Review

Study of Technological Advancement and Challenges of Façade System for Sustainable Building: Current Design Practice

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Abstract: Currently, several façade systems exist to enable sustainable building design. The biggest challenges for façade designers are to identify new technology and effective, sustainable systems that enable high structural and sustainable performance while producing a good aesthetic. Therefore, this paper aims to review the performance of existing façade systems for sustainable building designs and their limitations. Among modern façade systems, Double Skin Façades (DSF) show promise for energy efficiency, indoor air quality, and aesthetics. However, they face challenges like sound transmission between floors, higher initial costs, and outer skin vibrations. Furthermore, adaptive façades gained popularity for their active methods of achieving energy performance and comfort benefits but encountered complexities in design and construction, demanding codes and standards. Green wall systems enhance air quality and aesthetics, while photovoltaic façade systems reduce electricity costs, but both systems face higher initial costs and maintenance challenges. The review indicates that to produce a sustainable building design, architects, engineers, and builders must consider a sustainable façade system that enables high energy efficiency, less cost, better occupant comfort, and fewer environmental impacts.

Keywords: double skin façades (DSF); adaptive façade systems; green wall systems; photovoltaic façades; sustainable façade materials

1. Introduction

Modern buildings in Australia contribute to 28% of annual greenhouse gas emissions and consume a significant amount of primary energy [1]. Furthermore, Australia is one of the world’s highest greenhouse gas emitters per capita [2]. This has led to the development of strategies and policies towards sustainable building in line with the Paris Agreement [1]. Over the past twenty years, the interest of building designers has focused on reducing the energy requirements of buildings. Efforts such as the AIA 2030 Commitment and the Department of Energy Building Technologies Program’s energy conservation initiatives have propelled the industry towards realising zero-energy building solutions in the future [3].

The façade, which is the skin of a building, plays a significant role in the building’s sustainability performance [4]. Moreover, it acts as a filter between indoor and outdoor environments, regulating temperatures, generating breezes, and filtering air and water to contribute to public health and energy conservation [5]. The earliest way of achieving the sustainability of building façades is by reducing the overall mass and orientation of major façades and roof surfaces [6]. Furthermore, in modern building envelopes, different approaches have been taken to minimise the energy requirements of the building systems [7,8]. A significant amount of energy can be saved in modern façades using natural ventilation [9,10], optimisation of daylight [11,12] generating solar and wind energy [13,14] using smart and adaptive devices [15,16], combining plants with façades [17,18] and using sustainable materials [19,20].
With the aid of building information modelling (BIM) and finite element analysis software, architects and façade engineers have enabled complex design capabilities [21]. Computer-aided design software can analyse and simulate façade design before construction. Building energy simulation (BES) tools like EnergyPlus, TRNSYS, IDA-ICE, and IES-VE can now be used to analyse the energy consumption of buildings throughout all the design stages [22,23]. Structural technology solutions and materials engineering advancements have led to the development of cable networks, cable structures, structural glass façades, space frames, and self-loading frameworks [24]. Furthermore, external shading devices, adjustable overhangs, and solar control glass reduce interior cooling loads and decrease building façade heat by up to 20% [25]. Reflective coatings and insulation material are used to improve energy efficiency, and thermoelectric modules can be integrated into façade systems along with PV material to generate electricity [24]. Technological advances, such as smart materials, wireless sensors, smart actuators, and microprocessors, have enabled façade designers to regulate real-time climatic factors such as light, temperature, and humidity in interior spaces, ensuring thermal and visual user satisfaction [26]. With all these technological advancements, new façade systems are developed to achieve a sustainable building with the required economic, social, and aesthetic features.

Double-skin and green wall façade systems have been developed mainly using passive energy-saving techniques, and adaptive and photovoltaic (PV) façade systems integrate a combination of both passive and active methods [27–30]. Specifically, double-skin façades (DSF) and green walls contribute to enhanced thermal insulation, improved indoor air quality achieved through natural ventilation and air filtration, and maintaining the acoustic performance of buildings [31,32]. A basic DSF has the potential to cut heating requirements by as much as 90% and cooling demands by up to 30% when compared with traditional building façades [33]. Adaptive façades have been designed to dynamically respond to various environmental factors, such as sunlight, temperature, and occupancy levels [34,35]. These systems possess the capability to autonomously regulate transparency, shading, and insulation properties, thereby reducing energy consumption by 20% within the buildings they encase [36,37]. Furthermore, PV façades have been predominantly engineered to generate electricity for buildings [38]. However, they also offer the added benefits of providing shading and assisting in the attainment of crucial sustainability parameters for building structures [39].

However, when implementing new technology in façade construction, it is important to note that several constraints and limitations exist. With recent advancements in high-rise building construction and a growing demand for innovative architectural designs, façade engineering has evolved into a complex engineering profession that requires daily technical analyses and adjustments [40]. To meet the evolving standards of sustainable building design, façade material elements and systems must adhere to these standards. One of the major limitations is the need for specialised expertise and skills in designing, installing, and maintaining these systems [41]. Additionally, façade technology may be more vulnerable to wear and tear than traditional materials, increasing maintenance and replacement costs over time [42]. Integrating complex systems such as lighting and shading can also pose challenges related to costly construction and expensive material usage [43]. These limitations have been discussed in this paper.

Given the historical evolution of façade engineering and the current considerations regarding sustainability and limitations, the need for a comprehensive review of the latest technological advancements and their impact on façade engineering practices is critical in guiding future sustainable building design [44]. Moreover, the rapid pace of technological advancements has led to the development of new façade systems and materials that require careful evaluation to ensure that they meet sustainability goals [45]. Hence, this study thoroughly examines the most recent technological advancements in façade engineering to comprehensively understand their implications for sustainable building design. By delving into these advancements, the study intends to provide valuable insights that can serve as guidance for architects and engineers in shaping the architecture of the future. In doing so,
it seeks to ensure that façade engineering practices stay aligned with contemporary sustainability objectives and continue to evolve and adapt to effectively address the multifaceted challenges posed by modern construction and environmental considerations.

2. Methodology

This study examined journal papers, articles, and books from several sources, including, but not limited to, Science Direct, ICE Virtual Library, ASCE Library, and Springer. Table 1 depicts the search string used in this investigation, where several topical aspects were examined. The keyword combinations shown in Table 1 interpret the required scope of content assessed in this study. The searches were restricted to publications between 2010 and 2023. This investigation focused more on the studies conducted in the Australian context. It is evident from this investigation that the source of most studies is Science Direct.

