sustainability

MDPI

Review

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

Dushan Fernando [1], Satheeskumar Navaratnam [2], Pathmanathan Rajeev [1,*] and Jay Sanjayan [1]

[1] Department of Civil & Construction Engineering, School of Engineering, Swinburne University of Technology, Melbourne, VIC 3122, Australia
[2] School of Engineering, RMIT University, Melbourne, VIC 3001, Australia
* Correspondence: prajeev@swin.edu.au

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

check for updates

Citation: Fernando, D.; Navaratnam, S.; Rajeev, P.; Sanjayan, J. Study of Technological Advancement and Challenges of Façade System for Sustainable Building: Current Design Practice. *Sustainability* **2023**, *15*, 14319. https://doi.org/10.3390/su151914319

Academic Editor: Antonio Caggiano

Received: 22 August 2023
Revised: 21 September 2023
Accepted: 26 September 2023
Published: 28 September 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

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 1. Search string of the investigation.

Keyword Combinations	Sources			
	Science Direct	**ICE**	**ASCE**	**Springer**
'façade system AND energy conservation'	4668	87	215	4041
'façade system AND weather tightness'	1145	53	104	438
'façade system AND efficiency improvement'	8329	298	856	3058
'façade system AND performance'	18,117	497	1678	8579
'façade system AND location AND environmental conditions'	9208	329	1051	4395
'façade system AND structural design'	8523	477	1617	6200
'façade system AND constructability'	10,044	611	1756	116
'façade system AND deformation AND deterioration'	812	35	107	560
'façade system AND natural hazard AND resistance'	893	48	241	1084
'façade material AND limitations'	8518	529	1369	5191
'façade system AND sustainable material'	9621	299	712	4216
'photovoltaic façade material'	4099	41	117	910
'responsive shading AND geometry façade material'	447	18	37	415
'façade system AND cost AND economic'	7294	258	592	5751
'façade system AND inspection AND maintenance'	1441	157	429	1384
'façade system AND green concept'	4856	140	307	4328
'adaptive façade system'	9531	246	567	2056
'façade system AND building energy system'	16,679	333	1012	6935
'façade system AND building information modelling'	12,969	355	1096	8676
'façade system AND building monitoring system'	8676	278	663	4944

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.

Façades	Application	Properties	Construction Methods	Materials
Masonry  Brick Façade in Sunshine, Australia (Photo courtesy of D.F)	It is commonly used in low-cost industrial buildings and prestige structures [47].	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].	Composite construction method with individual units (bricks, stones) overlapping in horizontal layers bonded with mortar [46].	Bricks-Clay, Calcium Silicate, Concrete [46], Blocks-Concrete, Stone [49]
Profiled Metal Systems  Colorbond Façade in Epping, Australia (Photo courtesy of D.F)	It is traditionally employed in agricultural and industrial structures. It has been extended to retail, commercial, and school buildings [46].	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].	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].	Aluminium or galvanised steel single skins, double skin of metal sheeting with insulation, and composite metal panels with polyurethane or polyisocyanurate foams [46].

Table 2. *Cont.*

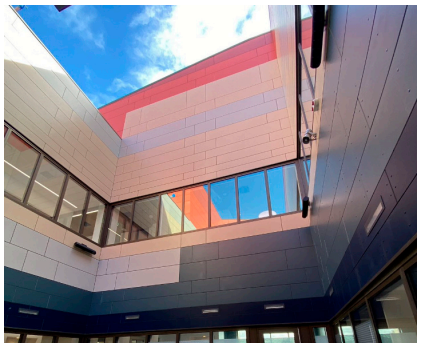
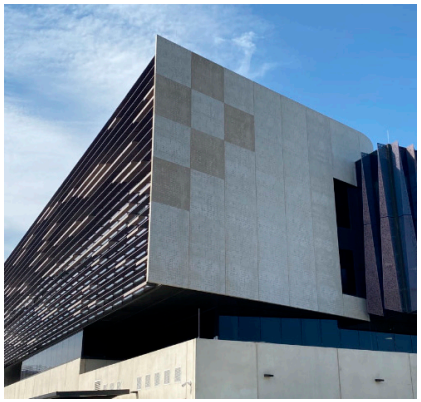
Façades	Application	Properties	Construction Methods	Materials
Small Cladding Panels  Fiber cement sheet Façade in Sunshine, Australia (Photo courtesy of D.F)	Commonly used in commercial structures [46].	Cost-effective and less maintenance requirements [54], lightweight and achieve complex colours or textures [55]. It can be used with sealed joints or as rainscreen panels.	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].	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].
Large Cladding Panels  GRC façade in Werribee, Australia (Photo courtesy of D.F)	Mainly in public and institutional buildings [56].	Panels have the strength to bridge between separate places on the main building structure panels [57]. Have higher acoustic performance [58].	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],	Glass fibre-reinforced polyester, glass fibre-reinforced cement, composite metal panels and reinforced precast concrete panels [46].

Table 2. *Cont.*

Façades	Application	Properties	Construction Methods	Materials
Curtain Walling  Curtain Wall Façade in Burwood, Australia (Photo courtesy of D.F)	They are typically used in high-rise construction—shopping centres, office buildings and educational centres [60,61].	They are used in high-end commercial structures [46], Lightweight [62], smaller wall footprint [63], structural flexibility [64]	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].	Aluminium or steel framing, stone, glass, metal, or thin stone panels [68]
Fully Supported Metal Sheeting  Copper sheet Façade in Christchurch, New Zealand	Normally used on prestige buildings [69].	Expensive [46], extremely durable façades [70].	Sheets are typically required to support plywood boards [46] entirely.	Copper and lead sheets [46].

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].

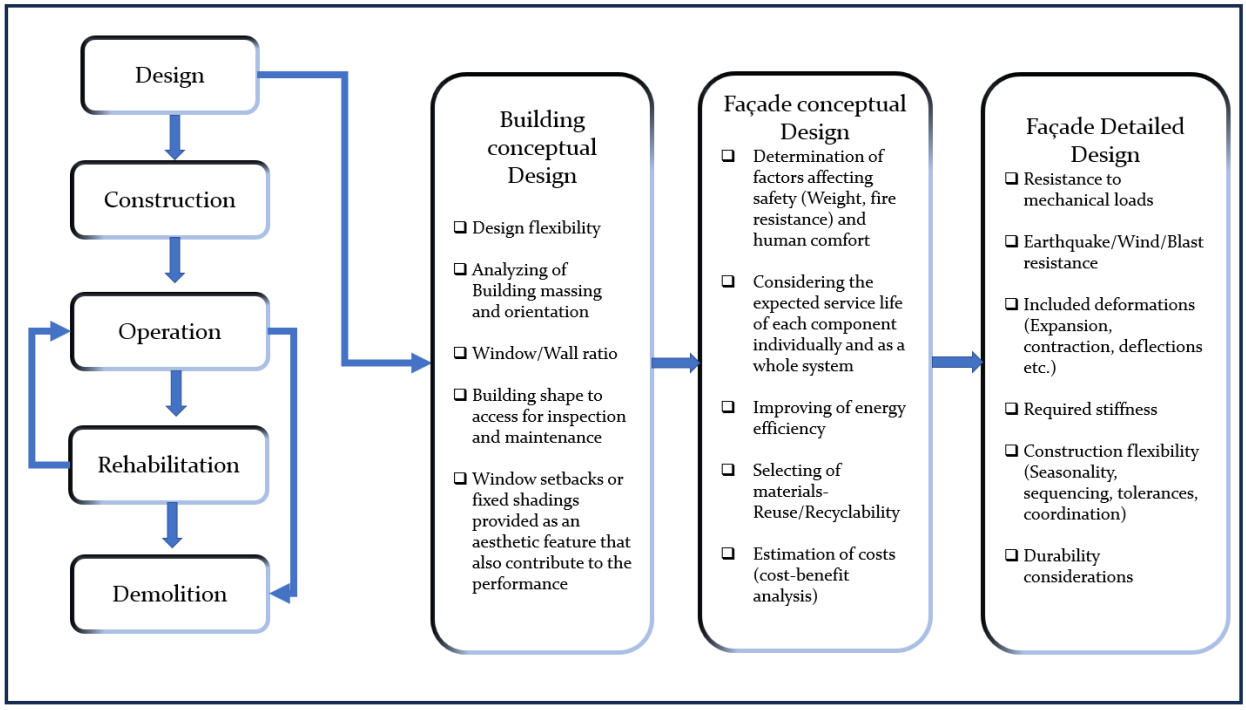


Figure 1. Building façade life cycle and necessary considerations in the façade design process [8].

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.

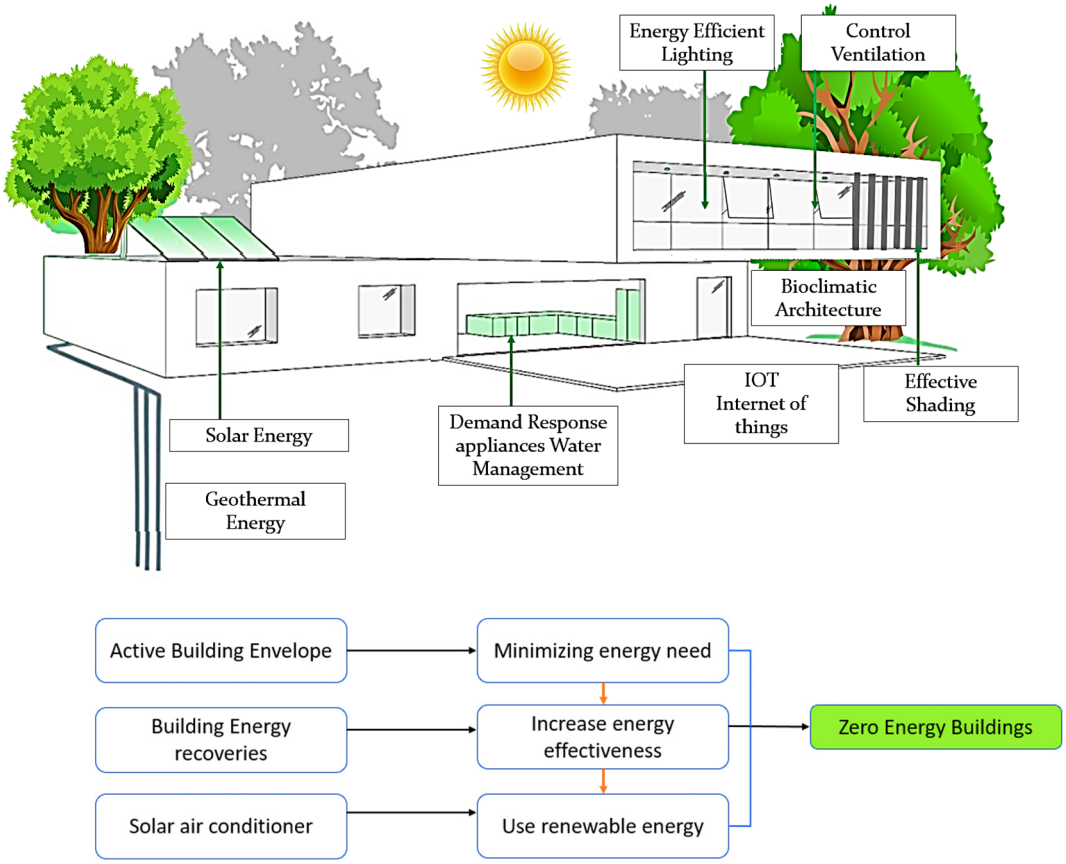


Figure 2. Zero energy building and route of use of technology towards zero energy building [101].

