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Façade Design
Challenges and Future Perspective

Edited by Chiara Bedon,
Marcin Kozlowski and Mislav Stepinac

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Aims and Scope of the Series

Civil engineering is a traditional field of engineering from which most other branches of engineering have evolved. It comprises traditional sub-areas like transportation, structures, construction, geotechnics, water resources, and building materials. It also encompasses sustainability, risk, environment, and other concepts at its core. Historically, developments in civil engineering included traditional aspects of architecture and urban planning as well as practical applications from the construction industry. Most recently, many elements evolved from other fields of knowledge and topics like simulation, optimization, and decision science have been researched and applied to increase and evolve concepts and applications in this field. Civil engineering has evolved in the last years due to the demands of society in terms of the quality of its products, modern applications, official requirements, and cost and schedule restrictions. This series addresses real-life problems and applications of civil engineering and presents recent, cutting-edge research as well as traditional knowledge along with real-world examples of developments in the field.

Meet the Series Editor

Professor Assed N. Haddad is a Civil Engineer with a degree from the Federal University of Rio de Janeiro (UFRJ) earned in 1986, as well as a Juris Doctor degree from the Fluminense University Center earned in 1993, and a Master's degree in Civil Engineering from the Fluminense Federal University (UFF) obtained in 1992. He completed his Ph.D. in Production Engineering from COPPE / Federal University of Rio de Janeiro in 1996. Professor Haddad's academic pursuits have taken him to postdoctoral stays at the University of Florida, USA in 2006; at the Universitat Politècnica de Catalunya, Spain in 2010; and at the University of New South Wales Sydney, Australia in 2019. Currently, he serves as a Full Professor at the Federal University of Rio de Janeiro. He has held visiting professorships at various institutions including the University of Florida, Universitat Politècnica de Catalunya, Universitat Rovira i Virgili, and Western Sydney University. His research expertise encompasses Civil, Environmental, and Production Engineering, with a primary focus on the following topics: Construction Engineering and Management, Risk Management, and Life Cycle Assessment. He has been the recipient of research grants from the State of Rio de Janeiro, Brazil: CNE FAPERJ from 2019 to 2022 and from 2023 to 2025. Additionally, his research grants obtained from the Brazilian Government CNP since 2012 last to this date. Professor Haddad has been involved in several academic endeavors, being the Guest Editor of the International Journal of Construction Management; MDPI's Sustainability, Energies, and Infrastructures; Associate Editor at Frontiers in Built Environment / Sustainable Design and Construction; Guest Editor at Frontiers in Built Environment / Construction Management; and Academic Editor of the Journal of Engineering, Civil Engineering Section of Hindawi. He is currently a Professor of the Environmental Engineering Program at UFRJ and the Civil Engineering Program at UFF.

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Marcin Kozłowski is an expert in the structural use of glass in construction, the safety of glass structures, and numerical modeling of complex engineering issues, including the brittle fracture of glass and the simulation of both static and dynamic loads. Since 2020, he has been an associate professor in the Department of Structural Engineering, Silesian University of Technology, Gliwice, Poland. Professor Kozłowski has served as the project manager in two international research projects and several others with national funding. He is a national delegate to the European Committee for Standardization CEN/TC 250/SC 11 "Structural Glass" and serves as the chairman of the technical committee for the design of glass structures in the Polish Standardization Committee. He actively contributed to several research networks and projects, including the European Cooperation in Science and Technology (EU-COST) Action TU1403, "Adaptive Facades Network" and the MINIATURE 5 competition financed by the National Science Center (NCN) with a research proposal entitled "Analysis of the internal pressure in 3D bent insulating glass".

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Contents

Preface

Façade design is a challenging task in which multidisciplinary issues and aspects should be optimally considered and addressed. The primary reason for this is that multiple objectives are required for these building systems, from several points of view. This is especially the case for building façades that are expected to act as physical barriers and protect the occupants from extreme occurrences, such as seismic events, impacts, or fire. The use of special monitoring and technologies could be required for the residual capacity assessment of existing façades. Special attention and major efforts are also required for the detection and application of new technologies in the generation of modern, adaptive façade systems and building envelopes.

In this regard, to support the assessment and refinement of new strategies, technologies, trends, and challenges of façade design, this book presents a selection of research contributions from international scholars and façade experts, in which the aforementioned aspects are investigated by means of experimental methods, finite element modelling strategies, application of new technologies, and development of innovative design concepts. This book is designed for researchers and scholars as well as professionals in the field.