<table>
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<th>Keyword Combinations</th>
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<th>ICE</th>
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3. Basic Façade Types, Design Criteria & Material Selection

Types of façade systems vary based on climatic conditions, energy requirements, and architectural and construction needs (Table 2). Basic types of façades include masonry, profiled metal systems, small and large cladding panels, curtain walling, and window walling [46].
### Table 2. Type of Façades.

<table>
<thead>
<tr>
<th>Façades</th>
<th>Application</th>
<th>Properties</th>
<th>Construction Methods</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Masonry</strong></td>
<td></td>
<td>Economic and require minimum repair costs [46], withstand various weather conditions [48], Variety of textures, colours and patterns [49], and used for both load-bearing and non-load-bearing applications [46].</td>
<td>Composite construction method with individual units (bricks, stones) overlapping in horizontal layers bonded with mortar [46].</td>
<td>Bricks-Clay, Calcium Silicate, Concrete [46], Blocks-Concrete, Stone [49]</td>
</tr>
<tr>
<td>Small Cladding Panels</td>
<td>Installed on battens or studs spanning on structural columns [53]. Panels will be fixed only on the edges. Composite panels can be achieved with an insulation layer separating two cladding layers. Thermal movement between the panels should be allowed in joints [46].</td>
<td>Wider choice of features and colours [46], different profile shapes [50], lightweight compared with other Façades [51]. It is a relatively cheap form of cladding compared with others [52].</td>
<td>Installed on battens or studs spanning on structural columns [53]. Panels will be fixed only on the edges. Composite panels can be achieved with an insulation layer separating two cladding layers. Thermal movement between the panels should be allowed in joints [46].</td>
<td>Aluminium or galvanised steel single skins, double skin of metal sheeting with insulation, and composite metal panels with polyurethane or polyisocyanurate foams [46].</td>
</tr>
<tr>
<td>Brick Façade in Sunshine, Australia (Photo courtesy of D.F)</td>
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<td><strong>Profiled Metal Systems</strong></td>
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<tr>
<td>Colorbond Façade in Epping, Australia (Photo courtesy of D.F)</td>
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</table>
### Table 2. Cont.

<table>
<thead>
<tr>
<th>Façades</th>
<th>Application</th>
<th>Properties</th>
<th>Construction Methods</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Cladding Panels</td>
<td></td>
<td>Cost-effective and less maintenance requirements [54], lightweight and achieve complex colours or textures [55]. It can be used with sealed joints or as rainscreen panels.</td>
<td>The panels will be built on supporting rails with a backing wall. Panels will be fixed to the rails using screws, reverts or structural adhesive [46].</td>
<td>Fibre cement sheets including cellulose and glass fibres, fibre-reinforced calcium silicate, resin laminate, glass-reinforced polyester Aluminium and steel panels, polyethylene-coated composite aluminium panels, thin stone panels made of granites, marbles, hard limestones, tiles [46].</td>
</tr>
<tr>
<td>Fiber cement sheet Façade in Sunshine, Australia (Photo courtesy of D.F)</td>
<td>Commonly used in commercial structures [46].</td>
<td></td>
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</tr>
<tr>
<td>Large Cladding Panels</td>
<td></td>
<td>Panels have the strength to bridge between separate places on the main building structure panels [57]. Have higher acoustic performance [58].</td>
<td>Panels are typically supported by main structural members with brackets or cleats inserted into the panel [59]. Packing shims can be used to provide vertical adjustment, while horizontal adjustment will be achieved through adjustable bolts. Panel-to-panel connections are either weather sealed with wet applied sealants or left exposed [46].</td>
<td>Glass fibre-reinforced polyester, glass fibre-reinforced cement, composite metal panels and reinforced precast concrete panels [46].</td>
</tr>
<tr>
<td>GRC façade in Werribee, Australia (Photo courtesy of D.F)</td>
<td>Mainly in public and institutional buildings [56].</td>
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</table>
### Table 2. Cont.

<table>
<thead>
<tr>
<th>Façades</th>
<th>Application</th>
<th>Properties</th>
<th>Construction Methods</th>
<th>Materials</th>
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<tbody>
<tr>
<td><strong>Curtain Walling</strong></td>
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<tr>
<td>GRC façade in Werribee, Australia (Photo courtesy of D.F)</td>
<td>They are typically used in high-rise construction—shopping centres, office buildings and educational centres [60,61].</td>
<td>They are used in high-end commercial structures [46], Lightweight [62], smaller wall footprint [63], structural flexibility [64]</td>
<td>Panels are fixed to the metal framing and typically span between floors [65]. The curtain walls are supported with brackets fixed to the metal framing and the main structure [66]. Adjustments are typically provided in the brackets for vertical and horizontal movement [67].</td>
<td>Aluminium or steel framing, stone, glass, metal, or thin stone panels [68]</td>
</tr>
<tr>
<td><strong>Fully Supported Metal Sheeting</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Copper sheet façade in Christchurch, New Zealand</td>
<td>Normally used on prestige buildings [69].</td>
<td>Expensive [46], extremely durable façades [70].</td>
<td>Sheets are typically required to support plywood boards [46] entirely.</td>
<td>Copper and lead sheets [46].</td>
</tr>
</tbody>
</table>
From the systems in Table 2, curtain walling can be considered the most advanced system, which provides the required flexibility for designers and architects. This will help achieve higher performance requirements and aesthetic features. Curtain walls concentrate all essential protective shield functions of a building envelope in a lightweight, thin, impermeable, and sometimes vulnerable shell, often thinner than the respective load-bearing walls, and include individual components responsible for performing dedicated functions. Different types of curtain wall systems exist according to the assembly type, material, and connection methods [71].

The life cycle of the façade consists of 5 stages: design, construction, operation, rehabilitation, and demolition (Figure 1). Figure 1 also shows the necessary considerations in the design stage of the façade. The design stage of the façade can be divided into concept design and detailed design. During the concept design stage, the critical performance criteria, including thermal, acoustic, structural, fire, weather tightness, sustainable parameters, security, and buildability, are identified [72]. To achieve these criteria, architects research new façade systems and materials that align with their aesthetic requirements. When selecting a façade material, factors such as mechanical and chemical characteristics, technical properties, affordability, lifecycle cost, and availability should be considered [73]. Façade materials should perform optimally during their service life and function properly in their intended role [74]. The next step in the façade design process is the detailed façade design. In this stage, the performance requirements are refined and coordinated across different engineering disciplines to ensure compliance with planning and building regulations [75]. Moreover, the critical details of the façade interface are further developed, and the performance criteria are established [8].