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].

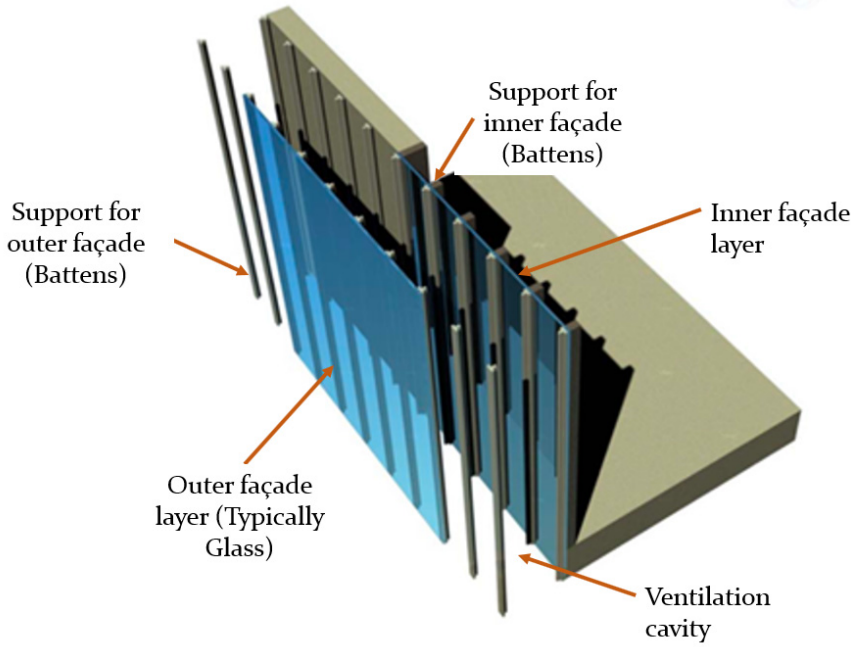


Figure 3. The technical details of the double skin façade (DSF) in a schematic cut [110].

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].

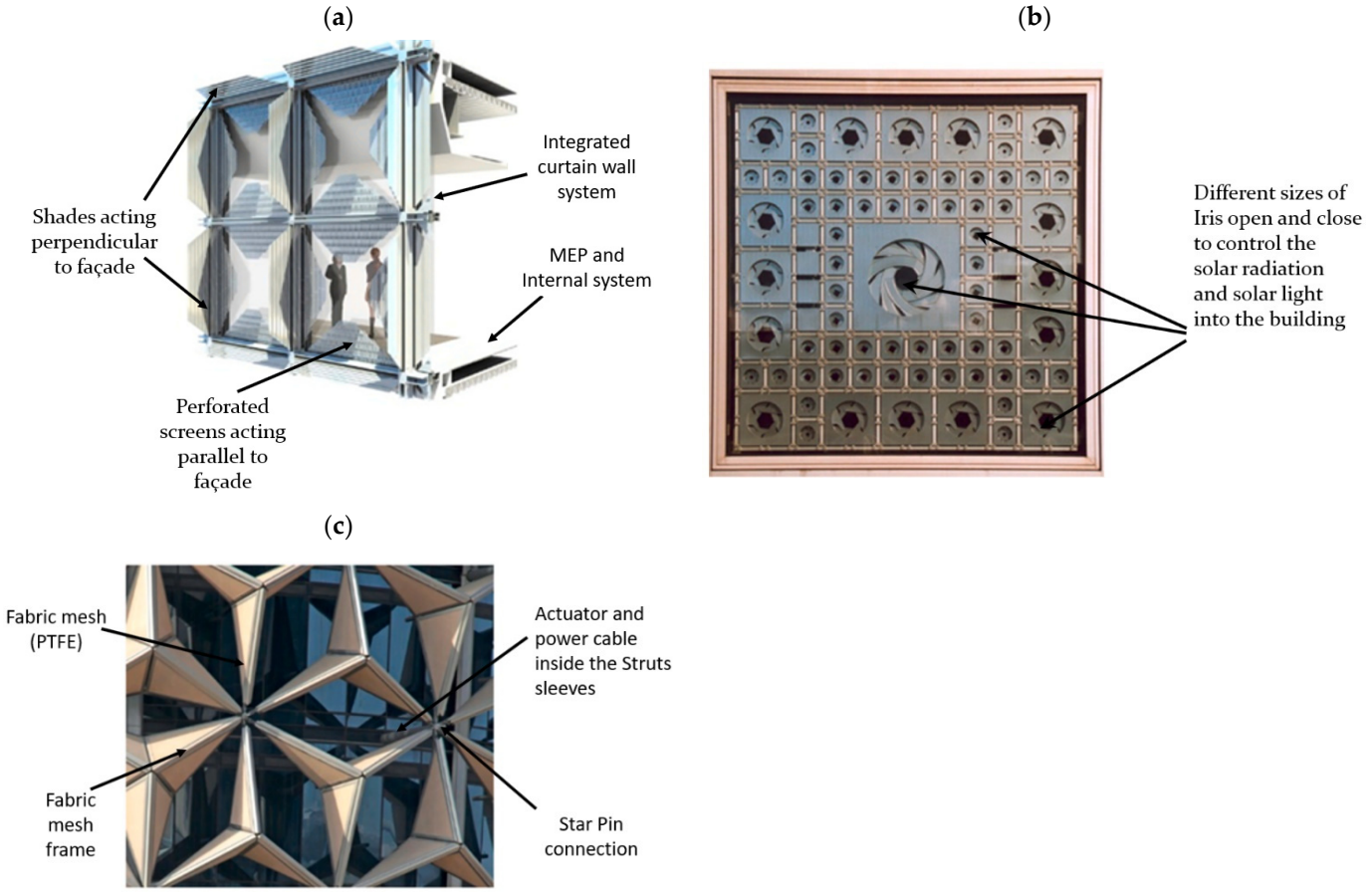


Figure 4. Examples of kinetic façades: (**a**) Helio Trace in New York (USA); (**b**) Arab World Institute in Paris (France); (**c**) Al-Bahar Towers in Abu Dhabi (UAE) [29].

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].

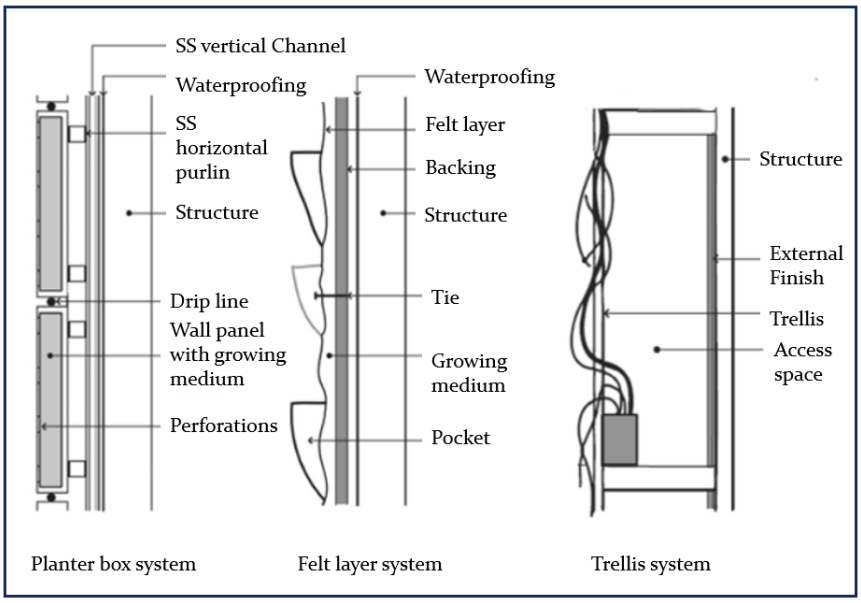


Figure 6. Type of living wall systems [132].

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 change. 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].

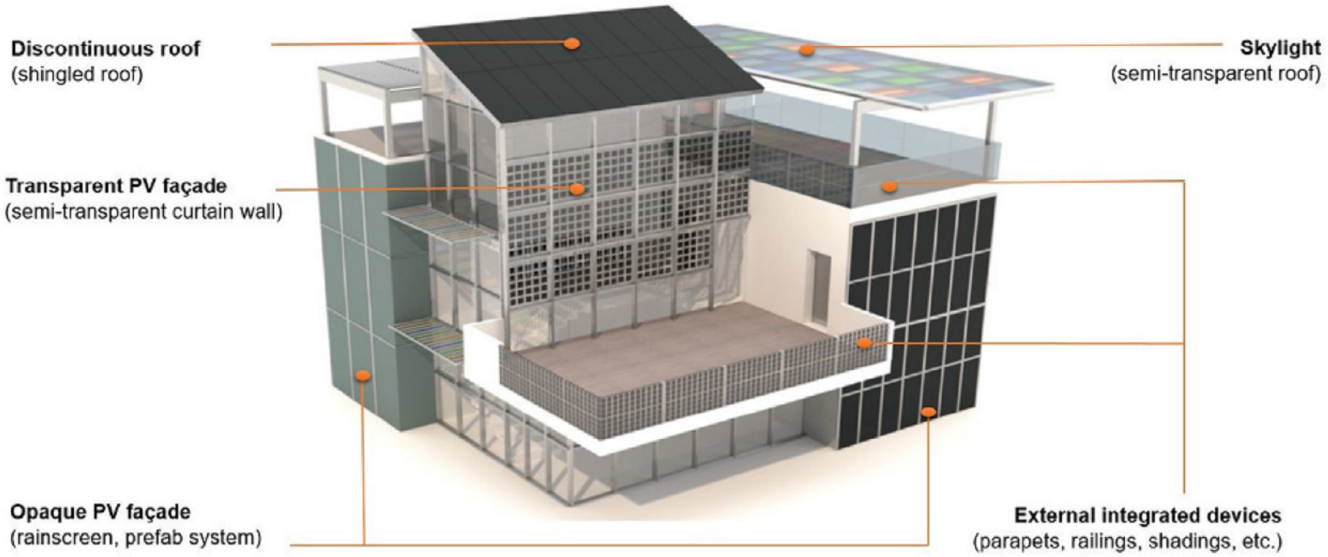


Figure 7. Archetypes PV façade system [142].