The selected book chapters are the results of recent research efforts of several authors as well as the support and input from a team of experts on the topic. We gratefully acknowledge the authors and reviewers for sharing their time and experience.

As editor of this book, I would like to thank my co-editors Prof. Marcin Kozłowski (Silesian University of Technology, Poland) and Asst. Prof. Mislav Stepinac (University of Zagreb, Croatia), for their fruitful scientific collaboration and for our long-term networking in the fields of structural engineering, dynamics, structural glass, and building façades.

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Chapter 6

Smart Façades: Technological Innovations in Dynamic and Advanced Glazed Building Skins for Energy Saving

Silvia Brunoro and Valentina Frighi

Abstract

This chapter deals with the analysis of the potential offered by the integration of smart solutions in dynamic glass façades to improve buildings' energy performances. Dynamic solutions are here examined with reference to dry ventilated systems, active and passive cooling, solar gain, greenhouse effect, and technologies able to react and self-regulate, according to the environmental inputs. The first part is dedicated to the state of knowledge, assessing the performance evolution of dynamic and interactive architectural envelopes (smart skins). Then, the core of the chapter is divided into clusters according to different strategies that allow the building skin to react and self-regulate according to the environmental inputs: double-layer glass façades, solar shadings, PV integration, etc. The goal is to produce a sort of "smart skin guideline" divided by requirements/strategies of intervention to investigate a range of solutions able to regulate buildings' behavior and characterize their image: from systems that allow to transform solar gain into heat to improve buildings' energy performance in winter season, to others that integrate passive cooling, to systems that transform the façades in a real active element of energy production, thanks to the integration of renewable energy sources.

Keywords: glass building skin, smart envelope, double layer façades, active and passive system, advanced building skin, smart windows

1. Introduction

The aim of this chapter is to explore the innovative incorporation of glass into façade systems to promote the energy efficiency and enhance the architectural perception of buildings. The research is focused on the sustainability of glass as a material for façade, as a very powerful opportunity, often associated with natural light, and lightness, and other qualities that have earned universal reception from modern architecture.

Firstly, a brief introduction frames the research background, the concept of glass envelope, its evolution, and role toward the definition of dynamic and smart envelope.

Then, the methodology is explained in paragraph 2; later technical solutions are classified by their technical requirements and energy performance. The core of the chapter is divided into clusters according to different strategies that allow the building skin to become an active and dynamic layer: double layer glass façades, solar shadings, PV integration, etc.

Finally, the goal is to produce a sort of "smart skin guideline" divided by requirements/strategies of intervention to investigate a range of solutions able to regulate buildings' behavior and characterize their image.

Historically, the use of glass envelopes was mainly focused on esthetics, as it was estimated that it did not need to be ecologically responsive to the environment.

Adverse energy and mechanical performances usually associate with excessive thermal gain and direct sunlight, have created uncomfortable buildings, and caused inefficient energy consumption [1, 2].

Hence, the application of a glazing system cannot be followed without truly understanding the underlying principles and implications.

Since energy costs have been affordable (before the oil crisis of the 1970s), the low thermal performances of the fully glazed building have been compensated by totally mechanical heating and cooling systems. By the 1970, the high costs of fuel led the building industry to develop new and performing glass products such as photosensitive and photochromic glass, and new coatings such as reflective or selective (Low-E) to help in reducing energy consumption in buildings with large glass area [3, 4].

The increasingly frequent use of transparent surfaces for the construction of building development began in the nineteenth century, during the Industrial Revolution, and involves the research and development of new materials able to guarantee energy performance like massive walls [5].

The envelope becomes progressively independent from the load-bearing structure of the building and its first requirements are to regulate the energy flows such as heat transfer, light transmission, protection of solar radiation (**Figure 1**) [6].

In the recent years, sustainability has become a more and more important feature in architecture: A sustainable design process can produce high-performance buildings that are energy efficient, healthy, and economically feasible, wisely using renewable resources to minimize the impact on the environment and to reduce, as much as possible, the energy demand [7–9].

Following the developments in international environmental policy, after the Kyoto agreement on climate change [10], the International Energy Agency has developed a set of scenarios on international energy development up to 2030 and 2050, showing how the construction sector remains, alongside the industrial sector, the most responsible for energy consumption and CO_2 emissions [11].

Consequently, several European standards and regulations concerning energy efficiency in buildings have been promulgated, focusing on the importance of the energetic control of buildings to reach, since 2020, NZEB requirements for new and relevant refurbishment actions [12].

Since the publication of the European Directive 31/2010 UE, the building envelope has been the subject of a great number of research aimed at demonstrating the possibility of build with zero or passive emission house [13].

