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Review on mechanical behavior of solar cells for building integrated photovoltaics

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Abstract: The energy crisis and environmental pollution have promoted the rapid development of renewable solar technology. Building integrated photovoltaics (BIPV) is an important field for the future development of solar energy. This review presents the mechanical property studies of existing BIPV and analyzes its research status to offer advice for engineering applications. By analyzing the types and mechanical characteristics of solar cells in the existing BIPV and determining the load conditions that need to be considered in different application modes, this paper summarizes the relevant existing studies at the photovoltaic material, cell and component levels and offers corresponding suggestions for mechanical research, which consequently results in the proposal of a new BIPV structure. Since the mechanical properties of BIPV have seldom been studied, and research on practical engineering applications is lacking, further comprehensive and in-depth research is needed to promote the safe and reliable application and popularization of photovoltaic building integration.

Keywords: Building integrated photovoltaics; mechanical properties; solar cells; FRP sandwich panel

1 Introduction

Energy is the material basis for human survival and social progress [1,2]. Energy security issues have received increasing attention since the energy crisis in 1973 and have been discussed many times since being listed as the first issue at the 2006 G8 Summit [3]. The development of renewable energy is a fundamental way to achieve sustainable development [4,5]. According to energy consumption data in 2008, building energy consumption accounts for 40% of the world's total energy consumption and thus produces more than 30% of carbon dioxide emissions, exceeding the proportions of industrial and transportation energy consumption [6,7].

In the building energy consumption area, the use of HVAC (heating, ventilation and air conditioning) is the main way to meet increasing residential comfort requirements and accounts for the vast majority of energy consumption, 50% in developed countries [8] and more than 60% in China [9]. Therefore, reducing the energy consumption of the HVAC system is the key to reducing building energy consumption and is an effective way to deal with the global energy crisis [10].

Air pollution is another negative effect of energy problems. The rapid industrialization and urbanization of developing countries have caused atmospheric pollution that many developed countries have previously experienced [11]. Atmospheric pollution is mainly dominated by atmospheric particles.

Epidemiological studies have shown that significant correlations exist between atmospheric granules in urban areas and the number of daily deaths and hospitalizations due to cardiopulmonary disease [12,14].

An effective way to control air pollution is to improve the energy structure and develop green renewable energy [15,16].

Renewable energy mainly refers to solar energy, wind energy, tidal energy, biomass energy and so on [4,17], while green energy refers to energy whose production and consumption release no pollution or little pollution to the ecological environment, including renewable energy [18]. As a green renewable energy source, solar energy has received widespread attention from all over the world [19,20,21]. Solar energy is more accessible to each house with the techniques of the photovoltaics and solar heating. It is not necessary to build specific structures like wind farms or hydroelectric dams. China, with rich solar energy resources, is no exception [22]. The annual sunshine duration is more than 2000 hours, and the amount of radiation is higher than 5×10^6 kJ/(m^2a) in most areas of China (approximately 2/3) [23]. With energy depletion and increasing pollution, the development and utilization of solar energy resources have become a top priority.

Combining solar photovoltaic systems with buildings to realize building integrated photovoltaics (BIPV) [24], which can use green renewable solar energy to generate other energy for buildings, is one of the most important areas of photovoltaic applications [25,26]. The use of solar energy resources can provide hot water and electricity for operation of an HVAC system, broadening the sources of energy. Additionally, improving the thermal insulation performance of a building can reduce the use of the HVAC system and economize the building energy. This approach can relieve the energy pressure to ensure safety and sustainable development.

At present, studies on BIPV focus on improving the photoelectric conversion efficiency (PCE) [27,28,29], reducing costs [30,31], optimizing integration methods [32,33] and promoting applications [34]. However, few studies on the mechanical properties of BIPV have been performed. Due to the complex load conditions in the whole life cycle of BIPV, good mechanical properties are the basic premise and requirement for ensuring the safety of buildings and the proper functioning of photovoltaic systems. Therefore, this paper reviews the related research on the mechanical properties of BIPV at home and abroad and carries out related discussions.

2 Traditional building integrated photovoltaics

BIPV is a building system that combines solar photovoltaic systems with buildings, in which photovoltaic arrays are arranged on the sun surfaces of buildings to generate electricity [35]. According to the degree of integration, BIPV can be classified into two types: the installation type and the building material type [36].

The installation type involves attaching the photovoltaic system to the surface of the building. This type has a low degree of integration, which may adversely affect the waterproof effect, appearance and mechanical properties of the building. At present, this type is mostly utilized for photovoltaic renovation projects of completed buildings. For example, although the Capital Museum of China was originally built without considering photovoltaic design, BIPV was realized in 2008 without changing the exterior appearance of the building by bonding amorphous flexible solar panels to the roof panels [37].

The building material type involves packaging solar panels with building materials such as tiles, curtain walls, and wall panels. This type is designed and constructed at the same time as the building, thus has a high degree of integration, and can achieve large-scale production, which makes it the main development direction of BIPV in the future [38,39]. The first BIPV project, the Pompeu Fabra Library, was completed in 1996 using special glass curtain walls in the south facade and roof to achieve BIPV [40]. A similar approach was also used for the Berlin Central Station to integrate solar cells into the glass system of the roofs (Fig. 1) [41].

However, in the above two types of BIPV, the solar cells in the building may be subjected to a load from the building during operation, and the mechanical-photovoltaic properties of solar cells directly affect the power generation efficiency and stability of the photovoltaic system. Therefore, to deeply explore the mechanical properties of BIPV, the mechanical properties of solar cells and their application methods must be understood.

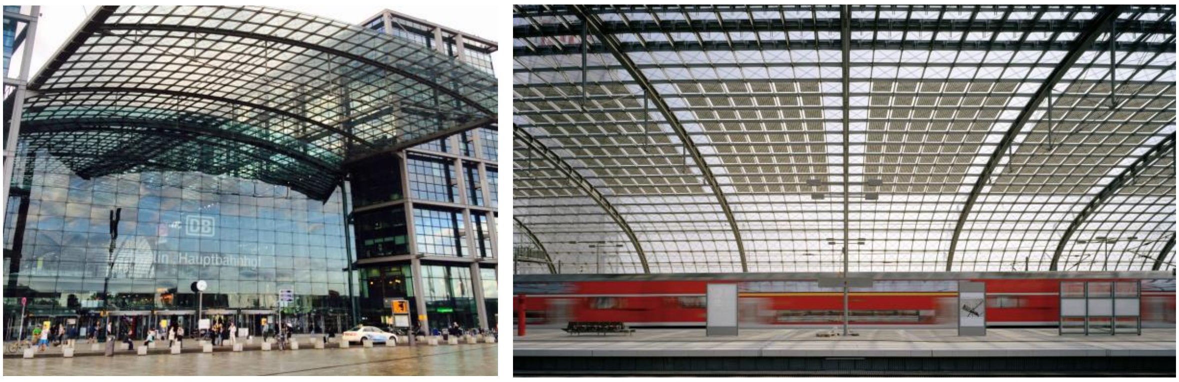

Fig. 1. Berlin central station with solar roofs [41].