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 UPHC'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 $W/m^2 \cdot K$ 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.

Technological Advancement	Structural Design and Construction	Performance	Economic Aspects	Environmental Aspects	Social Aspects
Double Skin Façade	1. Excessive vibration of the outer skin due to dynamic wind loads [231]. 2. Increase the weight of the primary structure [113]. 3. Uncertainties in glass type selection [104]. The glass must be strong enough to withstand wind loads and other external forces and be able to accommodate thermal expansion and contraction [232]. 4. Structural Stability of the support system is critical in the design of double-skin façades [233].	1. Sound transmission through the cavity to different floors [113]. 2. Natural ventilation is not possible throughout the year [113]. 3. Risk of overheating on warm sunny days [234]. 4. Higher fire hazard risk [235]. 5. Airflow calibration difficulties due to insufficient resources and experimental results [236].	1. Higher costs related to initial design, construction, and maintenance [113]. 2. Long payback periods of around 81 years [223].	1. Higher material usage [237]. 2. Increased embodied energy and carbon [238].	1. Reduction of living space [113]. 2. Odours can be transmitted through the cavity between rooms or floors [239].
Green Wall Systems	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].	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].	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].	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	1. Cultural issues associated with growing plants on walls [246].

Table 3. *Cont.*

Technological Advancement	Structural Design and Construction	Performance	Economic Aspects	Environmental Aspects	Social Aspects
Adaptive Façade	1. Limited movement capacities in the façade [43]. 2. Complex designs associated with preventing thermal bridges and achieving weather tightness [247].	1. Increase of heat transfer through thermal bridges [247]. 2. Difficulty achieving weather tightness due to complex construction [43].	1. Costly construction and expensive materials [43], such as smart and phase-changing materials [247]. 2. Higher maintenance costs [248]. 3. Long payback periods of around 26 to 33 years for residential while 57 and 61 years for commercial buildings [249].	1. The low life cycle of the façade [250]. 2. The number of fragile components [247].	1. Reduction in usable space [250]. 2. Effect on the outside view [247].
Photovoltaic Façade	1. Issues related to the design of PV materials to higher wind pressures [251]. 2. Technical complexity of solar tracking actuators [252]. 3. Requirement of particular manufacturing processes [253].	1. Lower system performances due to façade cover with possible shadows [254]. 2. Reduce the natural lighting required indoors [255].	1. Higher installation and maintenance costs associated with PV systems [42].	1. Less research on the elements' environmental effects and life cycle [256].	1. Effect on the outside view [42]. 2. Lack of willingness to adopt PV systems [257].

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.

Author Contributions: D.F.: Formal analysis, Investigation, Methodology, Visualization, Writing—original draft. S.N.: Conceptualization, Data curation, Methodology; Validation, Visualization, Writing—review & editing. P.R.: Conceptualization, Data curation, Methodology, Supervision, Validation, Writing—review & editing. J.S.: Conceptualization, Data curation, Supervision, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

References

1. Bannister, P.; Moffitt, S.; Zhang, H.; Johnston, D.; Shen, D.; Robinson, D.; Cooper, P.; Ma, Z.; Gomis, L.L.; Green, L. *Building Code Energy Performance Trajectory: Final Technical Report*; CRC for Low Carbon Living: Sydney, Australia, 2018.
2. Yu, J.-S.; Kim, J.-H.; Kim, S.-M.; Kim, J.-T. Thermal and energy performance of a building with PV-applied double-skin façade. *Proc. Inst. Civ. Eng.-Eng. Sustain.* **2017**, *170*, 345–353. [CrossRef]
3. Klee, C.; Love, A. *Thermal Performance Of Façades, 2012 AIA Upjhon Grant Research Initiative*; Fayette Research: Boston, MA, USA, 2012.
4. Nadoushani, Z.S.M.; Akbarnezhad, A.; Jornet, J.F.; Xiao, J. Multi-criteria selection of façade systems based on sustainability criteria. *Build. Environ.* **2017**, *121*, 67–78. [CrossRef]
5. Sung, D. A new look at building façades as infrastructure. *Engineering* **2016**, *2*, 63–68. [CrossRef]
6. Hartkopf, V.; Aziz, A.; Loftness, V. Açades and enclosures: Building for sustainability. In *Sustainable Built Environments*; Springer: Cham, Switzerland, 2020; pp. 295–325.
7. Tzempelikos, A.; Athienitis, A.K. Simulation for façade options and impact on HVAC system design. In Proceedings of the Eighth International IBPSA Conference, Eindhoven, The Netherlands, 11–14 August 2003; pp. 1301–1308.
8. Moghtadernejad, S.; Mirza, M.S.; Chouinard, L.E. Façade design stages: Issues and considerations. *J. Archit. Eng.* **2019**, *25*, 04018033. [CrossRef]
9. Aflaki, A.; Mahyuddin, N.; Mahmoud, Z.A.-C.; Baharum, M.R. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy Build.* **2015**, *101*, 153–162. [CrossRef]
10. Ding, W.; Hasemi, Y.; Yamada, T. Natural ventilation performance of a double-skin façade with a solar chimney. *Energy Build.* **2005**, *37*, 411–418. [CrossRef]
11. Yi, Y.K. Building Façade multi-objective optimization for daylight and aesthetical perception. *Build. Environ.* **2019**, *156*, 178–190. [CrossRef]
12. Vartiainen, E.; Peippo, K.; Lund, P. Daylight optimization of multifunctional solar Façades. *Sol. Energy* **2000**, *68*, 223–235. [CrossRef]
13. Hassanli, S.; Hu, G.; Kwok, K.C.; Fletcher, D.F. Utilizing cavity flow within double skin façade for wind energy harvesting in buildings. *J. Wind Eng. Ind. Aerodyn.* **2017**, *167*, 114–127. [CrossRef]
14. Bayoumi, M. Impacts of window opening grade on improving the energy efficiency of a façade in hot climates. *Build. Environ.* **2017**, *119*, 31–43. [CrossRef]
15. Loonen, R.C.; Trčka, M.; Cóstola, D.; Hensen, J.L. Climate adaptive building shells: State-of-the-art and future challenges. *Renew. Sustain. Energy Rev.* **2013**, *25*, 483–493. [CrossRef]
16. Attia, S.; Bilir, S.; Safy, T.; Struck, C.; Loonen, R.; Goia, F. Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy Build.* **2018**, *179*, 165–182. [CrossRef]
17. Besir, A.B.; Cuce, E. Green roofs and Façades: A comprehensive review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 915–939. [CrossRef]
18. Akram, M.W.; Hasannuzaman, M.; Cuce, E.; Cuce, P.M. Global technological advancement and challenges of glazed window, Façade system and vertical greenery-based energy savings in buildings: A comprehensive review. *Energy Built Environ.* **2023**, *4*, 206–226. [CrossRef]
19. Junaid, M.F.; ur Rehman, Z.; Čekon, M.; Čurpek, J.; Farooq, R.; Cui, H.; Khan, I. Inorganic phase change materials in thermal energy storage: A review on perspectives and technological advances in building applications. *Energy Build.* **2021**, *252*, 111443. [CrossRef]
20. Balali, A.; Valipour, A. Identification and selection of building façade's smart materials according to sustainable development goals. *Sustain. Mater. Technol.* **2020**, *26*, e00213. [CrossRef]
21. Di Giuda, G.M.; Giana, P.E.; Masera, G.; Seghezzi, E.; Villa, V. A BIM-based approach to façade cladding optimization: Geometrical, economic, and production-control in a DfMA perspective. In Proceedings of the European Conference on Computing in Construction—EC3 Conference, Chania, Greece, 10–12 July 2019; pp. 324–331.
22. Al Ka'bi, A.H. Comparison of energy simulation applications used in green building. *Ann. Telecommun.* **2020**, *75*, 271–290. [CrossRef]
23. Gennaro, G.; Lucchino, E.C.; Goia, F.; Favoino, F. Modelling double skin façades (DSFs) in whole-building energy simulation tools: Validation and inter-software comparison of naturally ventilated single-story DSFs. *Build. Environ.* **2023**, *231*, 110002. [CrossRef]
24. Irshad, K.; Habib, K.; Saidur, R.; Kareem, M.; Saha, B.B. Study of thermoelectric and photovoltaic Façade system for energy efficient building development: A review. *J. Clean. Prod.* **2019**, *209*, 1376–1395. [CrossRef]