Among the European research in recent years contributing to the envelope evolution, through experimentation of new components and materials characterized by high performance, it can be cited: Best practice for double-skin Façades (BESTFACADE), European High Quality Low Energy Buildings (EULEB), Building Advanced Ventilation Technological examples (BUILDING ADVent).

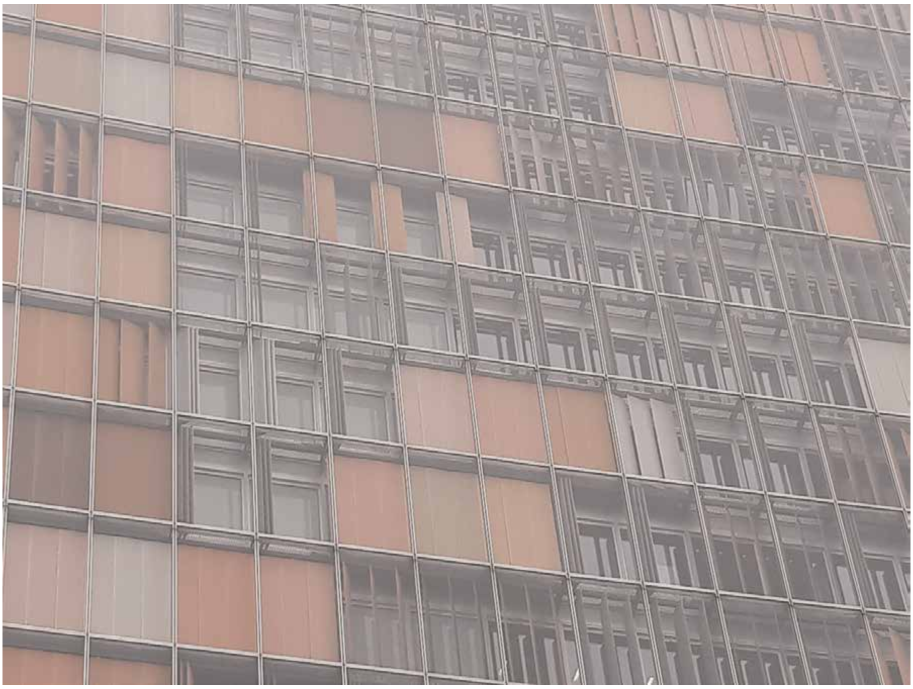

Figure 1.
GSW Headquarters, Berlin. Architects: Sauerbruch & Hutton. One of the first examples of high-efficient double layer glass façade. All moveable curtains of the façades can be controlled by the individual occupant but are also operated by a central building management system. This individual control provides for a continuously changing appearance, especially of the west façade.

As remarked in Ref. [14], for smart glass façades, the thermal and insulation properties, in addition to other important requirements like transparency to allow solar gains or solar control, are relevant aspects that are strictly linked on climate conditions and the desirable level of comfort.

Nowadays, the standardized prefabrication of high-quality multifunctional façades represents a foreseen frontier in the improvement of the envelope's performance. Dry-mounted prefabricated façades reduce the on-site construction costs and time by incorporating numerous functionalities into the same component, thanks to the inclusion of smart materials. This approach also integrates both solar active and passive solutions and optimizes building equipment, including heating, cooling, and ventilation.

Therefore, glass components' system becomes a multifunctional building layer, not only to be physically and functionally "integrated" in the building, but also to be used as an innovative chance for the building envelope design. For this reason, the façade system plays an important role for achieving energy and environmental goals [15].

Architecture of light envelopes is made of structural skins just like a shell, the first significant experiment took place in Northern Europe such as in the design experiences of Sauerbruch & Hutton, Herzog & de Meuron, Jean Nouvel, etc. [16].

In the design of dynamic envelope systems, it is fundamental to analyze the climatic and environmental conditions, to reach an adequate balance between climatic parameters, inner thermal and hygrometric conditions, and technical components/solutions.

Starting from this point, the chapter proposes an analysis of the most relevant active technologies based on their performances.

Relying on the most efficient products in terms of energy efficiency of glass components for façades, the aim of this work is to perform a multi-criteria analysis based on different requirement categories, to compare several technological possibilities for façade in terms of technological, architectural, energetic, and environmental requirements.

2. The role of glazed components

While glazed elements are an important aspect of architectural design, they are regarded as the least energy-efficient elements of the building envelope [17] since they contribute to approximately 60% of the overall energy usage of buildings [18]. In contrast to insulated walls of equivalent size, the heat-gain occurrences on windows can result in effects that are many times more impactful [19], resulting in significant implications for buildings' lighting, heating, and cooling needs.