![Figure 1. Building façade life cycle and necessary considerations in the façade design process [8].](image_url)

3.1. Critical Performance Parameters

The critical performance parameters of façade design can vary depending on the specific project requirements and goals. However, there are some standard performance parameters that architects and designers consider when designing façades. The following sub-section provides more information about the standard performance parameters.
3.1.1. Thermal Performance

The thermal performance of a building façade is an essential consideration in modern construction practices [76]. The properties of façade elements are primarily defined considering the temperature of the environment and building regulations for thermal insulation based on energy requirements [77]. A continuous thermal barrier across the building envelope can be considered the key to good thermal performance [78]. Where continuous insulation is impossible, the designers must focus on eliminating continuous conducting elements and using thermally broken systems [79]. Furthermore, the heat transfer coefficient of the façade materials and parameters such as building orientation, shading device, induced natural ventilation, and window-to-wall ratio can be considered as factors affecting the thermal performance of a building [80]. A person’s thermal comfort is influenced by psychological and physical factors. However, there’s a widely accepted temperature range where at least 80% of people feel comfortable and work efficiently. The Australian National Occupational Health and Safety Commission recommends 20 °C to 24 °C in winter with heavy clothing and 23 °C to 26 °C in summer with lighter attire for optimal comfort inside buildings [81].

3.1.2. Fire Performance

The early involvement of fire specialists in the design process has become essential for the façade’s fire resistance, as different building sections have their own requirements [82]. Around the world, highly combustible insulating materials are increasingly used to increase the energy efficiency of buildings, which can increase the risk of fire across the façade [83]. Although windproof membranes are often used to protect insulation, their usage is hazardous to fire safety and must be addressed [84]. After the Grenfell Tower fire in 2017, which spread through the façade, ultimately killing 72 people, it has been apparent that the new regulations about façade fire safety should be reviewed [85].

To prevent the spread of smoke through the façade’s interior space, the façade system can be complicated by using vertical and horizontal partitions to form compartments inside the gap [86]. Moreover, façade consultants and fire engineers are responsible for approving the façade materials and systems, considering compliance with the available fire regulations for a building.

3.1.3. Acoustic Performance

A building envelope must shield the internal conditions from external noises while preventing bothersome noise emissions from the building [87]. The Mass Law governs sound insulation, and the weakest element of the envelope controls the achieved noise reduction to external noise levels [88]. Those elements are usually windows, doors, walls, roofs, types of sealing, and slits and connections in the façade system [77]. Besides these factors, the designer needs to consider the façade shape and the high-performance components, such as overhangs and protrusions, in the reduction and absorption of sound energy outside the building envelope [89]. It is crucial to recognise acoustic failures to preserve a favourable acoustic atmosphere in the building. Standard sound insulation measurements are used to determine the amount of impact of different parameters affecting acoustical failures. In contrast, ultrasonic measurements enable quick and qualitative assessment that is very efficient in determining the exact position of the acoustic leak [90]. The Association of Australasian Acoustical Consultants (AAAC) Guideline for Commercial Building Acoustics 2011 recommends an interior design sound level of 40 dB for typical office rooms and public spaces.

3.1.4. Weather Tightness

The penetration of water through the building envelope can damage the exterior walls and reduce the performance of the building insulation layer. This can directly affect the health of building occupants and increase building maintenance costs [91]. To minimise future building costs related to weather tightness, correct secondary flashing system design
and details, air seals, sealants, and joint geometry are required [82]. Furthermore, to prevent the degradation of façade systems, surface seals and internal wall weather barriers must be maintained properly [92]. Performance mock-up tests and site water testing can be used to determine the weather-tightness of façade systems [84].

3.1.5. Structural Integrity

The façade must resist all the mechanical and environmental loads. Typically considered loadings are wind, rain, earthquake, and blast loading. To avoid failure, building façade members must support the weight of the façade and resist all expected and unexpected forces and movements [93]. Seismic loads on the façade can potentially impose in-plane loading and damage the system if adequate detailing is not provided [94]. The building movements must be considered at the very early stage of the façade design, as most of the façade systems are being developed with in-built movement capacities. Even with a safety factor in design, the façade’s or structure’s physical features may result in unexpected force directions and magnitudes, especially when using a façade material with a high thermal expansion coefficient in combination with stiff connections [95]. A detailed wind calculation report or a wind tunnel test can be used to design the façade more efficiently as the wind pressure changes according to the elevation, level, and location of a building. A wind tunnel test is recommended for buildings with complex geometrical shapes, as most design codes discuss only common shapes and have limitations.

The choice of façade systems is a critical consideration in architectural design, influenced by climatic conditions, energy demands, and construction requirements. This diversity is exemplified by various façade types, including masonry, profiled metal systems, small and large cladding panels, curtain walling, and window walling, each tailored to specific applications and offering distinct properties and construction methods. Among these, curtain walling emerges as a sophisticated system, affording designers the flexibility to meet high-performance standards while achieving aesthetic excellence. Moreover, the life cycle of a façade encompasses multiple stages, from design to demolition, with the design phase being divided into concept and detailed design. During this process, architects and designers must consider critical performance parameters such as thermal performance, fire safety, acoustic performance, weather tightness, and structural integrity to ensure the long-term functionality and safety of the façade. Ultimately, a comprehensive understanding of these parameters is indispensable for creating façades that seamlessly blend form and function, meeting the evolving needs of modern architecture.

4. Recent Technological Development

As elaborated in the previous sections, the façade is one of the most crucial elements in a building, without which the purpose of the building cannot be defined. Therefore, over the years, incorporating façade systems into buildings has evolved rapidly based on the aesthetic, geographical, cultural, technological, sustainability, and safety aspects [96]. By conducting timely reviews of these advancements, it is possible to understand the direction of these developments while identifying the areas that require more research and development [97]. It can be hypothesised that the façade systems will be designed entirely using durable but sustainable materials within the next hundred years because of the world’s impending energy crisis [98]. Many developed countries have proposed goals and policies for zero-energy buildings (ZEB) [99]. One main goal of ZEB is to use sustainable and environmentally friendly materials to achieve low embodied energy and support [100]. The components of modern buildings that contribute to sustainable performance are illustrated in Figure 2.
There are two ways of achieving energy savings in building façades—active and passive strategies [102]. The passive strategy mainly focused on building design (orientation, shading, and natural ventilation) and high-performance materials (insulation and glazing). The sustainable approach of naturally ventilated façades [9], green wall systems [103], and double-skin façades [104] was achieved through passive strategies. However, in some cases, more than passive strategies are needed to achieve energy efficiency goals, which requires implementing active strategies [105]. Passive strategies alone may not provide adequate thermal comfort in regions with extreme climate conditions, such as very hot summers or cold winters [105]. Furthermore, buildings located in areas with varying climates may face challenges in consistently optimising passive strategies. For instance, buildings in environments with significant temperature variations may need active strategies to overcome the high energy requirements [106]. Buildings with complex functions, such as laboratories, hospitals, or data centres, often have specialised requirements for temperature, humidity, and air quality that passive strategies alone cannot adequately address. Active methods mainly rely on mechanical or electrical systems to reduce energy consumption. These include high-performance HVAC systems, solar panels, smart control, devices and adaptive façades [107].