2.1 Categories and mechanical properties of solar cells

In 1839, a French physicist, E. Becquerel, observed the photovoltaic effect of liquids [36]. Since then, people began to study solar cells. In 1876, Adams and Day [42] observed similar phenomena in solid selenium. In 1883, an American electrician, C. E. Fritts, built the first selenium solar cell. Until 1954, researchers at Bell Labs, Chapin et al. [43] produced monocrystalline silicon solar cells with commercial prospects, but the conversion efficiency was only 6%. Since then, solar cells have been rapidly developed, from the first generation of solar cells represented by crystalline silicon cells to the second generation of solar cells represented by thin film cells, while the third generation of solar cells based on nanotechnology is being studied [44]. The solar cells currently widely used in photovoltaic buildings are shown in Fig. 2. Their characteristics are also listed in Table 1 [45,55].

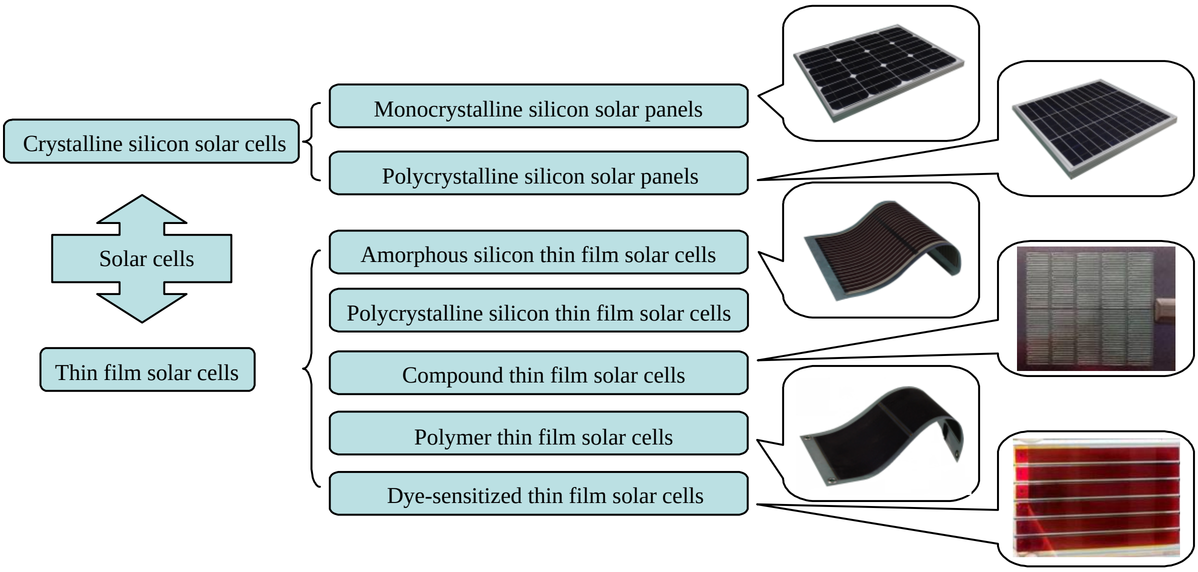

Fig. 2. Commonly used solar cells.

Table 1 shows that the crystalline silicon system has the highest conversion efficiency and most stable operation condition [46], but its high material cost and complicated process lead to higher manufacturing costs and a longer energy recovery period [49]. However, this system is still the leading product in the market, with a global market share of 90% in 2012 [50], based on the maturity and in-depth research of silicon-based solar products. Due to the Shockley-Queisser ultimate efficiency (32.8%) of existing silicon-based solar cells [28], the development of compound, polymer and dye-sensitized solar cells has been valued, while third generation nanoscale solar cells are being studied with the aim of breaking through this ultimate efficiency. The amount of silicon material used in these cells is greatly reduced or completely replaced with other inexpensive materials, resulting in a lower cost, but these cells face the dilemma of a low conversion efficiency for now.

At present, the conversion efficiency of compound solar cells is relatively high, especially for copper indium gallium diselenide (CIGS) thin film solar cells with more than 20% conversion efficiency

[45], but the materials contain rare elements, such as gallium and indium, and toxic elements, such as antimony and cadmium. Therefore, safety and environmental problems need to be paid extra attention to during production, operation and recycling [54]. Polymer solar cells, also known as organic solar cells, have a lower cost and a better flexibility but mainly face the problem of a low conversion efficiency [53,56]. Dye-sensitized solar cells, based on nanotechnology, are an intermediate technology between second generation and third generation solar cells. These cells have a low cost, good absorption of low light and good stability at high temperature, but their whole service life needs to be further improved [45,55,57,58].

Table 1. Comparison of commonly used solar cells in BIPV

Categories	Name	Conversion Efficiency	Stability	Manufacture	Cost	Mechanical Properties
Crystalline silicon system	Monocrystalline silicon solar panel [46,49,50]	17%-26.7% [49,50]	Most stable	Complicated	Expensive	Inflexible and brittle
	Polycrystalline silicon solar panel [48,50]	16.3%-21.9% [48,50,52]	Stable	A little complicated	A little expensive	
Thin film system	Amorphous silicon thin film solar cell [47,50]	4.6%-10.1% [47,50,52]	Unstable	Simple	Low	Brittle rigid film, bendable flexible film
	Polycrystalline silicon thin film solar cell [45,50]	12%-17% [45,50]	Stable	Simple	Low	
	Compound thin film solar cell [45,50,54]	10%-23% [45,50,54]	Stable	Simple	Inexpensive	
	Polymer thin film solar cell [50,51,53]	8.3%-10% [50,51,53]	Stable	Simple	Low	
	Dye-sensitized thin film solar cell [45,50,55]	8%-12.3% [45,50,55]	Stable	Simple	Low	

In terms of mechanical properties, since crystalline silicon solar cells and rigid thin film solar cells are generally packaged in glass, they have poor flexibility, a small deformation capacity under stress and poor adaptability to irregular surfaces. Flexible thin film solar cells, combining flexible thin films with functional layers (silicon, brittle at normal temperature [59], or other materials), can exhibit significantly improved deformation abilities and excellent mechanical properties [60]. Moreover, these cells can be easily, naturally and beautifully integrated into nonlinear buildings.

