analysis included changes in parameters based on module inclination and shape.	Optimal exposure of BIPV elements is crucial for energy generation. Photovoltaic tiles' integration into buildings can lead to energy losses.
Ota et al (2018)	Curve correction factor	Define curve-correction factor for car roof PV module energy generation accurately.	Ray trace simulator for curve correction factor calculation. Mobile multi pyranometer array system for annual irradiance evaluation. Ray trace simulation for three dimensional light source modeling.	Proposed curve correction factor for three dimensional car roof photovoltaic modules. Evaluated annual irradiance absorbed by car roofs using a ray trace simulator. Shape of curved PV module affects curve correction factor. Effective annual solar radiation for curved PV modules estimated.
Chen et al (2019)	Mathematical Modeling	Investigate induced current density mismatch in nonplanar photovoltaic surfaces. Build foundation for investigating NP-PV with added complexities.	Modeling nonplanar surfaces with specific geometric characteristics. Analyzing surfaces like semicylinder, ellipse, and sinusoid mathematically.	Curved surfaces enhance energy harvest and peak power. Diodes reduce mismatch current in nonsymmetric strings. Symmetry is crucial for optimal performance in curved photovoltaic applications.
Tanwar et al (2019)	Mathematical Modeling	Optimize power generation for flexible curve solar panels using genetic algorithm.	Analyzed power generation from flexible panels at different curve angles. Optimized field area design for flexible curve panels using genetic algorithm.	Optimal area design for flexible curve panels enhances power generation. Genetic algorithm in MATLAB optimizes field area for flexible curve panels.
Chen et al (2019)	Geometric Design	Achieve shape reconfiguration and structural stability through physical properties and architecture.	Programming and recovery enable autonomous transformation of the solar panel. Shape memory effect in 3Dprinted polymers is utilized for deployment.	Proposed metamaterial enables self deployment of solar panels autonomously. Achieved 1000% expansion ratio in under 40 seconds. Demonstrated controlled deployment without conventional actuators or power supply.
Tayagaki et al (2019)	Curve correction factor	To evaluate power generation of photovoltaic panels on different surfaces.	Numerical geometric calculation for power generation of photovoltaic panels. Evaluation using power generated, mileage, power density, and irradiation database.	Vertical panels generate 1/4 power of horizontal panels. Curve correction factor models power generation of nonplanar panels.
Assoa et al (2020)	Triangulation	To evaluate performance of a novel building integrated photovoltaic module.	Comparative analysis of temperatures in BIPV triangle layers for method. Evaluation of adhesion failures risks based on temperature gradients between layers.	Prototype BIPV module shows satisfactory thermal and electrical performance. South oriented facets tilted between 3060 degrees are relevant for PV integration. Validated numerical model predicts BIPV triangle performance over a year.

Araki et al., (2020)	Curve correction factor	To model and measure solar irradiance for vehicle-integrated photovoltaics accurately.	Solar irradiance modeled using shading objects and car orientation. Curve correction factor developed for efficiency measurements of curved modules. Simple shading and scattering reflection model used for solar irradiance modeling.	Developed and validated a simple shading model for VIPV. Established a curve correction factor for energy yield optimization. Conducted one year monitoring of solar irradiance on car roof and body.
Assoa & Levrard (2020)	Triangulation	To evaluate performance of a novel building integrated photovoltaic module.	Experimental and numerical studies on a triangular BIPV module. Thermal and electrical model development and validation for the component.	Prototype testing showed satisfactory thermal and electrical performance. South oriented facets tilted between 30 and 60 are recommended for integration. Annual energy production peaked at 5.9kWh with a 30° slope.
Yamada (2020)	Curve correction factor	To enhance 3D compatibility of solar cells for vehicle integration.	Three approaches to improve 3D compatibility of solar cells. Investigated effect of BPD on 3DPV module output by simulations. Prototype 3DPV module with triangle cut cSi cells.	VIPV applications include wireless power feeding and optical communication. Three approaches enhance 3D compatibility: stretchable PV, shape tailored cells, wafer thinning.
Arissetyadhi et al (2020)	Geometric Design	- Investigate the effect of arches setting on solar panel efficiency. - Analyze power generation in concave, convex, and plane settings.	Investigates semiflexible vs. rigid solar panels for power and efficiency. Focuses on PV panel installation for mobile robotics in agriculture.	Arches setting increases solar panel efficiency and electricity generation. Concave setting is most efficient, followed by convex setting.
González-Acevedo et al (2021)	Geometric Design	Evaluate solar tracker performance in Colombia using simulation and experimental data.	Discrete Proportional Derivative controller for solar tracker position control. Simulation using PvSyst software and validation with realtime data.	Solar tracker increases power output by 19% to 47.84%. Control system enhances energy production, especially in equatorial latitudes. Experimental validation shows a 0.5% difference from simulation results.
Segarra (2021)	Geometric Design	Compare performance of CIGS panels in semicircular and flat geometries. Study geometric effects on energy production of flexible PV panels.	Tests with CIGS flexible PV panels in semicircular and flat geometries. Analysis of geometric effects on energy production of flexible PV panels. Design of adaptable support for testing panels in various geometries.	Semicircular panels have reduced power compared to flat panels. Tests should be conducted in different parts of the year. Project aims to test CIGS flexible PV panels in various geometries.
Badi et al (2022)	Geometric Design	Investigate temperature effect on photovoltaic cell parameters in Tabuk region.	Mathematical modeling of PV module with temperature dependent parameters. PV characteristics output for various operating temperature values.	Investigated temperature effect on PV cell parameters using improved models. Validated method with experimental measurements on flat and curved panels. Solar power output increases with solar power density and curvature.
Yun et al (2022)	Geometric Design	Develop shape-transformable solar cells for urban environments with enhanced performance.	Solar cells transformed using shape memory alloy components for self tracking. Tessellated solar cells encapsulated with PDMS silicone material. Photovoltaic performance measured using solar simulator under various conditions.	Shape transformable solar cells outperform conventional tracking systems in urban environments. Modules increase electricity production by 60% over a day. Shape memory alloy components enable self solar tracking and shape transformation.
Waller et al (2022)	Mathematical Modeling	Evaluate performance of large-area OPV arrays on curved greenhouse roofs. Develop methods to	Description of OPV arrays, greenhouse, and data collection system. 3D surface modeling of	OPV arrays had 1.82% PCE, with afternoon losses. Need for robust OPV devices for agrivoltaic greenhouse applications.

		estimate solar irradiance on nonplanar surfaces.	curved OPV arrays on the greenhouse.	
Attia (2024)	Geometric Design	Analyze solar resource measurements and simulate curved thin-film modules.	Combined 1D3D model for photovoltaic module simulation. Utilized FEM analysis for detailed simulation of thin film solar modules. Data from 7 stations in Eastern Province used for solar resource analysis.	Solar resource analysis for PV in Eastern Province, Saudi Arabia. Hybrid model for simulation of flexible thin film modules developed.

5. Final Considerations

In conclusion, this review article delves into the exciting potential of flexible solar panels to revolutionize the aesthetics and functionality of building design. By seamlessly integrating with curved surfaces and offering enhanced visual appeal, these innovative panels open new possibilities for architects and designers. This review has also explored the various architectural design considerations and tools used to optimize the shape, arrangement, and integration of flexible PV panels within the built environment. As research and development in this field continue to advance, flexible solar panels are expected to play an increasingly significant role in shaping the future of sustainable and aesthetically pleasing architecture.

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Ethical Considerations

Not Applicable.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this article.

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