4.1. Energy Saving Façade Systems

The most important façade systems identified based on active and passive energy-saving strategies during the literature review process are discussed in the following sub-sections.

4.1.1. Double Skin Façades (DSF)

Double-skin façades (climate façades) were originally developed as a microclimate management technique, utilising the space between glass and the façade as a thermal buffer to slow heat exchange [108] (Figure 3). However, architects and designers are now using...
DSF strategies to create visually appealing designs that enhance the overall appearance of the building as well [109].

DSF is composed of two layers of materials separated by a gap. Usually, the outer layer consists of glass. The thickness of the gap can be varied from 0.2 m to 2 m [111]. Air movements in the gap can occur due to the surrounding wind and the pressure difference in the cavity. The pressure difference in the cavity occurs due to the thermal chimney effect caused by the difference in densities between warmer air inside and cooler air outside of the cavity [112]. The cavity depth, shading devices inside the cavities, outer skin glazing properties, type of building structure, and opening sizes are the parameters affecting the DSF performances [113].

DSF or climate façade can be used in new construction and rehabilitation [104]. The DSF can reduce the energy requirement for heating, cooling, and lighting, resulting in energy efficiency in buildings. According to the study by Pomponi et al. [33], simple DSF could reduce up to 90% of heating and 30% of cooling loads compared with conventional façades. Pomponi et al. [33] also show that using an operable shading device with DSF can reduce energy consumption. DSF provides better thermal insulation, reduces noise pollution, and improves air quality through natural ventilation [31]. Other than providing energy efficiency for buildings, DSF can improve the aesthetic value of the building by increasing its market value [114]. This is due to the use of transparent or translucent materials, which can create a sense of depth in the façade, creating a visual connection between the interior and exterior surfaces.

Fabrizio and colleagues investigated the influence of transparent double-skin façades on energy efficiency [115]. Their study revealed that incorporating photovoltaic modules into 80% of the outer layer leads to a notable 20% decrease in the building’s overall energy consumption [115]. This reduction in energy usage represents a synergy of active and passive energy strategies to achieve enhanced energy efficiency. These results support the effectiveness of transparent double-skin façades for energy retrofit purposes. The double-skin façade is applicable in a wide range of climatic conditions. According to research conducted by Abdelsalam, it was found that in Dubai, United Arab Emirates, the double-skin façade can reduce annual cooling consumption by 22% when compared with traditional curtain walls [116].
4.1.2. Adaptive Façade Systems

Adaptive façades (AF) are advanced building envelope systems that can alter their functions, characteristics, and behaviour in response to changing environmental conditions and performance requirements. This makes them highly versatile and multifunctional, with the ability to enhance the overall performance of buildings by optimising energy efficiency and providing occupants with greater comfort [117]. The adaptability of such façades is a crucial feature, enabling them to deliver optimal performance by adjusting their design variables in response to changing conditions and considering multiple criteria simultaneously [118].

Furthermore, the Bianco et al. [119] study highlighted that AF has the potential to make game-changing increases in energy efficiency and renewable energy consumption in the built environment. Moveable shading, electrochromic glass, and phase transition materials are examples of commercially available AF technology and components. The concept of adaptive façades is broad and encompasses various subtypes distinguished by the building technologies used and the complementary nature of the system. These subtypes include active façades, advanced façades, biomimetic façades, kinetic façades, intelligent façades, interactive façades, movable façades, responsive façades, smart façades, switchable façades, and transformable façades [118]. Each subtype has unique characteristics that enable the building envelope to respond dynamically to environmental conditions and occupant needs.

Kinetic Façade

Kinetic façades are an emerging technology in adaptive façade systems (Figure 4). These façades utilise movable components that dynamically adjust the building’s façade to changing environmental conditions [120]. The use of kinetic façades has become more widespread due to the advent of new technologies such as advanced sensors, actuators, and control systems [121]. For example, a study by Kim et al. [122] developed a façade system with movable shading devices that could optimise the daylighting and solar heat gain in a building. They used a genetic algorithm to optimise the system’s design, resulting in improved energy performance for the building.

Another area of development in kinetic façades is the integration of renewable energy sources. This integration not only increases the energy efficiency of the building but also reduces its carbon footprint. For instance, a study by Luo et al. [123] developed a dynamic solar façade system that utilises photovoltaic modules and movable shading devices to optimise the energy performance of the building. Furthermore, new materials and construction methods are being developed for kinetic façades in modern façade construction. Biomimicry, technology, and architecture come together to drive the development of kinetic concepts. The architectural design concept encompasses concept, module, and morphology, while technology and movements form the basis of the mechanism [124]. Overall, the combination of advanced technologies, renewable energy sources, and innovative materials is driving the development of kinetic façades and making them a promising solution for the energy-efficient buildings of the future [124].

Responsive Façade

Responsive façades are designed to adapt to changing environmental conditions and user needs (Figure 4c). They can include dynamic shading systems, movable louvres, and smart glass [125]. Smart glass can adapt the transparency of the glass to adjust the heat and light transmittance through it. There are three types of smart glass: electrochromic, suspended particle, and polymer-dispersed liquid crystal (PDLC). Electrochromic smart glass is the most popular, which uses a tungsten oxide film between two transparent plates that changes colour and transparency when an electric potential is applied [126].
Figure 4. Examples of kinetic façades: (a) Helio Trace in New York (USA); (b) Arab World Institute in Paris (France); (c) Al-Bahar Towers in Abu Dhabi (UAE) [29].

Similarly to kinetic façades, technological advancements in sensors, materials, and control systems have improved responsive façades’ efficacy and energy efficiency [127]. A responsive façade aims to improve energy efficiency, occupant comfort, and the overall performance of a building by minimising the need for mechanical systems such as heating, cooling, or lighting [128]. According to Karanouh et al. [129], these façade systems can help reduce 20% of carbon emissions and save 50% in energy consumption.

4.1.3. Green Wall Systems

Green wall systems, known as living walls or vertical gardens, are a new trend in façade construction that incorporates living plants into the building envelope (Figure 5). These can be installed on the exterior or interior surface of the façade, providing a range of benefits such as thermal insulation, noise reduction, improved air quality, and aesthetic value [45]. A study by Cheng et al. [76] showed that green wall systems could have a cooling effect on exterior wall surfaces with a reduction of 20.8 °C and an interior environment of 11 °C.