2.2 Applications and load conditions of solar cells

In BIPV, the photovoltaic arrays are reasonably arranged on the building surface, which can not only realize the self-generation ability but also create technological beauty. Different arrangements may result in quite different load conditions for the solar cells. Once a solar cell is damaged, the efficiency of the photovoltaic system will be directly affected. The damage to a solar cell is generally irreversible, so the function restorability of BIPV is challenged. As shown in Table 2, by analyzing the application of solar cells and the load conditions that may appear during normal operation [33,34,61,62,63,64] the critical load state should be clarified and considered during design and installation to ensure the normal operation of the solar cells.

As shown in Table 2, the applications of solar cells in photovoltaic buildings involve the various sun surfaces of the building. Different application methods have different effects on the design of building structures, and the load conditions during the working processes are different. A reasonable arrangement of the positions and inclinations of the solar cells can maximize the comprehensive utilization of solar energy and simultaneously create architectural aesthetics. Therefore, while focusing on improving the working efficiency of the photovoltaic system, different application cases must adopt corresponding methods for mechanical analysis to ensure the safe and efficient operation of the BIPV system. The high efficiency and outstanding appearance of the system are based on the safety and reliability of the structures and components.

Table 2. Application methods and load conditions of solar cells for photovoltaic buildings

Application	Typical cases	Influence on the design of building structures	Load conditions
Roofs [33,34,61,62,63,64]	Solar tiles Solar brackets Solar glasses	Roof loads increase	Wind loads, snow loads, impact loads, temperature effects, earthquake effects
Walls [33,34,62,63,64]	Solar curtain walls Solar brackets Solar sandwich walls	Wall loads increase	Wind loads, temperature effects, earthquake effects
Functional components [33,62,63,64]	Sun breakers Solar canopies Solar sunroofs	Local loads increase	Wind loads, snow loads, temperature effects, earthquake effects
Exterior [33,62]	Solar shutters Solar balconies Solar fences	Local loads increase	Wind loads, temperature loads, earthquake loads

3 Proposed new form of BIPV

By analyzing the mechanical properties and load conditions of different types of solar cells, it is proposed to attach or embed a flexible thin film solar cell to or in the surface of a fiber-reinforced polymer (FRP) sandwich curved panel to create a new functional structure integrated with a solar cover [65], as shown in Fig. 3. The attached solar cell is at less level of the integrity, but shares the advantages of easy handling and replacement. The embedded solar cell is helpful to improve the integrity and the strength of the structure, but manufacturing process is more complicate. The resin for the embedded solar cell should be carefully selected to ensure the light transmission.

FRP has great advantages in nonlinear parametric design and convenient construction [66]. As shown in Fig. 3, the inner and outer FRP skins mainly provide bending capacity, and the sandwich layer mainly provides shear capacity. In this literature, glass fiber-reinforced polymer (GFRP) is adopted as the sandwich panel skins, and polyurethane foam is utilized as the sandwich layer. On the one hand, FRP is lightweight and high strength; on the other hand, the polyurethane foam has excellent thermal insulation performance. This structure can meet the structural and thermal requirements of buildings and eventually achieve the purpose of reducing energy consumption.

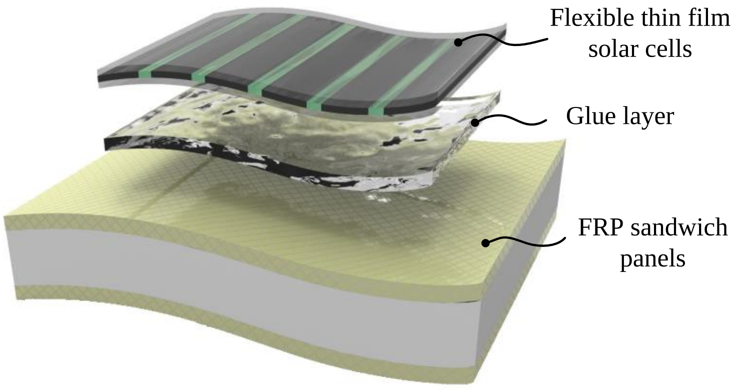

Fig. 3. Proposed new form of BIPV.

In addition, the FRP sandwich curved panels have excellent designability in the application to nonlinear buildings. However, irregular buildings set higher requirements on photovoltaic buildings. The function of power generation must be realized without damaging the aesthetics of the building itself. Section 2.1 shows that perfectly fitting crystalline silicon solar cells and rigid thin film solar cells with the irregular surfaces of nonlinear structures is difficult, while flexible thin film solar cells can meet the bonding requirements and absorb solar energy from multiple directions and over long durations. With convenient construction and low cost, flexible thin film solar cells are an important aspect of the future application of nonlinear photovoltaic buildings.

The flexible thin film solar cells are attached to or embedded in the FRP sandwich curved structures of photovoltaic buildings, combining the functions of photovoltaic power generation, heat preservation and noise reduction with the structural load. As a new structural form of BIPV, the interaction between the mechanical properties and the photovoltaic performances for this structure still needs to be discussed.

4 Research on the mechanical properties of building integrated photovoltaics

Previous studies on BIPV focused on improving the PCE, exploring integration methods and promoting applications. Only a few studies have been performed on the mechanical and mechanical-photovoltaic properties of BIPV, and studies of the continuous photovoltaic properties during loading are even fewer. Normally, the normal operation and improvement of photovoltaic systems are influenced by the load capacity, so relevant studies on the mechanical properties of BIPV should be carried out. In terms of mechanical properties and mechanical-photovoltaic properties, studies are mainly carried out on the following three aspects (as shown in Fig. 4): the mechanical properties of functional materials and packaging materials, the mechanical and mechanical-photovoltaic properties of solar cells, and the mechanical and mechanical-photovoltaic properties of BIPV components.