25. Dewidar, K.; Mahmoud, A.H.; Magdy, N.; Ahmed, S. The role of intelligent façades in energy conservation. In Proceedings of the International Conference on Sustainability and the Future: Future Intermediate Sustainable Cities (FISC 2010), Cairo, Egypt, 23–25 November 2010.
26. Aelenei, D.; Aelenei, L.; Vieira, C.P. Adaptive Façade: Concept, applications, research questions. *Energy Procedia* **2016**, *91*, 269–275. [CrossRef]
27. Hou, K.; Li, S.; Wang, H. Simulation and experimental verification of energy saving effect of passive preheating natural ventilation double skin façade. *Energy Explor. Exploit.* **2021**, *39*, 464–487. [CrossRef]
28. Karimi, K.; Farrokhzad, M.; Roshan, G.; Aghdasi, M. Evaluation of effects of a green wall as a sustainable approach on reducing energy use in temperate and humid areas. *Energy Build.* **2022**, *262*, 112014. [CrossRef]
29. Tabadkani, A.; Roetzel, A.; Li, H.X.; Tsangrassoulis, A. Design approaches and typologies of adaptive Façades: A review. *Autom. Constr.* **2021**, *121*, 103450. [CrossRef]
30. Efthymiou, M.; Kontonis, P.; Leonidou, A.; Kazanakis, G.; Vassiliades, C. Investigation of Sun Protection Issues via the Active and Passive Building Integration of Active Solar Energy Systems: A Case Study of the Renovation of an Existing Building in Cyprus. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *410*, 012063. [CrossRef]
31. Năstase, G.; Doboși, I.S.; Brezeanu, A.I.; Taus, D.; Tăbăcaru, M.B.; Vuțoiu, B.G.; Rusu, D.; Bulmez, A.M.; Iordan, N.F. Experimental heat transfer, sound insulation and interior comfort parameters assessment on a box double-skin Façade. *Buildings* **2022**, *12*, 730. [CrossRef]
32. Cortês, A.; Almeida, J.; Santos, M.I.; Tadeu, A.; de Brito, J.; Silva, C.M. Environmental performance of a cork-based modular living wall from a life-cycle perspective. *Build. Environ.* **2021**, *191*, 107614. [CrossRef]
33. Pomponi, F.; Piroozfar, P.A.; Southall, R.; Ashton, P.; Farr, E.R. Energy performance of Double-Skin Façades in temperate climates: A systematic review and meta-analysis. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1525–1536. [CrossRef]
34. Soudian, S.; Berardi, U. Development of a performance-based design framework for multifunctional climate-responsive façades. *Energy Build.* **2021**, *231*, 110589. [CrossRef]
35. Hartman, P.; Čeheľová, D.; Bielek, B. Principal solutions for sustainable adaptive Façades providing suitable indoor environment for inhabitants. *Appl. Mech. Mater.* **2019**, *887*, 435–442. [CrossRef]
36. Zolfagharpour, A.; Shafaei, M.; Saeidi, P. Responsive Architecture Solutions to Reduce Energy Consumption of High-Rise Buildings. *Iran Univ. Sci. Technol.* **2022**, *32*, 1–17.
37. Shi, X.; Abel, T.; Wang, L. Influence of two motion types on solar transmittance and daylight performance of dynamic façades. *Sol. Energy* **2020**, *201*, 561–580. [CrossRef]
38. Assoa, Y.B.; Thony, P.; Messaoudi, P.; Schmitt, E.; Bizzini, O.; Gelibert, S.; Therme, D.; Rudy, J.; Chabuel, F. Study of a building integrated bifacial photovoltaic Façade. *Sol. Energy* **2021**, *227*, 497–515. [CrossRef]
39. Luo, Y.; Zhang, L.; Su, X.; Liu, Z.; Lian, J.; Luo, Y. Improved thermal-electrical-optical model and performance assessment of a PV-blind embedded glazing façade system with complex shading effects. *Appl. Energy* **2019**, *255*, 113896. [CrossRef]
40. Valladares-Rendón, L.; Schmid, G.; Lo, S.-L. Review on energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems. *Energy Build.* **2017**, *140*, 458–479. [CrossRef]
41. Meggers, F.; Baldini, L.; Leibundgut, H. An innovative use of renewable ground heat for insulation in low exergy building systems. *Energies* **2012**, *5*, 3149–3166. [CrossRef]
42. Prieto, A.; Knaack, U.; Auer, T.; Klein, T. COOLFAÇADE: State-of-the-art review and evaluation of solar cooling technologies on their potential for façade integration. *Renew. Sustain. Energy Rev.* **2019**, *101*, 395–414. [CrossRef]
43. Attia, S.; Lioure, R.; Declaude, Q. Future trends and main concepts of adaptive Façade systems. *Energy Sci. Eng.* **2020**, *8*, 3255–3272. [CrossRef]
44. Saretta, E.; Caputo, P.; Frontini, F. A review study about energy renovation of building Façades with BIPV in urban environment. *Sustain. Cities Soc.* **2019**, *44*, 343–355. [CrossRef]
45. Radić, M.; Brković Dodig, M.; Auer, T. Green Façades and living walls—A review establishing the classification of construction types and mapping the benefits. *Sustainability* **2019**, *11*, 4579. [CrossRef]
46. CWCT. *Technical Note No. 15 Curtain Wall Types*; Centre for Window & Cladding Technology, University of Bath: Bath, UK, 2000.
47. Barbosa, A.R.; Fahnestock, L.A.; Fick, D.R.; Gautam, D.; Soti, R.; Wood, R.; Moaveni, B.; Stavridis, A.; Olsen, M.J.; Rodrigues, H. Performance of medium-to-high rise reinforced concrete frame buildings with masonry infill in the 2015 Gorkha, Nepal, earthquake. *Earthq. Spectra* **2017**, *33*, 197–218. [CrossRef]
48. Finken, G.R.; Bjarløv, S.P.; Peuhkuri, R.H. Effect of façade impregnation on feasibility of capillary active thermal internal insulation for a historic dormitory–A hygrothermal simulation study. *Constr. Build. Mater.* **2016**, *113*, 202–214. [CrossRef]
49. Hendry, A.W.; Khalaf, F.M. *Masonry Wall Construction*; CRC Press: Boca Raton, FL, USA, 2017.
50. Watts, A. Profiled Metal Cladding. In *Modern Construction Envelopes*; Springer: Cham, Switzerland, 2011; pp. 24–33.
51. Roque, E.; Santos, P. The effectiveness of thermal insulation in lightweight steel-framed walls with respect to its position. *Buildings* **2017**, *7*, 13. [CrossRef]
52. Gross, R. Modest masterpiece. *Sanctuary Mod. Green Homes* **2022**, *58*, 34–39.
53. White, N.; Delichatsios, M.; White, N.; Delichatsios, M. Combustible exterior wall systems in common use. In *Fire Hazards of Exterior Wall Assemblies Containing Combustible Components*; Springer: Cham, Switzerland, 2015; pp. 3–10.
54. Mohaney, P.; Soni, E.G. Aluminium composite panel as a Façade material. *Int. J. Eng. Trends Technol.* **2018**, *55*, 75–80. [CrossRef]

55. Silvestre, J.D.; De Brito, J. Ceramic tiling in building façades: Inspection and pathological characterization using an expert system. *Constr. Build. Mater.* **2011**, *25*, 1560–1571. [CrossRef]
56. Chen, D.; Deng, J.; Cheng, B.; Wang, Q.; Zhao, B. New anticracking glass-fiber-reinforced cement material and integrated composite technology with lightweight concrete panels. *Adv. Civ. Eng.* **2021**, *2021*, 7447066. [CrossRef]
57. Sukontasukkul, P. Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel. *Constr. Build. Mater.* **2009**, *23*, 1084–1092. [CrossRef]
58. Pastor, J.; García, L.; Quintana, S.; Peña, J. Glass reinforced concrete panels containing recycled tyres: Evaluation of the acoustic properties of for their use as sound barriers. *Constr. Build. Mater.* **2014**, *54*, 541–549. [CrossRef]
59. Donà, M.; Overend, M. Fatigue performance of a connection for GRC cladding panels. In Proceedings of the 8th International Conference on Advanced Composites in Construction (ACIC 2017), Sheffield, UK, 5–7 September 2017.
60. Aboulnaga, M.M. Towards green buildings: Glass as a building element—The use and misuse in the gulf region. *Renew. Energy* **2006**, *31*, 631–653. [CrossRef]
61. Naqash, M.T.; Formisano, A.; De Matteis, G. Aluminium framing members in Façades. *Key Eng. Mater.* **2016**, *710*, 327–332. [CrossRef]
62. Leśniak, A.; Górka, M. Evaluation of selected lightweight curtain wall solutions using multi criteria analysis. *AIP Conf. Proc.* **2018**, *1978*, 240003.
63. Boafo, F.E.; Kim, J.-H.; Kim, J.-T. Numerical study of slim curtain wall spandrel with integrated vacuum insulation panel: Concept, performance evaluation and challenges. *Energy Build.* **2019**, *183*, 139–150. [CrossRef]
64. Yu, Y.; Liu, T.; Zhang, Q.; Yang, B. Wind-induced response of an L-shaped cable support glass curtain wall. *Shock Vib.* **2017**, *2017*, 4163045. [CrossRef]
65. Rapone, G.; Saro, O. Optimisation of curtain wall façades for office buildings by means of PSO algorithm. *Energy Build.* **2012**, *45*, 189–196. [CrossRef]
66. Baniotopoulos, C.C.; Nikolaidis, T.N.; Moutsanidis, G. Optimal structural design of glass curtain-wall systems. *Proc. Inst. Civ. Eng.-Struct. Build.* **2016**, *169*, 450–457. [CrossRef]
67. Galli, U. *Seismic Behaviour of Curtain Wall Façades: A Comparison between Experimental Mock up Test and Finite Element Method Analysis*; Politecnico di Milano: Milan, Italy, 2012.
68. Yoshino, M.; Nakada, N.; Mori, T.; Yamagishi, K.; Yoshida, S.; Higashi, Y.; Shirasawa, K. Photovoltaic modules integrated with a metal curtain wall. In Proceedings of the IEEE 1st World Conference on Photovoltaic Energy Conversion-WCPEC (A Joint Conference of PVSC, PVSEC and PSEC), Waikoloa, HI, USA, 5–9 December 1994; pp. 969–972.
69. Forster, K.W. "The New Museum In New York: A Whitewash?" Log, no. 12, 2008, pp. 5–12. JSTOR. Available online: http://www.jstor.org/stable/41765605 (accessed on 25 September 2023).
70. Watts, A. Sheet metal. In *Modern Construction Envelopes*; Springer: Cham, Switzerland, 2011; pp. 14–23.
71. Muhammad, L.B. Systematic Evaluation of Curtain Wall Types. Master's Thesis, Eastern Mediterranean University (EMU), Famagusta, Cyprus, 2010.
72. Punjabi, S.A. Development of an integrated building design information interface. In Proceedings of the Ninth International IBPSA Conference, Montreal, QC, Canada, 15–18 August 2005.
73. Kanniyapan, G.; Nesan, L.J.; Mohammad, I.S.; Keat, T.S.; Ponniah, V. Selection criteria of building material for optimising maintainability. *Constr. Build. Mater.* **2019**, *221*, 651–660. [CrossRef]
74. Juaristi, M.; Gómez-Acebo, T.; Monge-Barrio, A. Qualitative analysis of promising materials and technologies for the design and evaluation of Climate Adaptive Opaque Façades. *Build. Environ.* **2018**, *144*, 482–501. [CrossRef]
75. Korsgaard, H.; Hansen, N.B.; Basballe, D.; Dalsgaard, P.; Halskov, K. Odenplan: A media façade design process. In Proceedings of the 4th Media Architecture Biennale Conference: Participation, Aarhus, Denmark, 15–17 November 2012; pp. 23–32.
76. Cheng, C.; Cheung, K.K.; Chu, L. Thermal performance of a vegetated cladding system on Façade walls. *Build. Environ.* **2010**, *45*, 1779–1787. [CrossRef]
77. Saarinen, A. Reduction of external noise by building Façades: Tolerance of standard EN 12354-3. *Appl. Acoust.* **2002**, *63*, 529–545. [CrossRef]
78. Berardi, U.; Naldi, M. The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance. *Energy Build.* **2017**, *144*, 262–275. [CrossRef]
79. Aksamija, A.; Peters, T. Heat transfer in Façade systems and energy use: Comparative study of different exterior wall types. *J. Archit. Eng.* **2017**, *23*, C5016002. [CrossRef]
80. Liping, W.; Hien, W.N. The impacts of ventilation strategies and Façade on indoor thermal environment for naturally ventilated residential buildings in Singapore. *Build. Environ.* **2007**, *42*, 4006–4015. [CrossRef]
81. Charles Sturt University. *Guidelines for Managing Issues Relating to Indoor Thermal Comfort (Hot Conditions)*; Charles Sturt University: Bathurst, Australia, 2010.
82. Lies, K.M.; Faith, B.A. Window detailing considerations for leakage prevention. *ASTM Spec. Tech. Publ.* **1998**, *1314*, 33–46.
83. Dhima, D.; Duny, M.; Garo, J.-P.; Wang, H.-Y.; Jullien, Q. Experimental study on vertical wooden façade combustion. *Procedia Eng.* **2017**, *210*, 520–527.
84. Alekhin, V.; Sharovarova, E.; Budarin, A. Façade structures for energy-efficient buildings. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *463*, 042051. [CrossRef]