The challenges associated with glazed elements lead to winter heat losses, due to air leaks and insufficient insulation. Similarly, in summer, they can lead to overheating due to the entering of solar radiation, which significantly elevates indoor temperatures. Additionally, beyond their architectural and energy-related aspects, these components must also fulfill essential structural prerequisites. These requirements encompass structural integrity, usability, longevity, resilience, and fire performance [20–22], particularly if considering systems with adaptive features.

Hence, effectively intervening in the design of glazing systems offers a significant chance for the construction industry to manage energy needs, contributing to the advancement of the objectives set by the European energy agenda.

2.1 Characteristics of glass products

Throughout years, artists and architects have worked with glass due to its shaping, tactile qualities, and interaction with light, also considering its stability, waterproofing, and see-through nature [23].

Since the development of the float glass technique in the 1950s, glass surfaces appropriate for construction purposes are primarily made of silica (SiO_2). Transparent typical glasses have a light-transmission coefficient ranging from 60 to 80% for wavelengths approximately falling within the 400- to 2500-nm range. Nevertheless, by altering the chemical composition of the glass through adjustments in its mixture, it becomes possible to alter this threshold or impact other aspects like its chemical, physical, or mechanical characteristics.

Due to the evolution of technological advancements and industrial methods, glass is nowadays available in a variety of shapes and compositions, typically distinguishable based on the production techniques that generated them.

2.2 Glass energy performance features

The primary characteristic of glass is its ability to transmit light, facilitated by its transparency, which arises from the interactions between light photons and the atomic structure of the glass. Generally, a glazed surface transmits most of the incoming solar radiation, depending on the constituents that form it and/or any surface modifications it undergoes.

Within the entire solar spectrum, three segments significantly impact the comfort of indoor environments in buildings, as they pass through the glass: Ultraviolet (UV), Visible Light (VL), and Infrared Energy (IR). UV light can be further categorized into three groups; two of them are rejected by the earth's atmosphere and float glass as well.

IR constitutes the heat energy emitted by the sun that enters an interior space. Managing this transmission involves limiting heat within rooms, thus averting potential overheating during the summer. The greater the ability of a glass panel to block IR, the more energy and cost can be saved.

Lastly, VL represents the portion of light visible to the human eye and encompasses natural daylight. It can contribute to undesired glare and strain on the eyes. Generally, the VL of a glass pane can be decreased by adjusting tints.

Regarding VL, glass is almost completely transparent, whereas concerning IR, it behaves opaquely; this is the cause of the so-called greenhouse effect, due to which, bodies located in a space protected by glass surfaces experience temperature elevation due to direct exposure to radiation. This energy is then re-emitted as sensible heat in the form of infrared radiation, which remains confined within the space.

IR solar radiation upon a glass surface can be reflected, transmitted, or absorbed. In normal incidence conditions, the reflected energy is the quantity of solar radiation bounced back into the atmosphere. The transmitted energy represents the solar radiation directly passing through the glass's surface, while the absorbed energy expresses the quantity of solar radiation absorbed by the glass, leading to an increase in its temperature.

Total transmission instead represents the total amount of solar radiation that, in normal incidence conditions, is transmitted through the glass. This measurement encompasses direct transmission (short-wave component) as well as the component dissipated inward due to radiation and convection (long-wave component).

The ability of a surface to absorb or emit electromagnetic radiation is reflected by the emissivity value. By its nature, glass has a high emissivity. Coatings able to act on this feature are existing, reflecting heat inside buildings and thus reducing heat losses through windows, increasing in this way the system's U-value.

2.2.1 Reference parameter for glass energy performance evaluation in buildings

Defining and characterizing the energy performance of transparent components is quite tricky due to their interaction with solar radiation. Because of these complexities, such building elements must adhere to specific criteria and be described using both thermal and optical parameters. These parameters address the system's thermal insulation capacity and the ability in regulating the quantity of solar energy into rooms. The benchmarks commonly used for assessing the performance of glazing include the following:

- Thermal transmittance, or Heat Transfer Coefficient (also called U-factor), which is the rate at which a transparent pane conducts non-solar heat flow. A lower U-factor indicates higher energy efficiency.