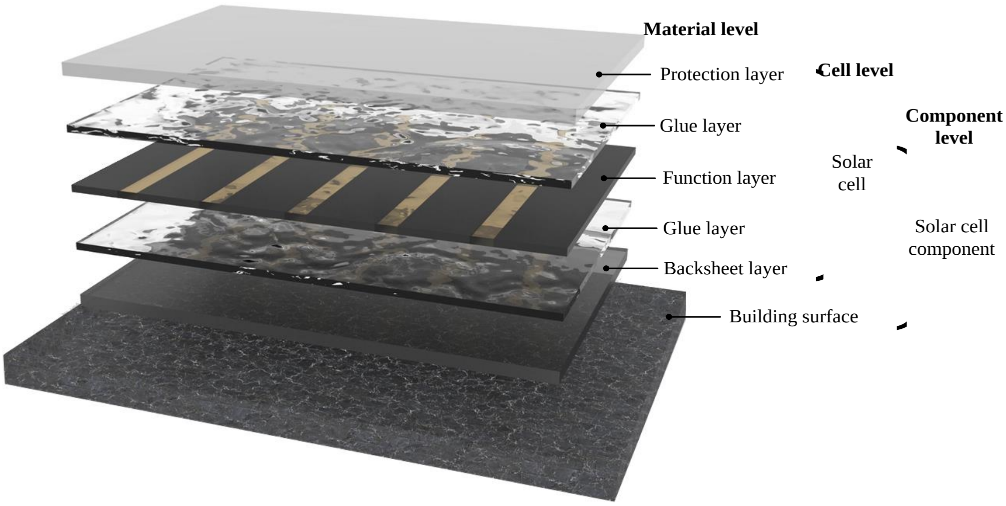

Fig. 4. Levels of research on BIPV.

4.1 Mechanical properties of solar cells at the material level

Researchers engaged in developing and manufacturing solar cells mainly concentrate on mechanical properties at the solar cell material level. As shown in Fig. 4, a general silicon solar cell is composed of a protection layer, glue layers, a functional layer, and a backsheet layer. The mechanical properties of the different materials affect the overall mechanical properties of the solar cells.

4.1.1 Mechanical properties of protection and backsheet layers

The roles of the protection and backsheet layers are to protect the functional layer of solar cells, improve its resistance to external adverse effects (such as impact, corrosion and abrasion), and ensure the normal operation of solar cells. Research on the mechanical properties of protection and backsheet layers has focused on two aspects: the material level and structural level. The former aspect involves the addition of other materials, thereby leading to better mechanical properties of the protection and backsheet layers themselves. The latter aspect involves improving the overall mechanical properties of the solar cells by using different materials or parameters for the protection and backsheet layers.

The influences of different component materials on the mechanical properties have been discussed, aiming to achieve better mechanical properties of protection and backsheet layers. By adding a low viscosity amine curing agent, an epoxy reactive diluent and a dibutyl phthalate (DBP) plasticizer to the epoxy resin potting compound and changing the ratio of each component, the tensile strength was varied from 8.84 to 141.65 MPa [67]. In addition, Zhu [68] studied the mechanical properties of a polyvinyl butyral (PVB) solar cell encapsulation film when adding plasticizer triethylene glycol di-2-ethylhexoate (3G8) and Al2O3 fillers. The results showed that when the plasticizer content was 35 phr, the mechanical properties were better, the tensile strength reached 23.2 MPa, and the elongation at break was 267%. When the Al2O3 amount was 70 phr, the comprehensive performance was better, and the tensile strength reached 21.4 MPa. The elongation at break was 265% [68]. Nambala et al. [69] studied the performances of ZnO and 5 at% Al-doped ZnO on glass and n-Si(111) backsheets by XRD, RBS, DRS and other techniques and found that the type of backsheets affected the crystallinity of the functional layers via interface effects, which thus affected the performance of the solar cells.

The use of different materials and parameters for the protection and backsheet layers can also achieve mechanical improvement of solar cells. Li [70] plated a single layer of SiO2 film and a single layer of Eu:SiO2 film on glass substrates. Their three-point bending tests showed that the bending strength of the sample after plating the single layer of SiO2 film was improved, while when the Eu:SiO2 film was plated and the Eu3+ ion doping amount was less than 0.5%, the bending strength was slightly increased. Then, DMA three-point bending experiments were performed to determine the flexural strengths of the multilayer films plated on solar cells. The flexural strength of the specimen plated with a nine-layer SiO2 film significantly increased from 114.44 MPa (unplated) to 159.22 MPa [70]. Haase et al. [71] studied the cracking conditions of solar cells attached to glass backsheets under bending conditions by four-point bending experiments and then proposed a theoretical formula. They also proved that the crack width of the solar cells without glass is 30% larger [71]. Gerthoffer et al. [72] studied flexible Cu(In,Ga)Se2 (CIGS) solar cells with ultrathin glass as the substrate and constructed a bending model of flexible solar cells. They verified by relevant experiments that a thin substrate with a low Young's modulus can reduce the strain of flexible solar cells under the bending state [72].

The protection and backsheet layers, as relatively independent solar cell structures, are generally utilized as the main mechanical structures of the solar cell, which can effectively avoid large strain and deformation of the functional layer of solar cells. For solar cells with rigid materials, such as glass as protection and backsheet layers, the protective effect is outstanding, but the shapes of the protection and backsheet layers must be specially designed, which greatly limits their practical applications. As for flexible solar cells with more flexibility, flexible materials utilized as protection and backsheet layers still need to be researched further.

4.1.2 Mechanical properties of glue layers

The glue layers connect the functional layer with the protection or backsheet layer to improve the cooperative properties. Zhang et al. [73] studied the performance of an ethylene vinyl acetate copolymer (EVA) glue film under a long-term UV aging test. The tensile strength of the sample degraded from 16 MPa to 0.6 MPa when the UV aging time increased to 1000 hours [73]. Kang et al. [74] found that the use of larger particle size or higher volume ratio polystyrene nanoparticles as a bonding layer could improve the mechanical properties of polymer solar cells. Due to the bonding properties and interfacial alteration ability of the polystyrene nanoparticles, the bonding energy could be increased by approximately 1.5 times, thereby increasing the critical cracking strain in the functional layer from 40% to 60% [74].