Furthermore, they benefit users by improving public health and mental well-being, reducing stress, and increasing hospital patient recovery rates [130]. Several methods of cultivating plants on the building façades include aeroponic, hydroponic, and soil-based systems. Aeroponic and hydroponic methods use nutrient-rich water or mist solutions to nutrify the plants, while soil-based systems use traditional mediums [131].

Further to the above, living walls can be classified according to the type of construction. There are three main types (Figure 6): panel systems, felt systems, and trellis systems [132]. Environmental factors, plant species, and maintenance requirements should be considered when selecting the appropriate green wall systems [133]. However, the design and
installation of green wall systems require specialised knowledge of irrigation, horticulture, and structural engineering, which can be technically challenging. Moreover, these systems require ongoing maintenance to ensure the plants’ health and vitality, including fertilisation, pruning, and regular watering [134].

Figure 5. Green wall system [135].

Figure 6. Type of living wall systems [132].

4.1.4. Photovoltaic Façades

A PV, or Building Integrated Photovoltaics (BIPV) façade, is a building envelope system that integrates solar panels into the façade to generate electricity from sunlight and provide energy to the building (Figure 7). Solar façades can be divided into opaque, transparent, or semi-transparent façades [136]. Recent studies have shown that PV glazing systems can help reduce the cost of generated electricity from integrated systems by 32% and 16% for the UK and Greece, respectively, compared with non-integrated systems [137].
A study by Chow et al. [138] evaluated the energy performance of a high-rise building in Hong Kong. It confirmed that the semitransparent single-glazing PV systems saved 23% of the electricity consumed in space cooling per year, while semitransparent natural ventilated PV systems were able to save 28%. These façades provide other benefits besides energy savings, such as thermal insulation and shading. Comparatively to other façade systems, photovoltaic (PV) façades offer shorter payback periods, typically averaging around 13 years [139].

However, the efficiency of the photovoltaic effect decreases with the increasing temperature of PV panels. Introducing artificial ventilation to the air layer between the PV façade modules can reduce the temperature of PV panels and maintain their electricity generation efficiency [38]. To further enhance energy generation efficiency in façades, the refractive index of the anti-reflecting layer of a silicon solar cell should be changed. This approach can reduce reflection and increase light absorption, thereby enhancing the efficiency of the solar cell. Implementing these techniques in the design and construction of buildings can significantly contribute to sustainable building design and renewable energy production. However, the practicality and feasibility of these techniques require careful evaluation and planning to ensure their effectiveness and cost-effectiveness.

Furthermore, the limited sunlight exposure during the daytime and the high cost of covering the building wall with PV panels must be considered before implementing this system [140]. Moreover, this requires proper maintenance and regular cleaning to ensure the system’s safety. Addressing these challenges will require appropriate planning, design, installation, education, and stakeholder awareness [141].

![Figure 7. Archetypes PV façade system](image)

In the face of the global energy crisis, sustainable façade systems emerge as a crucial frontier in the quest for more energy-efficient and environmentally responsible building practices, ultimately contributing to a more sustainable future. The pursuit of zero-energy buildings (ZEB) underscores both passive and active strategies to optimise energy efficiency while enhancing buildings’ visual and functional aspects. Innovations like double-skin façades (DSF), adaptive, responsive, green wall systems, and photovoltaic façades offer substantial energy-saving potential and environmental benefits. However, it is essential to acknowledge the accompanying challenges related to cost, maintenance, and operational efficiency that must be carefully addressed to fully realise this sustainable façade solutions’ potential.
4.2. Sustainable Materials

4.2.1. Timber

Timber façades have a natural and warm look that enhances a building’s appearance [143]. Architects often prefer this in modern designs because wood comes in many different grain patterns and types, giving them a variety of options to create unique and appealing façades [144]. Timber is considered a sustainable material choice with a smaller carbon footprint than other façade materials [145]. Timber is good at insulating, which means it helps make buildings more energy-efficient [146]. This can lead to savings on heating and cooling costs in the long run [147]. Furthermore, timber is a lighter material than concrete or steel, which reduces the weight of a building’s structure [148]. This can potentially save money on the building’s foundation and structural support [149].

But regardless of their treatments, timber façades require regular maintenance [150]. Furthermore, global fire regulations consistently limit the utilisation of timber in façade construction [151]. Another noteworthy consideration is the reduced biological resistance of timber when employed in façades [152].

However, world trends in economic and ecological justification of construction materials and the invention of new modern technological solutions in timber production have impacted the re-use of timber-based products in construction [145]. Using timber behind a glass façade is a new technique that can protect the timber by having a glass layer in front of it while giving the façade the required aesthetic appearance [153]. Furthermore, ventilated timber behind glass façades can provide adequate energy savings for the buildings. Another new trend in timber can be identified as the cross-laminating of timber (CLT) to achieve higher performance parameters [154]. These façades offer fire resistance when designed with appropriate coatings [155], contribute to energy efficiency through thermal insulation [156], and enhance acoustic performance for a quieter indoor environment [157]. Their design flexibility accommodates innovative architectural shapes, and their prefabricated nature ensures quick installation, potentially reducing construction timelines and costs [158]. CLT façades also possess an aesthetically pleasing natural appearance, with texture and colour options that can be tailored to suit various design preferences. Additionally, they have a low environmental impact, aligning with eco-friendly construction practices [159].

4.2.2. Ultra-High-Performance Concrete (UHPC)

UHPC is a new trend for architectural precast concrete panels with a compressive strength of around 120 MPa [160]. UHPC can be a viable option for modern building façades, especially for projects where durability and aesthetics are paramount [161]. It is a lightweight, ultra-thin decorative perforated façade with complex shapes, curvatures, and textures. UHPC is more energy-efficient in cold climates and reduces condensation and mould formation behind the insulation layer compared with conventional concrete panels [162]. By adding photocatalytic TiO2 or coping with the Lotus effect, the sustainability of UHPC façades can be increased further [163]. Textile-reinforced UHPC can be used to develop skinny façade panels with high mechanical resistance and aesthetic features due to the corrosion resistance of textiles [164].

Despite its use in the industry for 25 years, UHPC is still considered an unknown material due to the lack of investigation [165]. Additionally, the elevated expense associated with UHPC has acted as a barrier to its widespread adoption as a façade material [166]. The production of UHPC often requires more energy and resources compared with conventional concrete. Cooperation with technical universities, governments, and end-users is necessary to fully exploit UHPC’s potential. Developing a UHPC product that can be efficiently produced without laboratory conditions is also crucial [167].