85. McKenna, S.T.; Jones, N.; Peck, G.; Dickens, K.; Pawelec, W.; Oradei, S.; Harris, S.; Stec, A.A.; Hull, T.R. Fire behaviour of modern façade materials—Understanding the Grenfell Tower fire. *J. Hazard. Mater.* **2019**, *368*, 115–123. [CrossRef] [PubMed]
86. Ahmed, M.M.; Abel-Rahman, A.K.; Ali, A.H.H.; Suzuki, M. Double skin façade: The state of art on building energy efficiency. *J. Clean Energy Technol.* **2016**, *4*, 84–89. [CrossRef]
87. Kültür, S.; Türkeri, N.; Knaack, U. A holistic decision support tool for Façade design. *Buildings* **2019**, *9*, 186. [CrossRef]
88. CWCT. *Technical Note No. 38 Acoustic Performance of Windows*; Centre for Window & Cladding Technology, University of Bath: Bath, UK, 2003.
89. Busa, L.; Secchi, S.; Baldini, S. Effect of façade shape for the acoustic protection of buildings. *Build. Acoust.* **2010**, *17*, 317–338. [CrossRef]
90. Blasco, M.; Belis, J.; De Bleecker, H. Acoustic failure analysis of windows in buildings. *Eng. Fail. Anal.* **2011**, *18*, 1761–1774. [CrossRef]
91. Pérez-Bella, J.M.; Domínguez-Hernández, J.; Rodríguez-Soria, B.; Del Coz-Díaz, J.J.; Cano-Suñén, E. Optimised method for estimating directional driving rain from synoptic observation data. *J. Wind Eng. Ind. Aerodyn.* **2013**, *113*, 1–11. [CrossRef]
92. Beasley, K.J. Building Façade failures in the urban environment. *Proc. Inst. Civ. Eng.-Forensic Eng.* **2016**, *170*, 8–13. [CrossRef]
93. Beasley, K.J. Latent building Façade failures. In *Forensic Engineering 2012: Gateway to a Safer Tomorrow*; ASCE: Reston, VA, USA, 2013; pp. 918–927.
94. Sivanerupan, S.; Wilson, J.L.; Gad, E.; Lam, N. Seismic assessment of glazed Façade systems. In Proceedings of the Annual Technical Conference of the Australian Earthquake Engineering Society, Newcastle, Australia, 29 November–1 December 2019.
95. Tabatabaee, S.; Weil, B.S.; Aksamija, A. Negative life-cycle emissions growth rate through retrofit of existing institutional buildings: Energy analysis and life cycle assessment of a case study of University Dormitory Renovation. In Proceedings of the Architectural Research Centers Consortium (ARCC), Chicago, IL, USA, 6–9 April 2015.
96. Nguyen, Q.; Ngo, T.; Mendis, P.; Tran, P. Composite materials for next generation building Façade systems. *Civ. Eng. Archit.* **2013**, *1*, 88–95. [CrossRef]
97. Krstić-Furundžić, A.; Vujošević, M.; Petrovski, A. Energy and environmental performance of the office building Façade scenarios. *Energy* **2019**, *183*, 437–447. [CrossRef]
98. Bauer, E.; Pavon, E.; Barreira, E.; De Castro, E.K. Analysis of building Façade defects using infrared thermography: Laboratory studies. *J. Build. Eng.* **2016**, *6*, 93–104. [CrossRef]
99. Panagiotidou, M.; Fuller, R.J. Progress in ZEBs—A review of definitions, policies and construction activity. *Energy Policy* **2013**, *62*, 196–206. [CrossRef]
100. Yang, B.; Wei, Z.; Li, Q.; Li, J. Semiautomated building Façade footprint extraction from mobile LiDAR point clouds. *IEEE Geosci. Remote Sens. Lett.* **2012**, *10*, 766–770. [CrossRef]
101. Cabeza, L.F.; Chàfer, M. Technological options and strategies towards zero energy buildings contributing to climate change mitigation: A systematic review. *Energy Build.* **2020**, *219*, 110009. [CrossRef]
102. Rahiminejad, M.; Khovalyg, D. Numerical and experimental study of the dynamic thermal resistance of ventilated air-spaces behind passive and active façades. *Build. Environ.* **2022**, *225*, 109616. [CrossRef]
103. Manso, M.; Castro-Gomes, J. Green wall systems: A review of their characteristics. *Renew. Sustain. Energy Rev.* **2015**, *41*, 863–871. [CrossRef]
104. Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Berardi, U.; Tookey, J.; Li, D.H.W.; Kariminia, S. Exploring the advantages and challenges of double-skin façades (DSFs). *Renew. Sustain. Energy Rev.* **2016**, *60*, 1052–1065. [CrossRef]
105. Noaman, D.S.; Moneer, S.A.; Megahed, N.A.; El-Ghafour, S.A. Integration of active solar cooling technology into passively designed Façade in hot climates. *J. Build. Eng.* **2022**, *56*, 104658. [CrossRef]
106. Özdemir, H.; Çakmak, B.Y. Evaluation of Daylight and Glare Quality of Office Spaces with Flat and Dynamic Shading System Façades in Hot Arid Climate. *J. Daylighting* **2022**, *9*, 197–208. [CrossRef]
107. Böke, J.; Denz, P.-R.; Suwannapruk, N.; Vongsingha, P. Active, Passive and Cyber-Physical Adaptive Façade Strategies: A Comparative Analysis Through Case Studies. *J. Façade Des. Eng.* **2022**, *10*, 1–18. [CrossRef]
108. Fuliotto, R.; Cambuli, F.; Mandas, N.; Bacchin, N.; Manara, G.; Chen, Q. Experimental and numerical analysis of heat transfer and airflow on an interactive building Façade. *Energy Build.* **2010**, *42*, 23–28. [CrossRef]
109. Joe, J.; Choi, W.; Kwak, Y.; Huh, J.-H. Optimal design of a multi-story double skin Façade. *Energy Build.* **2014**, *76*, 143–150. [CrossRef]
110. Halawa, E.; Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Trombley, J.; Hassan, N.; Baig, M.; Yusoff, S.Y.; Ismail, M.A. A review on energy conscious designs of building façades in hot and humid climates: Lessons for (and from) Kuala Lumpur and Darwin. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2147–2161. [CrossRef]
111. Pomponi, F.; Barbosa, S.; Piroozfar, P.A. On the intrinsic flexibility of the double skin façade: A comparative thermal comfort investigation in tropical and temperate climates. *Energy Procedia* **2017**, *111*, 530–539. [CrossRef]
112. De Gracia, A.; Castell, A.; Navarro, L.; Oró, E.; Cabeza, L.F. Numerical modelling of ventilated Façades: A review. *Renew. Sustain. Energy Rev.* **2013**, *22*, 539–549. [CrossRef]
113. Barbosa, S.; Ip, K. Perspectives of double skin façades for naturally ventilated buildings: A review. *Renew. Sustain. Energy Rev.* **2014**, *40*, 1019–1029. [CrossRef]