Currently, most glue layer materials are common adhesive materials with high light transmittance. Research on the mechanical properties of the adhesive material itself is relatively mature, but research on the interaction of the glue layers in solar cells still needs to be carried out.

4.1.3 Mechanical properties of the functional layer

The functional layer of solar cells is fabricated by attaching a photoelectric conversion material to a substrate material via a specific process. Its mechanical properties are basically determined by the photoelectric conversion material and the substrate material. The mechanical properties are researched by two main methods, experimental research and finite element analysis.

The tests used in the experimental research mainly include the three-point bending test, four-point bending test, nanoindentation test, and biaxial bending test [75]. The three-point bending test has been widely utilized because it is simple and easy to operate and can comprehensively reflect the mechanical properties of the functional layers of solar cells. Wang [76] used a three-point bending test to determine the fracture strength of silicon material and studied the effects of different wire cutting methods, germanium doping and grain boundaries on the characteristic rupture strength of monocrystalline silicon. The results revealed that the characteristic rupture strength of monocrystalline silicon increased from 114.5 MPa (standard line cutting) to 165.7 MPa when using diamond wire cutting. Moreover, when monocrystalline silicon was doped with germanium, the characteristic rupture strength after eliminating cutting damage was 396.2 MPa, compared with 353.9 MPa in undoped silicon. Additionally, after the grain boundaries were corroded and cutting damage was eliminated, the rupture strength of the polycrystalline silicon increased from 120.5 MPa to 491.8 MPa [76]. Celotti et al. [77] investigated the mechanical properties of ceramic mullite substrates produced by dry pressing in low-cost solar cells. After comparing them with solar cells fabricated by complex processes, they found that such substrates could exhibit a large elastic deformation. The elastic modulus was approximately 70-90 GPa, as measured by the resonance method, and the tensile strength was 35-70 MPa, as tested by the three-point bending test [77].

As for the four-point bending test, the test piece has a pure bending zone, which is beneficial to the analysis of the variables. Popovich et al. [78,79] studied the factors affecting the mechanical properties of polycrystalline silicon solar cells by four-point bending tests. The test results showed that defects at the edge can greatly improve the bending strength (from 155 MPa to 234 MPa). Different crystal modes resulted in quite different bending strengths (178-273 MPa). The bending strength also varied with different aluminized layers [78,79]. Using a series of tensile tests and two-point rotation tests, Dauzou et al. [80] found that the rupture strain and the functional failure strain of AZO (aluminum electrode) solar cells were both lower than those of ZTO (zinc electrode) solar cells. Furthermore, attaching a metal grid to the substrate can increase the functional failure strain by 8-10% [80].

The nanoindentation technique can be used to directly obtain the mechanical properties of a film material without separating the film and the substrate material, which can realize nanometer-scale measurement. Zbib et al. [81] found that the elastic modulus of polycrystalline silicon solar cell particles processed by a fluidized bed reactor was approximately 160 GPa according to the nanoindentation technique. Abib et al. [82] demonstrated the mechanical properties of each layer of CIGS solar cells using the nanoindentation technique combined with the JH model. They found that the Mo layer had the highest hardness and stiffness, 9.7 GPa and 185 GPa, respectively. The hardness and stiffness of the CIGS layer were only 3 GPa and 58 GPa [82]. Jin et al. [83] measured the mechanical properties of gallium arsenide crystals used in solar cells by the nanoindentation technique. The results showed that the Vickers hardness decreased nonlinearly from 5.59 GPa to 5.03 GPa with increasing indentation force, and the fracture toughness was also nonlinearly related to the applied indentation force [83]. Guo [84] studied the mechanical properties of nanosilicon films prepared at a high hydrogen dilution ratio using the nanoindentation technique. Their studies showed that the elastic modulus of the film decreased with increasing indentation depth and increased with increasing hydrogen dilution ratio within a certain range. These authors also determined that the maximum elastic modulus can reach 126.9 GPa [84].

In addition, the biaxial bending test is also a commonly used test method. Munzer et al. [85] measured the bending strength of single crystal silicon sheets by biaxial bending tests. The test results showed that the bending strength of the single crystal silicon film was related to the thickness and surface roughness of the sheet. Thicker or finer films had better bending strength and lower deflection [85]. Popoola et al. [86] studied the mechanical tolerance and stability of flexible perovskite solar cells and found that microcracks in TCO-film substrates lead to poor performance during biaxial bending tests. Different deposition methods and device structures greatly affect the mechanical-photovoltaic properties [86]. Jia et al. [87] developed new perovskite solar cells on flexible mica substrates, which retained more than 91.7% of the original PCE after 5000 cycles of large deformation bending.

When finite element analysis is applied, the selection of units, the establishment of models, the division of grids, and the application of boundary conditions all affect the accuracy and precision of the analysis. Zhan [88] used the finite element method to calculate the bending stress of monocrystalline silicon solar cells subjected to bending moments. By changing the ratio of the monocrystalline silicon pyramid dimensions to the thickness of the base plate and the transition radius between the pyramids, the influences of these two variables were studied using ANSYS software in two-dimensional and three-dimensional cases [88].

In brief, research on the mechanical properties of the functional layers of solar cells is concentrated on different photoelectric conversion materials and substrate materials. Bending experiments are widely utilized in the experimental studies, but finite element models are seldom used for analysis and research, mainly due to the complex functional layer structure of solar cells. Many factors affect the computation results, which makes obtaining accurate results difficult.

4.2 Mechanical properties of solar cells at the cell level

As shown in Fig. 4, solar cells are composed of functional, protection, backsheet and glue layers. The macroscopic mechanical properties of the solar cell itself can be obtained through experiments, and accurate analyses and finite element simulations can be performed according to the theory of the composite material.

4.2.1 Experimental research

The mechanical properties of solar cells determine the mechanical behavior during normal operation. According to investigations, the damage caused in solar cells generally includes excessive bending and tensile damage. Therefore, the bending test and the tensile test are usually utilized to observe the physical phenomena and mechanical failure of solar cells.