4.2.3. Glass Fibre Reinforced Concrete (GRC)

GRC can be formed into thin, lightweight, and complex shapes, making it an attractive option for façade design. Its durability, versatility, and thermal performance make it a
promising material for sustainable façade construction [168]. GRC can be considered a sustainable and innovative material for façade construction due to its low environmental impact. The glass fibres used in the material are typically reclaimed or recycled, and the cement mix includes fly ash, a waste product of industrial smokestacks, further reducing the cost and environmental impact [169].

A critical historical juncture in the development of this material can be traced back to 1967, with the introduction of alkali-resistant glass fibres incorporating a minimum of 16% zircon oxide [170]. As investigations into glass fibre-reinforced cement (GRC) panels unfolded, it was observed that the modulus of rupture (MOR) values of these panels experienced significant declines under accelerated ageing conditions [171]. In response, further research endeavours were launched to explore supplementary admixtures that could enhance the matrix’s durability. A significant breakthrough emerged when the Construction Technologies Laboratory of the Portland Cement Association presented findings from tests involving the addition of 5% polymer to the concrete matrix alongside 5% alkali-resistant glass fibres [172]. This innovative composite formulation obviated the need for wet curing in GRC production and bolstered its durability by mitigating shrinkage cracks. Additionally, incorporating polymers enhanced the composite mixture’s workability [173] and facilitated the seamless application of the material on vertical surfaces, eliminating concerns about face mix sag [172].

However, the presence of non-green polymers in GRC mixtures poses contamination hazards during disposal and diminishes the recyclable value of washing water [174]. Furthermore, polymer GRC is considered a combustible material, which will hinder its use in façade construction.

4.2.4. Stone

Stone is a natural material used for building façades from very early stages and can be considered sustainable. Typically, granite, marble, and limestone have been used preferentially as the exterior cladding, while travertine and sandstone have been used to some extent [175]. The use of stone façades in modern buildings proves this timeless material’s enduring appeal and versatility. Stone façades have significantly improved contemporary architecture, blending tradition with innovation [176]. In modern buildings, stone is employed not only for its aesthetic charm but also for its practical advantages. Its inherent durability makes it a sustainable choice, ensuring the building remains visually striking for generations while minimising the need for extensive maintenance [177]. Additionally, the non-combustible nature of stone is a paramount safety feature in building design. Stone does not contribute to the spread of fire, providing an added layer of protection to occupants and the structure itself [178]. Tuff stone clad has a low thermal conductivity of 0.4 W/mK, attributed to its porosity [179]. According to research findings, stone cladding is the preferred material for façades, showing the highest relative preference over aluminium panels and plaster. It’s recommended due to its ability to reduce cooling loads by 4% compared with aluminium panels and 1.5% compared with plaster systems [178].

However, the stone façade’s initial cost is higher than other façade materials [180]. This premium cost stems from several factors, including the expense of sourcing natural stone, labour-intensive installation, structural adaptations to support the added weight, and customisation demands to achieve specific design aesthetics. Furthermore, thin stone elements are more vulnerable to severe environmental conditions and degrade more rapidly than thick brick elements. This has led to the problems associated with detaching stone elements from the façade [181].

4.2.5. Phase Changing Material

Phase change materials (PCM) are transition materials showing a phase change (usually from solid to liquid) over a certain temperature change. These materials can exploit the latent heat of the phase change to store thermal energy [182]. These can be used in opaque as well as transparent façade systems. The PCM can be used along with PV façade systems
to increase the energy conversion efficiency of the plan [183]. Moreover, when used inside building materials, PCM can delay the temperature rise of the building, enhance the air quality of the indoor environments [184], and increase the thermal performance [185]. This can lead to energy savings and reduced operational costs.

However, integrating PCMs into façade systems requires careful design and consideration of factors like placement, insulation, and compatibility with other building components [186]. Furthermore, the amount of heat that can be stored by PCMs is finite, and if the thermal load exceeds the PCM’s capacity, the benefit may be limited [187]. The PCM is also affected by the intense summer weather conditions, which can be considered a major drawback hindering its use in current practice [188].

4.2.6. Insulation Materials

Insulation plays a critical role in the performance of a building’s façade. Insulation helps reduce the noise and heat transfer into the building. There are few technical advancements in insulation materials in modern building construction. Aerogel and vacuum insulation panels (VIP) are the most promising options [189]. Recent studies have shown that aerogel-based thermal insulation provides thinner solutions to building envelopes than conventional insulation materials. Furthermore, it mitigates greenhouse gas emissions remarkably [190]. Similar to Aerogel, the VIP helps to have a thinner insulation thickness with higher thermal performance and an overall cost reduction [191].

However, poor implementation and insufficient ventilation can lead to durability issues in these materials [192]. VIPs are delicate and easily damaged during handling, transportation, or installation. Careful handling is required to prevent punctures or tears in the vacuum-sealed envelope [193]. Another major disadvantage of these panels is their higher cost than conventional insulation products [194].

4.2.7. Aluminium Composite Material

Aluminium composite façade materials, or ACM or ACP, are popular for building exteriors due to their versatility, durability, and aesthetic appeal. The material comprises two thin aluminium sheets bonded to a non-aluminium core, such as polyethylene, providing a lightweight and rigid structure [195]. ACM panels are available in various colours and finishes, including metallic, high gloss, and matte, making them a popular choice for modern and contemporary building design. In addition to their visual appeal, ACM materials are weather-resistant and easy to maintain, making them an attractive and practical option for building façades [196]. Many ACM panels have insulating properties due to the core material, which can help improve building energy efficiency [197]. It can also provide sound insulation benefits [198]. ACM requires minimal maintenance [199]. The lightweight nature of ACM makes it relatively easy to install, reducing labour costs. It can be cut and shaped easily, allowing various design possibilities [200].

However, the aluminium sheets on the surface of ACM panels can be prone to denting or dings, particularly during storms or hurricanes, which may affect the appearance of the material [201]. It is crucial to thoroughly evaluate the combustibility of ACP panels to prevent fire hazards within the building and the potential spread of fires [195]. It is essential to ensure proper installation and maintenance to avoid any potential safety risks associated with these materials.

Sustainable façade design is a multifaceted endeavour where selecting environmentally friendly and low-carbon footprint materials plays a pivotal role. Each material option, from timber with its natural appeal and potential for enhanced energy efficiency to ultra-high-performance concrete (UHPC) offering durability and aesthetic benefits, presents a unique set of advantages and challenges. Glass Fibre Reinforced Concrete (GRC) showcases versatility and environmental friendliness but requires attention to polymer components and fire safety. Stone façades offer resilience and energy-saving potential but come with cost and maintenance considerations. Phase-changing materials (PCMs) promise energy efficiency, though careful design and weather factors are vital. Insulation materials like
aerogel and vacuum insulation panels (VIP) excel in thermal performance but require delicate handling and involve higher costs. Aluminium Composite Material (ACM) stands out for its adaptability and ease of maintenance but necessitates precautions for denting and fire safety. Ultimately, the choice of façade material should align with the specific project’s goals, considering aesthetics, energy efficiency, cost, and safety, to contribute to sustainable and visually appealing building designs.