114. Bostancioglu, E. Double skin façade assessment by fuzzy AHP and comparison with AHP. *Archit. Eng. Des. Manag.* **2021**, *17*, 110–130. [CrossRef]
115. Ascione, F.; Bianco, N.; de Rossi, F.; Iovane, T.; Mauro, G.M. Are transparent double-skin Façades effective for energy retrofit? Answers for an office building-with and without photovoltaic integration. *Energy Sources Part A Recovery Util. Environ. Eff.* **2022**, *44*, 257–271. [CrossRef]
116. Aldawoud, A.; Salameh, T.; Ki Kim, Y. Double skin façade: Energy performance in the United Arab Emirates. *Energy Sources Part B Econ. Plan. Policy* **2021**, *16*, 387–405. [CrossRef]
117. Attia, S.; Favoino, F.; Loonen, R.; Petrovski, A.; Monge-Barrio, A. Adaptive façades system assessment: An initial review. In Proceedings of the 10th Conference on Advanced Building Skins, Bern, Switzerland, 3–4 November 2015.
118. Romano, R.; Aelenei, L.; Aelenei, D.; Mazzucchelli, E.S. What is an adaptive façade? Analysis of Recent Terms and definitions from an international perspective. *J. Façade Des. Eng.* **2018**, *6*, 65–76.
119. Bianco, L.; Lo Verso, V.R.; Serra, V.; Perino, M. Monitoring energy and comfort performance of transparent adaptive façades. In Proceedings of the 10th Conference on Advanced Building Skins—Energy Forum, Bern, Switzerland, 3–4 November 2015; pp. 1234–1243.
120. Ibrahim, J.A.; Alibaba, H.Z. Kinetic Façade as a Tool for energy Efficiency. *Int. J. Eng. Res. Rev* **2019**, *7*, 1–7.
121. Kensek, K.; Hansanuwat, R. Environment control systems for sustainable design: A methodology for testing, simulating and comparing kinetic Façade systems. *J. Creat. Sustain. Archit. Built Environ.* **2011**, *1*, 27–46.
122. Kim, H.-J.; Yang, C.-S.; Moon, H.J. A study on multi-objective parametric design tool for surround-type movable shading device. *Sustainability* **2019**, *11*, 7096. [CrossRef]
123. Luo, Y.; Zhang, L.; Bozlar, M.; Liu, Z.; Guo, H.; Meggers, F. Active building envelope systems toward renewable and sustainable energy. *Renew. Sustain. Energy Rev.* **2019**, *104*, 470–491. [CrossRef]
124. Hosseini, S.M.; Mohammadi, M.; Rosemann, A.; Schröder, T.; Lichtenberg, J. A morphological approach for kinetic façade design process to improve visual and thermal comfort. *Build. Environ.* **2019**, *153*, 186–204. [CrossRef]
125. Yoon, J. SMP prototype design and fabrication for thermo-responsive façade elements. *J. Façade Des. Eng.* **2019**, *7*, 41–62.
126. Lampert, C.M. Large-area smart glass and integrated photovoltaics. *Sol. Energy Mater. Sol. Cells* **2003**, *76*, 489–499. [CrossRef]
127. Carlucci, F. A review of smart and responsive building technologies and their classifications. *Future Cities Environ.* **2021**, *7*, 10. [CrossRef]
128. Taveres-Cachat, E.; Grynning, S.; Thomsen, J.; Selkowitz, S. Responsive building envelope concepts in zero emission neighborhoods and smart cities-A roadmap to implementation. *Build. Environ.* **2019**, *149*, 446–457. [CrossRef]
129. Karanouh, A.; Kerber, E. Innovations in dynamic architecture. *J. Façade Des. Eng.* **2015**, *3*, 185–221. [CrossRef]
130. Elsadek, M.; Liu, B.; Lian, Z. Green façades: Their contribution to stress recovery and well-being in high-density cities. *Urban For. Urban Green.* **2019**, *46*, 126446. [CrossRef]
131. Dungca, D.M.R.; Larioza, M.D.M.; Mondoñedo, P.M.M.; Orence, H.F.A.; Sigue, A.-L.F.; Medina, O.A.; Soriano, A.J.; Mandayo, E.A. Innovating Green Wall: A Sustainable Way of Enhancing the Vertical Planting System. In Proceedings of the IEEE 13th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), Manila, Philippines, 28–30 November 2021; pp. 1–6.
132. Feng, H.; Hewage, K. Lifecycle assessment of living walls: Air purification and energy performance. *J. Clean. Prod.* **2014**, *69*, 91–99. [CrossRef]
133. Kim, J.-H.; Choi, W.-J.; Yoon, Y.-H. A Study on verifying the effect of thermal environment control of Street Canyons based on application of green wall system. *J. Environ. Sci. Int.* **2016**, *25*, 311–322. [CrossRef]
134. Francis, R.A.; Lorimer, J. Urban reconciliation ecology: The potential of living roofs and walls. *J. Environ. Manag.* **2011**, *92*, 1429–1437. [CrossRef]
135. Wong, I.; Baldwin, A.N. Investigating the potential of applying vertical green walls to high-rise residential buildings for energy-saving in sub-tropical region. *Build. Environ.* **2016**, *97*, 34–39. [CrossRef]
136. Lai, C.-M.; Hokoi, S. Solar façades: A review. *Build. Environ.* **2015**, *91*, 152–165. [CrossRef]
137. Spanos, I.; Duckers, L. Expected cost benefits of building-integrated PVs in UK, through a quantitative economic analysis of PVs in connection with buildings, focused on UK and Greece. *Renew. Energy* **2004**, *29*, 1289–1303. [CrossRef]
138. Qiu, Z.; Chow, T.; Li, P.; Li, C.; Ren, J.; Wang, W. Performance evaluation of the photovoltaic double-skin Façade. In Proceedings of the 11th International IBPSA Conference—Building Simulation (BS 2009), Glasgow, UK, 27–30 July 2009; pp. 2251–2257.
139. Ng, P.K.; Mithraratne, N. Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics. *Renew. Sustain. Energy Rev.* **2014**, *31*, 736–745. [CrossRef]
140. Quesada, G.; Rousse, D.; Dutil, Y.; Badache, M.; Hallé, S. A comprehensive review of solar Façades. Transparent and translucent solar Façades. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2643–2651. [CrossRef]
141. Radhi, H. Energy analysis of façade-integrated photovoltaic systems applied to UAE commercial buildings. *Sol. Energy* **2010**, *84*, 2009–2021. [CrossRef]
142. Frontini, F.; Bonomo, P.; Moser, D.; Maturi, L. 8—Building integrated photovoltaic Façades: Challenges, opportunities and innovations. In *Rethinking Building Skins*; Gasparri, E., Brambilla, A., Lobaccaro, G., Goia, F., Andaloro, A., Sangiorgio, A., Eds.; Woodhead Publishing: Sawston, UK, 2022; pp. 201–229. [CrossRef]

143. Almusaed, A.; Yitmen, I.; Almsaad, A.; Akiner, İ.; Akiner, M.E. Coherent investigation on a smart kinetic wooden façade based on material passport concepts and environmental profile inquiry. *Materials* **2021**, *14*, 3771. [CrossRef]
144. Xu, H.; Li, J.; Wu, J.; Kang, J. Evaluation of wood coverage on building Façades towards sustainability. *Sustainability* **2019**, *11*, 1407. [CrossRef]
145. Schoof, J. Timber construction returns to the city. *Detail* **2018**, 1–2. Available online: https://www.detail.de/de_en/detail-1-2-2018 (accessed on 25 September 2023).
146. Kukk, V.; Kaljula, L.; Kers, J.; Kalamees, T. Designing highly insulated cross-laminated timber external walls in terms of hygrothermal performance: Field measurements and simulations. *Build. Environ.* **2022**, *212*, 108805. [CrossRef]
147. Fedorczak-Cisak, M.; Radziszewska-Zielina, E.; Orlik-Kożdoń, B.; Steidl, T.; Tatara, T. Analysis of the thermal retrofitting potential of the external walls of podhale's historical timber buildings in the aspect of the non-deterioration of their technical condition. *Energies* **2020**, *13*, 4610. [CrossRef]
148. Bader Eddin, M.; Vardaxis, N.-G.; Ménard, S.; Bard Hagberg, D.; Kouyoumji, J.-L. Prediction of Sound Insulation Using Artificial Neural Networks—Part II: Lightweight Wooden Façade Structures. *Appl. Sci.* **2022**, *12*, 6983. [CrossRef]
149. Gasparri, E.; Lucchini, A.; Mantegazza, G.; Mazzucchelli, E.S. Construction management for tall CLT buildings: From partial to total prefabrication of façade elements. *Wood Mater. Sci. Eng.* **2015**, *10*, 256–275. [CrossRef]
150. Ivanović-Šekularac, J.; Šekularac, N. Impacts of traditional architecture on the use of wood as an element of Façade covering in Serbian contemporary architecture. *Spatium* **2011**, 57–62. [CrossRef]
151. Maniak-Huesser, M.; Tellnes, L.G.; Zea Escamilla, E. Mind the gap: A policy gap analysis of programmes promoting timber construction in nordic countries. *Sustainability* **2021**, *13*, 11876. [CrossRef]
152. Davies, I. Development of performance-based standards for external timber cladding. *Energy Procedia* **2015**, *78*, 183–188. [CrossRef]
153. Brzezicki, M. Glass protected timber façades–new sustainable façade typology. *Tech. Trans.* **2019**, *116*, 5–22. [CrossRef]
154. Lehmann, S. Sustainable construction for urban infill development using engineered massive wood panel systems. *Sustainability* **2012**, *4*, 2707–2742. [CrossRef]
155. Schmid, J.; Werther, N.; Klippel, M.; Frangi, A. Structural fire design-statement on the design of cross-laminated timber (CLT). *Civ. Eng. Res. J.* **2019**, *7*, 113–117. [CrossRef]
156. Nunes, G.; de Melo Moura, J.D.; Güths, S.; Atem, C.; Giglio, T. Thermo-energetic performance of wooden dwellings: Benefits of cross-laminated timber in Brazilian climates. *J. Build. Eng.* **2020**, *32*, 101468. [CrossRef]
157. Di Bella, A.; Mitrovic, M. Acoustic characteristics of cross-laminated timber systems. *Sustainability* **2020**, *12*, 5612. [CrossRef]
158. Younis, A.; Dodoo, A. Cross-laminated timber for building construction: A life-cycle-assessment overview. *J. Build. Eng.* **2022**, *52*, 104482. [CrossRef]
159. Eliassen, A.; Faanes, S.; Bohne, R. Comparative LCA of a concrete and steel apartment building and a cross laminated timber apartment building. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012017. [CrossRef]
160. Game, D.; Noorvand, H.; Arce, G.; Hassan, M.M. Evaluation of Cementitious Matrices for the Development of Ultra-High Performance Engineered Cementitious Composites. In Proceedings of the Tran-SET 2021 Conference, Online, 3–4 June 2021; American Society of Civil Engineers: Reston, VA, USA, 2021; pp. 188–198.
161. Sidodikromo, E.P.; Chen, Z.; Habib, M. Review of the cement-based composite ultra-high-performance concrete (UHPC). *Open Civ. Eng. J.* **2019**, *13*, 147–162. [CrossRef]
162. Kishore, M.V.; Yadav, H.; Garg, A. Architectural Use of Precast Ultra High Performance Concrete. *Int. J. Sci. Res.* **2015**, *4*, 4–5.
163. Von Werder, J.; Fontana, P.; Hoppe, J.; Bilgin, S.; Meng, B. Composite Façade Elements with Self-Cleaning Surface made of Ultra-High-Performance Concrete (UHPC). In *Current Topics and Trends on Durability of Building Materials and Components, Proceedings of the XV Edition of the International Conference on Durability of Building Materials and Components (DBMC 2020), Barcelona, Spain, 20–23 October 2020*; International Center for Numerical Methods in Engineering: Barcelona, Spain, 2020; pp. 1289–1297.
164. Novotná, M.; Kostelecká, M.; Hodková, J.; Vokáč, M. Use of textile reinforced concrete–especially for Façade panels. *Adv. Mater. Res.* **2014**, *923*, 142–145. [CrossRef]
165. O'Hegarty, R.; Kinnane, O.; Newell, J.; West, R. High performance, low carbon concrete for building cladding applications. *J. Build. Eng.* **2021**, *43*, 102566. [CrossRef]
166. Shah, H.A.; Yuan, Q.; Photwichai, N. Use of materials to lower the cost of ultra-high-performance concrete—A review. *Constr. Build. Mater.* **2022**, *327*, 127045. [CrossRef]
167. Buitelaar, P.; ApS, C. Ultra high performance concrete: Developments and applications during 25 years. In Proceedings of the Plenary Session International Symposium on UHPC, Kassel, Germany, 13–15 September 2004.
168. Onyszkiewicz, J.; Sadowski, K. Proposals for the revitalization of prefabricated building Façades in terms of the principles of sustainable development and social participation. *J. Build. Eng.* **2022**, *46*, 103713. [CrossRef]
169. Vahidi, E.; Malekabadi, M. GRC and sustainable building design. In Proceedings of the GRCA 2011 Congress, Istanbul, Turkey, 4–8 September 2011.
170. Blackman, L. Glass fibre-reinforced cement: A progress report. *Composites* **1979**, *10*, 69–72. [CrossRef]
171. Bijen, J. Glass fibre reinforced cement: Improvements by polymer addition. In Proceedings of the Materials Research Society. Annual Meeting, Boston, MA, USA, 17–18 November 1980; pp. 239–249.
172. Ball, H. 25 years of forton polymer modified GRC: Reasons for its use. In Proceedings of the GRCA 2005 Congress, Hong Kong, China, 14–16 November 2005; Chapter 11.