Regarding the flexible organic solar films produced by gravure printing, Cho et al. [89] performed round-axis bending tests, tensile tests, torsion tests and bending fatigue tests to evaluate the flexibility. The test results showed that the flexibility was quite outstanding during the bending tests, and the resistance almost did not change when the radius of curvature was reduced to 10 mm. The 2000 cycle bending fatigue test had little influence on the resistance. When the strain of the substrate reached 4% during the tensile tests, the resistance changed slightly, and no cracking or delamination occurred. When the torsion angle was within 40 degrees, the resistance remained almost the same [89]. Iii et al. [90] tested organic solar cells via bending fatigue tests and torsional fatigue tests. The P3HT and PEDOT:PSS layers of the organic solar cell began to delaminate after 5,000 to 8000 bending cycles, and all solar cells were completely broken after 4000 cycles of twisting. These authors proposed that the organic solar cells used in the experiments can withstand conventional deformation, but for use in solar blankets, solar wearable devices and other complex circumstances, the toughness of the backsheets and sealing materials need to be improved [90]. Sander et al. [91] studied the cracking behavior of silicon solar cells by four-point bending tests and finite element simulations. The results showed that the cracking load parallel to the solar strips was less than the cracking load perpendicular to the solar strips, which provided a basis for optimizing solar cell structures to reduce breakage [91]. Kaule et al. [92] also combined four-point bending tests with finite element simulations to study the influence of the loading direction and the solar strip direction on the mechanical behavior of silicon solar cells. The results showed that a reasonable loading direction can improve the loading capacity [92]. Chen et al. [93] measured the tensile stress-strain curves of whole organic thin film solar cells and of each layer by conducting tensile tests. The results showed that the elongation at break of the electrode material was quite low (0.2%), which limited the use of the solar cells. In contrast, the protection film, the photovoltaic reaction layer and the backsheet material had a certain flexibility because of their good mechanical properties. The maximum stress of the solar cells during the overall tensile tests was 66 MPa, and the elongation at break was 34% [93,94]. For amorphous silicon films prepared on flexible polyimide film substrates, Ding et al. [60] measured the tensile strength of the polyimide film by film tensile tests and then performed bending and tensile tests under a scanning electron microscope. The bending test results showed that the amorphous silicon film of the flexible substrate had excellent flexibility and could maintain a good elastic deformation ability under the curvature radius of 5 mm. The tensile test results showed that the amorphous silicon thin film of the flexible substrate had a tensile strength of 1.45 GPa and an elastic strain of 0.17%; thus, it can be attached to various curved surfaces and subjected to large stresses [60]. Zhou and Luo [95] measured the mechanical parameters and output voltage of flexible thin film solar cells by tensile experiments to analyze the mechanical-photovoltaic properties. The experimental results showed that the tensile strength (57.25 MPa) and elastic modulus (3.65 GPa) of the flexible thin film solar cells parallel to the solar strips were much higher than the tensile strength (26.5 MPa) and elastic modulus (2.72 GPa) perpendicular to solar strips, and the damages were quite different when loading in different directions [95,96].

Furthermore, some researchers have also tested the photovoltaic properties of solar cells during loading experiments considering that the mechanical-photovoltaic properties determine the longevity of the cells in engineering applications. They were eager to determine the critical mechanical failure state of solar cells. Suo et al. [97] performed bending tests on flexible thin film solar cells, bending them around circular axes with different diameters. The results showed that the photovoltaic properties degraded when the tensile strain reached 0.4% or the compression strain reached 1.3% [97]. Jones et al. [98] carried out round-axis bending tests to analyze the influence of mechanical strain on the photovoltaic properties of flexible triple junction amorphous silicon solar cells. The results showed that when the compressive or tensile strain reached 0.2%, the solar cell began to show plastic deformation. When the compressive strain was increased to 1.7%, the photovoltaic performance was hardly degraded, while the photovoltaic performance began to degrade when the tensile strain reached 0.75% [98]. Kim et al. [99] found that flexible polymer solar cells with silver as the electrodes still maintained 70% of the initial PCE after 500 bending cycles, while flexible polymer solar cells with indium tin oxide as the electrode failed to work after 500 bending cycles [99]. Schulte-Huxel et al. [100] used the laser welding technique to assemble crystalline silicon solar cells, and they studied the effects of the pulse energy and aluminum substrate thickness on the overall performance of the solar cells. The results showed that only when the thickness of the aluminum substrates was in a certain range could the maximum peel strength be obtained, and the higher the pulse energy was, the higher the peel strength (up to 303 kPa) [100]. Lee et al. [101] applied the electrochemical mechanical polishing (ECMP) technique to process 430 stainless steel substrates of flexible amorphous silicon solar cells and found that the resulting smooth substrates and plating of Cr2O3 and Fe2O3 changed the resistivity. At the same time, the fill factor (FF) of the solar cells increased from 0.45 to 0.6 [101]. Antartis and Chasiotis [102] bonded amorphous silicon thin film solar cells to carbon fiber backsheets and tested their residual stress and mechanical-photovoltaic properties under tension. The test results showed that the residual stress in amorphous silicon was approximately 466 MPa (compressive stress); when the tensile strain reached 0.9%, the photovoltaic properties of the solar cells began to degrade [102]. Kim and Cheong [103] obtained the current-voltage curves of monocrystalline silicon solar cells with a fiber composite as the backsheets through tensile tests. The test results showed that as the tensile strain increased, cracks appeared on the surface and in the interior of the solar cells and then expanded, eventually resulting in a reduction in the power generation efficiency [103]. Pathirane and Wong [104] performed different degrees of bending tests on amorphous silicon thin film cells with composite zinc oxide nanowires. The short-circuit currents of the concave cells increased by 15% and the currents of the convex cells decreased by 12% at a curvature radius of 38 mm. The authors attributed these results to the orientation of the nanowires during bending, which changed the reflectivity and absorptivity of the cells [104]. Sibiński and Znajdek [105] found that the efficiency of commercial modules contacted by ITO dropped to 50% of the initial value after 15000 bending cycles around a 25 mm cylinder because of microcracks in the TCO and active layers of the cell. Dai et al. [106] applied tensile strains on amorphous silicon and organic PV cells and determined that they degraded at tensile stains of 1.51% and 1.46% considering the open-circuit voltage and short-circuit current.