4.3. Australian Design and Construction Practice

The design parameters for Australian façades primarily rely on the requirements outlined in Australia’s National Construction Code (NCC). As detailed in Section 3, the façade design process commences with the conceptual design of the building. This method, which employs data-driven and multi-variable considerations, is the foundation for establishing the principles of façade design. Subsequently, the next phase involves refining the façade design, focusing on detailed aspects such as thermal efficiency, acoustic properties, fire performance, and cost optimisation. During this stage, an Environmentally Sustainable Design (ESD) report is generated, summarising the essential performance criteria for the building.

The performance parameters of the building’s various components are assessed against either the minimum requirements specified by the NCC or more stringent building target parameters. Notably, the NCC’s Section J employs a deemed-to-satisfy (DTS) approach or performance solution, which prescribes minimum U-values and solar heat gain coefficients (SHGC) for different building elements, including roofs, solid walls, glazed walls, and floors, as well as the building’s airtightness [202]. To determine the overall U-value of the façade, the U-values of the individual materials used in the building envelopes are considered. The total U-value of a wall glazing construction can be calculated in accordance with AS/NZS 4859.2:2018 [203] or specification J1.5b of the NCC. The average air tightness of Australian residential buildings is 15.5 ACH at 50 Pa [204]. The acoustic values of the walls are measured by the acoustic rating (Rw) of the product. The Australian Building Codes Board has introduced an NCC 2019 façade calculator, which serves as a valuable tool for comprehending and implementing the J1.5 Building Fabric DTS Provisions. This tool should be employed at the outset of the building design process to determine the necessary U-value and SHGC (Solar Heat Gain Coefficient) criteria. It also aids in the precise specification of wall and window products required to achieve compliance with the regulations.

Based on these values, the façade consultant compiles the façade performance report, which is subsequently provided to the Façade contractor during the tender stage. It is the responsibility of the façade contractor to ensure that the façade complies with the parameters outlined in the performance reports and adheres to Australian standards. The typical design life expectancy for an Australian façade is 50 years [205], encompassing all elements such as framing, brackets, and fixings, except for structural silicone. The façade must undergo testing in accordance with AS4284-2008-Testing of Building façades [206]. This standard sets out the testing methods for assessing building façades against environmental loads, encompassing water and air infiltration and structural tests. Furthermore, the façade’s combustibility should be according to the NCC Part C1 fire resistance and stability.

The double-skin façade can be considered a better option to use in the Australian context, as these façade systems have better U and SHGC values. The study by Yanjin et al. [207] presents that double skin façade can achieve lower U values, such as 2.13 W/m²·K and SHGC values close to 0.25 [207]. In addition, Siliag et al. [208] presented that photovoltaic—double skin façade use in Australia can produce energy savings of 34.1%, 86%, and 106%, respectively, in Darwin, Sydney, and Canberra. Furthermore, an adaptive façade will always be a better option, as these systems can adapt to changing environmental conditions and optimise the façade’s SHGC values to suit [209]. A research work by Ayusu et al. [210], which focused on a school building in Western Australia, presents that these systems will help improve thermal comfort levels and energy efficiency significantly. According to Nimish et al. [211], the adaptive BIPV shading systems have
the ability to increase visual comfort and energy generation simultaneously within the subtropical climate of Sydney, Australia.

The living wall façade systems can also be considered a favourable option in the Australian context. Hasan et al. [212] investigated the energy-saving potential of living wall systems in Australia and concluded that these systems could save 8–13% of cooling energy consumption according to the building elevations. Moreover, Australia has undertaken a commitment to enhance the proliferation of top-tier green roofs and vertical greening systems through the implementation of the “Green Roofs and Walls Policy”. This policy serves as a guideline for local councils to encourage the adoption of green roofs and walls in both residential and commercial domains [213]. Alam et al. [214] investigated using phase-changing material in eight Australian cities. Their research shows that PCM was effective at different times of the year, depending on local weather conditions. The study further shows that PCM contributed to 17–23% of annual energy savings, except in hot and humid cities like Darwin [214]. Further to that, in 2022, Oscar et al. [215] researched PCM use in residential buildings in Alice Springs, Australia. Their results show that the PCM is promising but requires low-cost technology to make it financially attractive [215].

Steffen Lehmann [216] used cross-laminated timber (CLT) panels for Australia’s multi-story inner-city infill housing. The research concluded that the CLT panels save significant funds during construction and have many advantages over concrete and steel [216]. However, fire safety and earthquake performance can be challenges. Glass fibre-reinforced concrete has been used in Australia due to its higher structural strength and lightweight properties [217]. However, Charles Richard stated at the 2015 GRC conference that, from 2011 to 2014, 30 million of GRC work was removed from projects in Sydney due to higher labour costs in Australia [218]. Based on the above, it can be inferred that Australia incorporates novel materials and façade systems. However, their widespread adoption is hindered by cost considerations, fire safety concerns, and the challenging Australian climate. Consequently, further research is needed to address these challenges and pave the way for their broader implementation.

5. Constraints of Using Technology and Sustainable Materials

Integrating sustainable materials and technology in building design presents significant opportunities to enhance the sustainability of the built environment. However, implementing such materials and technology is not without its constraints, particularly concerning performance issues [219]. One of the primary challenges is the lack of understanding and expertise in the design and construction industry, leading to improper specification and installation of such materials and technology [220]. This can result in performance issues, including reduced durability, weather tightness, increased maintenance costs, and decreased energy efficiency. To overcome these constraints, it is essential to raise awareness and educate people on the proper use of sustainable materials and technology in building design and construction [48]. Regularly monitoring and maintaining these materials and technologies can also help ensure optimal performance and longevity [221].

5.1. Higher Upfront Cost (Long Payback Periods)

Technology and sustainable materials in construction present a significant challenge due to the higher upfront costs associated with these materials and systems. New façade systems and materials are often more expensive than traditional alternatives, resulting in long payback periods [222,223]. This can be a constraint for many developers, who prioritise short-term cost savings over long-term sustainability. Additionally, there is often a lack of understanding among stakeholders regarding the long-term benefits of investing in sustainable materials and technology, further hindering their adoption [224].