173. Bijen, J. Improved mechanical properties of glass fibre reinforced cement by polymer modification. *Cem. Concr. Compos.* **1990**, *12*, 95–101. [CrossRef]
174. Sturm, M.T.; Horn, H.; Schuhen, K. Removal of microplastics from waters through agglomeration-fixation using organosilanes—Effects of polymer types, water composition and temperature. *Water* **2021**, *13*, 675. [CrossRef]
175. Lello, J.C.; Camposinhos, R.S. Natural stone panels—An innovative façade system. In Proceedings of the Global Stone Congress, Alicante, Spain, 2–5 March 2010.
176. Dadakhanov, F.; Sharopov, B.; Umarov, I.; Mukhtoraliyeva, M.; Hakimov, S.; Abdunazarov, A.; Kazadayev, A. Prospects of Innovative Materials Production in the Building Materials Industry. *J. New Century Innov.* **2022**, *18*, 162–167.
177. Albu, D.; Lesan, A. Opportunities for rehabilitation of Façades of historic buildings in Moldova with limestone elements. *Conf. Ser. Mater. Sci. Eng.* **2021**, *1209*, 012008. [CrossRef]
178. Dabous, S.A.; Ibrahim, T.; Shareef, S.; Mushtaha, E.; Alsyouf, I. Sustainable façade cladding selection for buildings in hot climates based on thermal performance and energy consumption. *Results Eng.* **2022**, *16*, 100643. [CrossRef]
179. Ozkahraman, H.T.; Bolatturk, A. The use of tuff stone cladding in buildings for energy conservation. *Constr. Build. Mater.* **2006**, *20*, 435–440. [CrossRef]
180. AlizadehKharazi, B.; Alvanchi, A.; Taghaddos, H. A novel building information modeling-based method for improving cost and energy performance of the building envelope. *Int. J. Eng.* **2020**, *33*, 2162–2173.
181. Ferreira, C.; Silva, A.; De Brito, J.; Dias, I.; Flores-Colen, I. Definition of a condition-based model for natural stone claddings. *J. Build. Eng.* **2021**, *33*, 101643. [CrossRef]
182. Vigna, I.; Bianco, L.; Goia, F.; Serra, V. Phase change materials in transparent building envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) analysis. *Energies* **2018**, *11*, 111. [CrossRef]
183. Karthick, A.; Murugavel, K.K.; Ramanan, P. Performance enhancement of a building-integrated photovoltaic module using phase change material. *Energy* **2018**, *142*, 803–812. [CrossRef]
184. Madhumathi, A.; Sundarraja, B. Experimental study of passive cooling of building Façade using phase change materials to increase thermal comfort in buildings in hot humid areas. *Int. J. Energy Environ.* **2012**, *3*, 739–748.
185. Balocco, C.; Petrone, G. Numerical modelling for the thermal performance assessment of a semi-opaque façade with a multilayer of nano-structured and phase change materials. *Buildings* **2017**, *7*, 90. [CrossRef]
186. Li, D.; Yang, R.; Arıcı, M.; Wang, B.; Tunçbilek, E.; Wu, Y.; Liu, C.; Ma, Z.; Ma, Y. Incorporating phase change materials into glazing units for building applications: Current progress and challenges. *Appl. Therm. Eng.* **2022**, *210*, 118374. [CrossRef]
187. Liang, J.; Zhang, X.; Ji, J. Hygroscopic phase change composite material—A review. *J. Energy Storage* **2021**, *36*, 102395. [CrossRef]
188. Souayfane, F.; Fardoun, F.; Biwole, P.-H. Phase change materials (PCM) for cooling applications in buildings: A review. *Energy Build.* **2016**, *129*, 396–431. [CrossRef]
189. Gangåssæter, H.F.; Jelle, B.P.; Mofid, S.A.; Gao, T. Air-filled nanopore based high-performance thermal insulation materials. *Energy Procedia* **2017**, *132*, 231–236. [CrossRef]
190. Cuce, E.; Cuce, P.M.; Wood, C.J.; Riffat, S.B. Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings. *Energy Build.* **2014**, *77*, 28–39. [CrossRef]
191. Simões, N.; Gonçalves, M.; Serra, C.; Resalati, S. Can vacuum insulation panels be cost-effective when applied in building façades? *Build. Environ.* **2021**, *191*, 107602. [CrossRef]
192. Campbell, C.L. Durability Characterization of a High Performance Building Envelope with Vacuum Insulation Panels and Energy Recovery Ventilation. Master's Thesis, Carleton University, Ottawa, ON, Canada, 2021.
193. Boafo, F.E.; Kim, J.-H.; Ahn, J.-G.; Kim, S.-M.; Kim, J.-T.; Zhang, L. Study on thermal characteristics and electrical performance of a hybrid building integrated photovoltaic (BIPV) system combined with vacuum insulation panel (VIP). *Energy Build.* **2022**, *277*, 112574. [CrossRef]
194. Peter, A.E.K.; Balasubramanian, M.; Arul Jayakumar, A.; Mukilan, P.; Aishwarya, S. A.E.K.; Balasubramanian, M.; Arul Jayakumar, A.; Mukilan, P.; Aishwarya, S. A partial replacement of cement using extract powder form of silica aerogel. In *Sustainable Construction Materials: Select Proceedings of ACMM 2021*; Springer: Cham, Switzerland, 2021; pp. 61–73.
195. Khan, A.A.; Lin, S.; Huang, X.; Usmani, A. Façade fire hazards of bench-scale aluminum composite panel with flame-retardant core. *Fire Technol.* **2021**, *59*, 5–28. [CrossRef]
196. Yılmaz, E.; Aykanat, B.; Çomak, B. Environmental life cycle assessment of rockwool filled aluminum sandwich Façade panels in Turkey. *J. Build. Eng.* **2022**, *50*, 104234. [CrossRef]
197. Luong, D.L.; Truong, N.-S.; Ngo, N.-T.; Nguyen, Q.T. Enhancing Building Energy Efficiency with Aluminum Composite Material Façade: A Performance Simulation Study using Building Energy Modeling and Building Information Modeling. *IOP Conf. Ser. Mater. Sci. Eng.* **2023**, *1289*, 012040. [CrossRef]
198. Kumar, N.; Soni, K.; Agarwal, R. Design and development of sodar antenna structure. *Mapan* **2021**, *36*, 785–793. [CrossRef]
199. Almarzooqi, A.; Alzubaidi, A.; Alkatheeri, S. Fire hazards by aluminum composite cladding in high-rise buildings. In Proceedings of the 5th European International Conference on Industrial Engineering and Operations Management, Rome, Italy, 26–28 July 2022.
200. Kamatchi, R.M.; Muraliraja, R.; Vijay, J.; Bharathi, C.S.; Eswar, M.K.; Padmanabhan, S. Synthesis of Newly Formulated Aluminium Composite through Powder Metallurgy using Waste Bone Material. *E3S Web Conf.* **2023**, *399*, 03016. [CrossRef]