4.2.2 Theoretical research

Precise modeling and analysis of solar cells are important parts of the current mechanical analysis procedure. Dietrich et al. [107] simulated crystalline silicon solar cells fabricated by a potting process through finite element software. In the parameter study, the effects of temperature cycling on the thermodynamic behavior of the solar cells and the stress distribution after cooling and operation were analyzed. In addition, the mechanical properties were investigated by applying uniform loads. The results showed that the stiffness of the potting compound greatly influenced the thermodynamic properties and stress distribution, and the solar sheets controlled the overall deformation. On this basis, these researchers established a simplified finite element model and used the Weibull distribution probability theory method to calculate the failure probability of solar cells for different integration modes, frame sections and potting compounds. The results showed that the integration mode and frame section under different loads should change. The potting compound affected the basic mechanical mode of the solar cells. When the glue stiffness was large, the solar cells tended to show the mechanical behavior of the sandwich panels, while when the stiffness was small, the interlaminar shear deformation of the solar cells was more significant [108]. In addition, the finite element results were compared with four-point bending test results focusing on the effects of different loading rates and cell spacings. The test results showed that the solar cell stiffness increased at high loading rates, and the fracture probability increased when reducing the cell spacing [93]. These authors also verified the finite element results and performed four-point bending experiments under different loading directions and found that the loading directions of solar cells affected the failure probability; loading parallel to the solar cell strips had less influence on the metallization layout than loading in the vertical direction [109]. Thakur et al. [110] established a finite element model of crystalline silicon solar cells to determine the influence of the material thickness and colloidal elastic modulus on the stress of silicon materials under temperature changes, and they gave the corresponding parameters for reducing the stress of silicon materials [110]. Liu [111] analyzed the mechanical properties of rigid solar panels bonded with a cementing agent or glue strips under a uniform load using ANSYS finite element software. The analysis results showed that different bonding methods significantly affected the stress of the joints. When the cementing agent was utilized, the deformation of the solar panel was large, but the stress of the glue layer was small. The behavior was the opposite when the glue strip was utilized [111]. To realize the storage of as many flexible monocrystalline silicon solar cells as possible in a limited space and restore the initial state after the constraint is released, Fan [112] simulated the buckling behavior of structures using the ABAQUS finite element software. Furthermore, they analyzed the buckling law of flexible solar cells with a metal or a polymer as the substrate by adjusting the buckling mode, substrate thickness and film thickness. This study showed that the compressive strain-amplitude curves of the structures were mainly affected by the buckling mode, and rupture of the single crystal silicon solar cells was the primary failure mode [112].

In the experiments and modeling studies above, some foundations for the tensile and bending tests of flexible solar cells can be found, but we mainly concentrate on crystalline silicon thin film solar cells, amorphous silicon thin film solar cells and other traditional solar cell types. The related test is relatively simple, aiming for damaging only a single loaded solar cell. Moreover, little research on the durability of solar cells over the life cycle has been performed, and the relevant mechanical-photovoltaic data under repeated load conditions are lacking. At the same time, cases are found where the corresponding evaluation criteria are not uniform. For example, different papers use the internal resistance, cracking stress, FF, voltage, etc. as the evaluation criteria and obtain their own respective conclusions. All of these issues have hampered achieving uniformity of the mechanical properties of solar cells, thereby reducing the reliability of solar cells and hindering the further development of solar cell applications to some extent.

4.3 Mechanical properties of solar cells at the component level

Integrating solar cells with buildings will ultimately achieve BIPV. For the two types of BIPV, the installation type and the building material type, separate research must be carried out because of the different stress conditions.

4.3.1 Mechanical properties of the installation type

For the installation type, the solar energy system is attached to the surface of the building. Therefore, in addition to ensuring the good mechanical properties of the solar cells, the bearing capacities of the connecting nodes and the mechanical properties of the original building must also be considered. Xu et al. [113] developed embedded modular photovoltaic integrated components by investigating the integration types of existing photovoltaic systems and steel structures, and they tested the mechanical properties and mechanical-photovoltaic parameters by conducting mechanical tests and mechanical-photovoltaic coupling tests. The test results showed that the mechanical properties of the PV module (maximum tensile stress of 0.59 MPa and maximum compressive stress of 11.35 MPa) can meet the bearing capacity requirements, and the power was reduced to 4.65% after loading, which meets the requirements of the specification [113,114]. Yang [115] proposed methods for analyzing the mechanical properties of photovoltaic glass components in curtain wall and roof-mounted components, including methods for calculating the maximum stress and deformation of photovoltaic glass components in a curtain wall under wind loads and earthquake loads and a test method for the impact resistance [115]. Yang [116] used ABAQUS software to analyze the stress state and deformation of frames and its joints under static loads, temperature loads and loads from the couplings supporting the photovoltaic roof composed of monocrystalline silicon solar cells [116]. Tian [117] applied a solar photovoltaic system to the exterior wall of buildings to study the influence of different building walls on the power generation efficiency of the photovoltaic system, the resulting temperature stress of the wall and the indoor thermal environment. The studies showed that the opacity of the photovoltaic modules reduced the internal temperature of the wall, by 0.58 ℃ on average, but the temperature distribution in the original wall was also changed such that the temperature tensile stress of the wall increased along the width of the wall [117].

According to previous research, the main problems of the installation type are the performance of the installed solar cells and the effects on the mechanics and thermal insulation of the original buildings. The related research is limited by the building structures, the exterior wall materials, and the influence of the support design. Therefore, the practical significance of the research results is small, and applying the results to other BIPV installation types is difficult.

4.3.2 Mechanical properties of the building material type

For the building material type, the solar cells are packaged in or pasted on the surfaces of the buildings. FRP and glass are usually chosen as the attached materials because of their unique mechanical advantages. Hence, the interface performance, temperature stress and processing technology need to be studied and discussed to ensure the normal operation of the solar energy system.