5.2. Complex Preliminary Design Approaches

New façade systems and sustainable materials offer a promising way to improve building performance and reduce environmental impact. However, there are several
constraints that designers and architects face when integrating these technologies. This complexity can arise due to the lack of established regulations and the need for specialised expertise in the field [225]. In addition, the selection of sustainable materials may be limited by cost, availability, and durability, which can further complicate the design process [226]. These constraints highlight the importance of a collaborative and interdisciplinary approach to addressing the challenges of integrating sustainable materials and new façade systems into complex building designs [227].

With the increasing number of building façade components and systems available, selecting an appropriate building façade solution has become more challenging. Improper preliminary designs can lead to problems between stakeholders, delays in projects, and ultimately affect the performance of the entire building façade [43].

5.3. Lack of Manufacturing, Installation, and Operation Expertise

Even though there are significant advancements in façade design and construction, the production plants and installers are still not up to par with the required expertise. There is a substantial gap between the design and construction phases of the façade when the systems deviate from the traditional ways. Three major problems are associated with the performance of modern façade systems. The first problem is related to the project delivery method and contact type. Typically, the architect finalises the façade design along with the required façade specifications without the involvement of the façade contractor. Only after receiving the architectural façade documents can the façade contractor investigate the actual structure of the façade. This involves checking material availability, feasible engineering designs, and prototypes. This method creates space for performance errors as the primary design will change to suit the available resources and engineering requirements. The second problem is related to the handover and commissioning. The lack of a third party to commit to the adaptive façades has led to the system handover without assessing the adaptive systems’ quality and performance [228]. The third problem is the users’ lack of knowledge about the façade operation. The adaptive façade systems must have a soft-landing process and an operation manager. The façade operators must take enough time to program the façade actions, considering the occupant requirements. However, this approach was not thoroughly considered in recent projects, leading to lower performance than planned during the initial stage.

5.4. Lack of Standard Criteria for Optimisation

Testing solar and thermoelectric technologies in a controlled laboratory may only partially account for real-world building conditions [24]. Climate-specific requirements must be considered during the design phase of high-performance building enclosures [229]. Practical strategies for one climate may not work in another. Building materials embody energy, and environmental consequences should also be addressed. Sustainable façade design must have design regulations and standards, complicating integration with other building systems [230]. Specialised decision analysis tools are needed to achieve building façade sustainability, whereas the environmental effects of building insulation façade systems vary based on the design, materials used, and structure location. Table 3 provides constraints for using new technological developments in façade engineering.
Table 3. Constraints of using Technological Advancements in Façade Engineering.

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<thead>
<tr>
<th>Technological Advancement</th>
<th>Structural Design and Construction</th>
<th>Performance</th>
<th>Economic Aspects</th>
<th>Environmental Aspects</th>
<th>Social Aspects</th>
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<tbody>
<tr>
<td><strong>Green Wall Systems</strong></td>
<td>1. Installation difficulties [134]. 2. Possible damage from plant roots to the structure [103]. 3. Structural Load: This can add significant weight to the building structure, impacting the building’s structural stability. The design should consider the building’s appropriate support structure and load-bearing capacity [240].</td>
<td>1. Dry and dead plants can create fire hazards [241]. 2. Risk of moisture retention in the surface walls [242]. 3. Clogging of drainage systems with leaves and debris [243].</td>
<td>1. Higher investment and maintenance costs [134,243]. 2. Property Value: Green wall systems can increase the property value of buildings. The design should consider the potential increase in property value and the impact on the building’s overall return on investment [244]. 3. Longer payback periods around 20 years [245].</td>
<td>1. Pests animal attacks [246]. 2. Water use: green wall systems require irrigation, which can consume significant amounts of water. The design should consider the availability of water and the use of efficient irrigation systems to minimise water consumption</td>
<td>1. Cultural issues associated with growing plants on walls [246].</td>
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Table 3. Cont.

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<th>Technological Advancement</th>
<th>Structural Design and Construction</th>
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6. Summary and Conclusions

This paper discusses the need for sustainable building envelopes due to the high energy usage and carbon dioxide emissions from buildings. The study emphasises the need for a balanced combination of critical performance parameters while considering the available cost for the project. It also underscores the importance of involving expert consultants in relevant fields during the design process to avoid costly consequences for building owners. Furthermore, the paper discusses the significance of sustainable approaches and emerging technological developments in façade engineering to reduce energy consumption, enhance occupant comfort, and minimise environmental impacts. Contemporary façade designs should consider a combination of passive and active strategies to maximise energy savings. This study comprehensively discusses several modern façade systems and materials used to achieve energy savings and sustainability.

Among these modern façade systems, Double Skin façades (DSF) are identified as a promising technological solution for improving energy efficiency, indoor air quality, and visual appeal. While DSF offers significant energy savings potential, challenges such as sound and odour transmission through floors, higher initial costs, structural design considerations, and excessive vibrations must be addressed through further research and development of novel materials and components. On the other hand, adaptive façades are gaining popularity for their ability to enhance building performance and occupant comfort through active concepts. However, complex design and construction challenges, such as thermal bridging and weather tightness, require the development of appropriate standards and regulations. Additionally, research should focus on exploring new materials to extend the life cycle of adaptive façades and reduce maintenance needs.

The green wall systems offer numerous advantages, including enhanced air quality, thermal insulation, and aesthetic appeal. They contribute positively to public health and well-being. However, ensuring the health and vitality of plants in these systems and addressing structural damage, fire hazards, and drainage system issues require further research and establishing design parameters and regulations. PV façade systems provide cost reductions in electricity generation, thermal insulation, and shading benefits. However, challenges such as high initial costs, maintenance requirements, and potential performance reduction due to shading and environmental considerations need to be addressed through ongoing research. Innovations in materials and system design can improve the effectiveness and efficiency of PV façades.

Several sustainable materials (e.g., timber, ultra-high-performance concrete, glass fibre, phase change materials, etc.) are available to produce high-performance façade systems. However, the sustainable performance enabled by these materials is different. Therefore, combining these materials with modern technical and technological solutions can lead to highly efficient and sustainable building façades. Each material has advantages and disadvantages, and its successful implementation relies on carefully considering project requirements and goals.

In summary, comparing façade types highlights the importance of considering multiple factors, such as energy efficiency, cost, occupant comfort, and environmental impacts, in sustainable building design. Each façade type offers unique benefits and challenges. Architects, engineers, and builders must carefully evaluate these aspects and make informed decisions based on project requirements and available resources. Continued research, collaboration, and innovation are crucial to enhancing façade systems’ performance and sustainability, ultimately contributing to a greener and more energy-efficient built environment.

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