201. Sharma, A.K.; Bhattacharya, B. Engineering design of sustainable aluminium composite material with rice husk core. *Int. J. Sustain. Eng.* **2021**, *14*, 1372–1385. [CrossRef]
202. Australian Building Code Board. *National Construction Code*; Australian Building Code Board: Canbera, Australia, 2020.
203. *AS/NZS 4859-2018*; Thermal Insulation Materials for Buildings Design. Standards Australia: Sydney, Australia, 2018.
204. Ambrose, M.; James, M.; Law, A.; Osman, P.; White, S. *The Evaluation of the 5-Star Energy Efficiency Standard for Residential Buildings*; Commonwealth of Australia: Canberra, Australia, 2013.
205. Stephan, A.; Jensen, C.A.; Crawford, R.H. Improving the life cycle energy performance of apartment units through façade design. *Procedia Eng.* **2017**, *196*, 1003–1010. [CrossRef]
206. *AS/NZS 4284:2008*; Testing of Building Facades. Standards Australia: Sydney, Australia, 2008.
207. Wang, Y.; He, F.; Lv, Z.; Yang, W.; Wang, Q. Experimental investigations on thermal performance of spray cooling double skin façade in hot humid climate region. *Energy Build.* **2022**, *277*, 112605. [CrossRef]
208. Yang, S.; Cannavale, A.; Di Carlo, A.; Prasad, D.; Sproul, A.; Fiorito, F. Performance assessment of BIPV/T double-skin façade for various climate zones in Australia: Effects on energy consumption. *Sol. Energy* **2020**, *199*, 377–399. [CrossRef]
209. Shan, R.; Junghans, L. "Adaptive radiation" optimization for climate adaptive building Façade design strategy. *Build. Simul.* **2018**, *11*, 269–279. [CrossRef]
210. Kuru, A.; Fiorito, F.; Oldfield, P.; Bonser, S.P. Multi-functional biomimetic adaptive façades: A case study. In Proceedings of the FAÇADE 2018—Final Conference of COST TU1403 "Adaptive Façades Network", Lucerne, Switzerland, 26–27 November 2018.
211. Biloria, N.; Makki, M.; Abdollahzadeh, N. Multi-performative façade systems: The case of real-time adaptive BIPV shading systems to enhance energy generation potential and visual comfort. *Front. Built Environ.* **2023**, *9*, 1119696. [CrossRef]
212. Hasan, M.M.; Karim, A.; Brown, R.; Perkins, M.; Joyce, D. Estimation of energy saving of commercial building by living wall and green Façade in sub-tropical climate of Australia. In Proceedings of the 7th International Green Energy Conference and the 1st DNL Conference on Clean Energy (IGEC-DCCE), Dalian, China, 28–30 May 2012; pp. 672–686.
213. Giordano, R.; Montacchini, E.; Tedesco, S.; Perone, A. Living wall systems: A technical standard proposal. *Energy Procedia* **2017**, *111*, 298–307. [CrossRef]
214. Alam, M.; Jamil, H.; Sanjayan, J.; Wilson, J. Energy saving potential of phase change materials in major Australian cities. *Energy Build.* **2014**, *78*, 192–201. [CrossRef]
215. Acuña-Díaz, O.; Al-Halawani, N.; Alonso-Barneto, M.; Ashirbekov, A.; Ruiz-Flores, C.; Rojas-Solórzano, L. Economic viability of phase-changing materials in residential buildings–A case study in Alice Springs, Australia. *Energy Build.* **2022**, *254*, 111612. [CrossRef]
216. Lehmann, S. Developing a prefabricated low-carbon construction system using cross-laminated timber (CLT) panels for multi-storey inner-city infill housing in Australia. *J. Green Build.* **2012**, *7*, 131–150. [CrossRef]
217. Wasim, M.; Oliveira, O.; Ngo, T.D. Structural performance of prefabricated glass fibre concrete floor panel versus compressed fibre cement floor panel for an optimised volumetric module—A case study. *J. Build. Eng.* **2022**, *48*, 103819. [CrossRef]
218. Rickard, C. GRC developments in Australia. In Proceedings of the GRCA Congress 2015, Dubai, United Arab Emirates, 19–21 April 2015.
219. Jalali, Z.; Noorzai, E.; Heidari, S. Design and optimization of form and Façade of an office building using the genetic algorithm. *Sci. Technol. Built Environ.* **2020**, *26*, 128–140. [CrossRef]
220. Perini, K.; Ottelé, M.; Haas, E.; Raiteri, R. Vertical greening systems, a process tree for green façades and living walls. *Urban Ecosyst.* **2013**, *16*, 265–277. [CrossRef]
221. Sandberg, K.; Orskaug, T.; Andersson, A. Prefabricated wood elements for sustainable renovation of residential building façades. *Energy Procedia* **2016**, *96*, 756–767. [CrossRef]
222. Shi, L.; Pouramini, S. Adaptive façade for building energy efficiency improvement by arithmetical optimization algorithm. *Concurr. Comput. Pract. Exp.* **2022**, *34*, e7152. [CrossRef]
223. Ascione, F.; Bianco, N.; Iovane, T.; Mastellone, M.; Mauro, G.M. The evolution of building energy retrofit via double-skin and responsive façades: A review. *Sol. Energy* **2021**, *224*, 703–717. [CrossRef]
224. Theodosiou, T.; Tsikaloudaki, K.; Tsoka, S.; Chastas, P. Thermal bridging problems on advanced cladding systems and smart building Façades. *J. Clean. Prod.* **2019**, *214*, 62–69. [CrossRef]
225. Silva, A.; De Brito, J.; Gaspar, P.L. *Methodologies for Service Life Prediction of Buildings: With a Focus on Façade Claddings*; Springer: Cham, Switzerland, 2016.
226. Prieto, A.; Knaack, U.; Auer, T.; Klein, T. Solar façades-Main barriers for widespread façade integration of solar technologies. *J. Façade Des. Eng.* **2017**, *5*, 51–62.
227. Wang, P.; Liu, Z.; Zhang, L. Sustainability of compact cities: A review of Inter-Building Effect on building energy and solar energy use. *Sustain. Cities Soc.* **2021**, *72*, 103035. [CrossRef]
228. Attia, S. Evaluation of adaptive Façades: The case study of Al Bahr Towers in the UAE. *QScience Connect* **2017**, *2017*, 6.
229. Oral, G.K.; Yener, A.K.; Bayazit, N.T. Building envelope design with the objective to ensure thermal, visual and acoustic comfort conditions. *Build. Environ.* **2004**, *39*, 281–287. [CrossRef]
230. Aksamija, A. Design methods for sustainable, high-performance building Façades. *Adv. Build. Energy Res.* **2016**, *10*, 240–262. [CrossRef]

231. Moon, K.S. Structural design of double skin Façades as damping devices for tall buildings. *Procedia Eng.* **2011**, *14*, 1351–1358. [CrossRef]
232. Ngo, T.; Ding, C.; Lumantarna, R.; Ghazlan, A.; Zobec, M. Structural performance of double-skin façade systems subjected to blast pressures. *J. Struct. Eng.* **2015**, *141*, 04015064. [CrossRef]
233. Poirazis, H. *Double Skin Façades for Office Buildings*; Report EBD; Lund Institute of Technology: Lund, Sweeden, 2004.
234. Zhou, J.; Chen, Y. A review on applying ventilated double-skin Façade to buildings in hot-summer and cold-winter zone in China. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1321–1328. [CrossRef]
235. Shameri, M.; Alghoul, M.; Sopian, K.; Zain, M.F.M.; Elayeb, O. Perspectives of double skin façade systems in buildings and energy saving. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1468–1475. [CrossRef]
236. Hensen, J.; Bartak, M.; Drkal, F. Modeling and simulation of a double-skin Façade system. *ASHRAE Trans.* **2002**, *108*, 1251–1259.
237. Hay, R.; Ostertag, C.P. Life cycle assessment (LCA) of double-skin façade (DSF) system with fiber-reinforced concrete for sustainable and energy-efficient buildings in the tropics. *Build. Environ.* **2018**, *142*, 327–341. [CrossRef]
238. Zomorodian, Z.S.; Tahsildoost, M. Energy and carbon analysis of double skin façades in the hot and dry climate. *J. Clean. Prod.* **2018**, *197*, 85–96. [CrossRef]
239. Yellamraju, V. Evaluation and Design of Double-Skin Façades for Office Buildings in Hot Climates. Master's Thesis, Texas A&M University, College Station, TX, USA, 2004.
240. Addo-Bankas, O.; Zhao, Y.; Vymazal, J.; Yuan, Y.; Fu, J.; Wei, T. Green walls: A form of constructed wetland in green buildings. *Ecol. Eng.* **2021**, *169*, 106321. [CrossRef]
241. Medl, A.; Stangl, R.; Florineth, F. Vertical greening systems—A review on recent technologies and research advancement. *Build. Environ.* **2017**, *125*, 227–239. [CrossRef]
242. Ikudayisi, A.E.; Chan, A.P.; Darko, A.; Adegun, O.B. Integrated design process of green building projects: A review towards assessment metrics and conceptual framework. *J. Build. Eng.* **2022**, *50*, 104180. [CrossRef]
243. Rakhshandehroo, M.; Mohd Yusof, M.J.; Arabi, R. Living wall (vertical greening): Benefits and Threats. *Appl. Mech. Mater.* **2015**, *747*, 16–19. [CrossRef]
244. Teotónio, I.; Silva, C.M.; Cruz, C.O. Economics of green roofs and green walls: A literature review. *Sustain. Cities Soc.* **2021**, *69*, 102781. [CrossRef]
245. Natarajan, M.; Rahimi, M.; Sen, S.; Mackenzie, N.; Imanbayev, Y. Living wall systems: Evaluating life-cycle energy, water and carbon impacts. *Urban Ecosyst.* **2015**, *18*, 1–11. [CrossRef]
246. Olusoga, O.; Adegun, O. Professionals' perception studies of vertical greening systems in Lagos, Nigeria. *Int. J. Build. Pathol. Adapt.* 2022, *ahead-of-print*. [CrossRef]
247. Voigt, M.; Roth, D.; Binz, H. Challenges with adaptive Façades-a life cycle perspective. In Proceedings of the 16th Advanced Building Skins Conference & Expo, Bern, Switzerland, 21–22 October 2021; pp. 459–468.
248. Borschewski, D.; Voigt, M.P.; Albrecht, S.; Roth, D.; Kreimeyer, M.; Leistner, P. Why are adaptive Façades not widely used in practice? Identifying ecological and economical benefits with life cycle assessment. *Build. Environ.* **2023**, *232*, 110069. [CrossRef]
249. Casini, M. Smart windows for energy efficiency of buildings. In Proceedings of the Second International Conference on Advances in Civil, Structural, and Environmental Engineering, Zurich, Switzerland, 25–26 October 2014.
250. Borkowski, E.; Luna-Navarro, A.; Michael, M.; Overend, M.; Rovas, D.; Raslan, R. Empirical validation of co-simulation models for adaptive building envelopes. *J. Façade Des. Eng.* **2022**, *10*, 119–154. [CrossRef]
251. Sultan, S.M.; Efzan, M.E. Review on recent Photovoltaic/Thermal (PV/T) technology advances and applications. *Sol. Energy* **2018**, *173*, 939–954. [CrossRef]
252. Orhon, A.V. 0171—A review on adaptive photovoltaic Façades. In Proceedings of the Solar TR2016 International Solar Conference & Exhibition, Istanbul, Turkey, 6–8 December 2016.
253. Fiorito, F.; Sauchelli, M.; Arroyo, D.; Pesenti, M.; Imperadori, M.; Masera, G.; Ranzi, G. Shape morphing solar shadings: A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 863–884. [CrossRef]
254. Shukla, A.K.; Sudhakar, K.; Baredar, P. Recent advancement in BIPV product technologies: A review. *Energy Build.* **2017**, *140*, 188–195. [CrossRef]
255. Abdelhakim, M.; Kandar, M.Z.; Lim, Y.-W. Experimental investigation of overall energy performance in Algerian office building integrated photovoltaic window under semi-arid climate. *J. Daylighting* **2019**, *6*, 23–41. [CrossRef]
256. Wu, J.; Zhang, X.; Shen, J.; Wu, Y.; Connelly, K.; Yang, T.; Tang, L.; Xiao, M.; Wei, Y.; Jiang, K. A review of thermal absorbers and their integration methods for the combined solar photovoltaic/thermal (PV/T) modules. *Renew. Sustain. Energy Rev.* **2017**, *75*, 839–854. [CrossRef]
257. Attoye, D.E.; Tabet Aoul, K.A.; Hassan, A. A review on building integrated photovoltaic façade customization potentials. *Sustainability* **2017**, *9*, 2287. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.