In experiments, Rion et al. [118,119] demonstrated that in the combined structure of polycrystalline silicon solar cells and CFRP sandwich panels (CFRP/core/CFRP), the solar panels would not be damaged even when the CFRP sandwich panels had large curvatures, and the solar cells could still work normally. Regarding the three types of GFRP sandwich flat panels, namely, panels with thin film solar cell skins, panels with rigid polycrystalline silicon solar cell skins and panels without covers, Keller et al. [120] exposed them to halogen lamps to study the temperature and compared the differences in the carrying capacities and damage situations. The results of the light test showed that the surface temperature of the sandwich panel increased rapidly under light illumination. In the thin film silicon solar cell skin GFRP sandwich flat panel, the temperature of the upper surface was almost 70 ℃, and that of the polycrystalline silicon solar cell almost reached 90 ℃. Despite the high temperature, the temperature stress in the material was quite small and remained below 10% of the material strength, and the structure of the composite was not destroyed. The results of the bending test showed that the solar cells in the different structures were not damaged when the load increased to the serviceability limit load. When the load was four times the serviceability limit load, the structure was degummed and destroyed [120]. Xia [121] and Zha et al. [122] proposed combining crystalline silicon solar panels with sandwich panels to form integrated solar panels. The outer surface of the integrated panel was a two-layer tempered glass-protected crystalline silicon solar panel, and the inner surface was a steel plate. The sandwich material could be made of polyurethane, rock wool or polystyrene foam. Since the PCE of crystalline silicon solar cells decrease as the temperature increases, a ventilation groove was provided between the outer surface of the solar cell and the core material. Then, mechanical analysis of the equivalent model of the panel was carried out according to the load specification and the curtain wall specification. Finally, finite element analysis of thermal and mechanical properties was carried out using ABAQUS finite element software. The analysis results showed that the use of tempered glass could increase the strength of the sandwich panel, and the panel had a good thermal insulation effect [121,122]. Dai et al. [123] bonded amorphous silicon PV solar cells to GFRP structural components by using different adhesive layers and determined that the ratio between the strains of the PV cell and the GFRP was controlled by the shear modulus and thickness of the adhesive and the elastic modulus, thickness and length of the PV cell based on the results of experimental, theoretical and FE methods. Xu et al. [124] glued a flexible thin film solar cell to a polyvinylidene fluoride (PVDF) architectural film and then carried out a tensile test on the composite solar module and simultaneously measured the photovoltaic property during stretching. The test results showed that the film was not damaged when the thin film solar cell was broken. The voltage output decreased more slowly compared with the separate flexible thin film solar cell. Finally, these authors proposed a formula for controlling the tensile stress of solar cells during normal operation for BIPV design [96,124].

In the integration of the building material type, the building surface is similar to the back sheet in the solar cell structure. The mechanical behavior of the building surface is not sensitive to the load conditions, which can effectively ensure the stress state of normal operation of the solar cells. The high degree of integration of the building surface material and the solar cell can realize a stable performance. In conclusion, the research results have promotion significance.

5 Discussions

Safety and reliability are always prerequisites for the design and use of buildings. To ensure the safety of photovoltaic buildings and promote the popularization of BIPV, thorough and systematic studies on the safety performance during the entire life cycle must be conducted. Different types of solar cells have large differences in applications and mechanical behaviors, which increase the difficulties in the current study of BIPV.

Due to the mature production process and equipment of silicon-based solar cells, despite the high processing cost, silicon-based solar cells still occupy the dominant position in the market. Among the flexible thin film solar cells, only compound solar cells and amorphous silicon solar cells have been relatively widely applied, and the other flexible thin film solar cells have not yet achieved large-scale production despite simpler processing and lower costs. Therefore, considering the development tendency of solar cells, flexible thin film solar cells will have more potential in BIPV, with the advantages of being flexible and lightweight, having a low-light capacity and a low temperature coefficient and so on.

Considering the complex market situation, the proposal of mechanical and photovoltaic evaluation parameters for all solar cells has become a top issue, such as the maximum stress or maximum strain level during normal operation. With these parameters, we can consider the loading conditions of solar cells in applications, especially in the design stage. In addition, the relevant performance analysis of the cyclic loading condition during long-term operation needs to be of more concern. The long-term abilities are quite important for solar cells, which can ensure the stable operation of the solar cells over the full life cycle.

As for BIPV, many integration methods for photovoltaic buildings have been developed. For the different integration methods, research on the corresponding mechanical properties must be conducted. For example, for the installation type of BIPV, more attention should be paid to the analysis of the mechanical properties of the solar, support and suspension systems and their mutual influence. For the building material type of BIPV, analysis of the mechanical characteristics of solar modules in buildings and selection of suitable solar cells and integration methods (embedded or pasted) are important.

At present, the macroscopic mechanical properties of solar cells are usually of more concern, whereas the mechanical properties at the material level tend to be ignored, which has slowed the development of BIPV. Only a few scholars have carried out related research on the mechanical properties of BIPV, but the existing research is relatively separate and tends to focus on the mechanical properties of solar cells themselves. The mechanical research areas at the component level, such as the mechanical-photovoltaic properties and thermal properties, and the structural level still need to be explored.

Therefore, to study the mechanical properties of BIPV from the perspective of engineering applications, in-depth research on the overall mechanical characteristics, photovoltaic characteristics and mechanical-photovoltaic coupling characteristics of solar cells must be conducted to ensure the normal and efficient operation of BIPV. For solar cells with complex loading conditions, finite element simulation analysis can be utilized to determine the control conditions and ensure the safety and reliability of the critical loading state.

Above all, with the popularization of BIPV, the urgency for further research on mechanical properties has gradually become prominent. In the future, through systematic and thorough research and analysis, standard specifications for related products, tests and engineering applications are expected to be established and corresponding simplified design formulas proposed as a reference for engineering design to guide and standardize the application of BIPV and ensure safety and reliability throughout the life cycle.

6 Conclusions

BIPV is an important approach to building energy conservation and an effective way to achieve a “zero energy building” or even a “negative energy building” [125,126,127]. A new form of photovoltaic building integration is proposed and the mechanical problems of BIPV from the material, cell and component levels are analyzed. After summarizing the existing research, some research recommendations are suggested as follows:

1) The types and models of solar cells should be especially considered in BIPV design. Different loading conditions in applications lead to quite different mechanical and photovoltaic behaviors, which should also be emphasized. The stress state of normal operation of the solar cells should be evaluated during the design stage.

2) A new form of BIPV is proposed, namely, the FRP sandwich curved panel covered with flexible thin film solar cells. This new form combines the functions of shape design, photovoltaic power generation, and heat preservation with the mechanical advantages, but the relationship between mechanical behavior and the photovoltaic properties still need to be examined.

3) The mechanical properties of BIPV are complicated when concerning different scales and levels. The relationships between properties and applications are determined at the material, cell and component levels. The mechanical damage is one of the reasons resulting in the degradation of power generation of solar cells.

4) Critical parameters showing mechanical and photovoltaic evaluation properties are still lacking in existing studies. Separate mechanical or photovoltaic parameters are not persuasive in BIPV applications. However, parameters such as the maximum stress or maximum strain level before solar cells show physical damage can be utilized in the design stages of applications, which can promote the safe and reliable application of BIPV.

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Conflicts of Interest

The authors declare no conflict of interest.

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