- Solar Heat Gain Coefficient (SHGC), or g-value. This quantifies the amount of incoming solar radiation that a window permits to pass through, either by direct transmission or absorption, and then released as heat within an indoor space. A

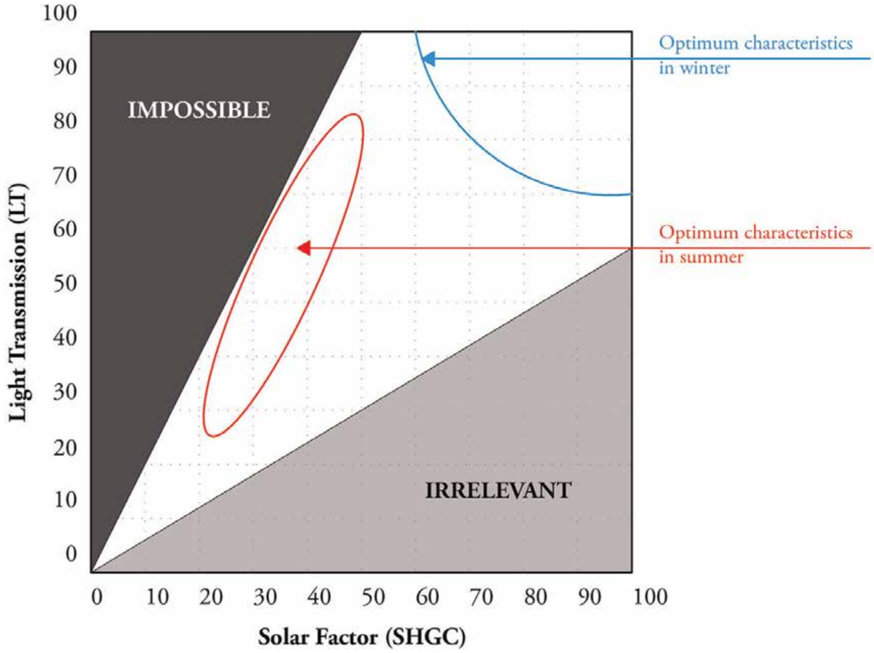

Figure 2.
Correlation between the Solar Factor (SHGC) and the Light Transmission (LT) coefficient.

lower SHGC means reduced solar heat transmission and enhanced shading capabilities. Glazed elements with high SHGC effectively capture solar heat in winter, while systems with low SHGC are efficient at reducing cooling loads in summer.

- Visible Light Transmittance, or light-transmission coefficient (τl), is the fraction of the visible sunlight spectrum perceived by the human eye which passes through the glazing. It is represented by a value between 0 and 1, with higher values denoting more transmitted visible light.

An additional crucial parameter for assessing the energy performance of transparent systems is the Light to Solar Gain (LSG) ratio, which measures the spectral selectivity of a glass system as an expression of the efficiency of different glass types in transmitting daylight (the visible solar radiation) while blocking heat gains. It is calculated as the ratio of VLT to SHGC; a higher LSG means more daylight transmitted without adding excessive heat. This parameter becomes particularly important for daylighting, especially in summer when more light is desired with minimal solar gain. Therefore, a higher LSG number implies a brighter room without excessive heat accumulation (**Figure 2**).

3. Methodology: Categories of requirements and performances

This work focuses on the technological innovation in glass façades systems and investigates the most relevant aspects from architectural and energetic point of view.

The first analysis involves identifying relevant factors—presented in the form of criteria—that define the main features of each system.

1. Architectural features (esthetical and functional):
Esthetical aspects, façade integration, transparency, translucence, multimedia.
2.Energy properties and comfort
Energy issues and aspects related to human comfort: light transmission, solar factor, thermal insulation, greenhouse effect (solar gain), thermal inertia, acoustic insulation, natural/mechanical ventilation, solar device integration, renewable energy integration.
3.Environmental properties
Environmental aspects: ecological and sustainable features (recyclability, green products).
4.Economical features

Table 1.
Significant criteria for façade components.

Each macro-category of requirements (architectural, energy, environmental, and economic) is further divided into sub-categories to define the peculiar aspects of components under investigation, as well as their operational strategies, in terms of the environmental and dynamic benefits within the overall concept of the building.

The assessment methodology for the analysis of the architectural and technological characteristics of the façade systems is based on the categories and sub-categories of requirements listed below (**Table 1**). These have been defined by authors based on their significance concerning the whole building envelope system—in relation to both technical and aesthetic features—and parameters indexed in the regulation framework for transparent building components, plus other qualitative considerations made based on their description related to the integration with technical systems and cost-related aspects.

According to this criteria, three macro-categories of environmental strategies have been proposed, to classify, in the following paragraphs, the most relevant technological innovations in advanced glass building skins for energy saving:

- STRATEGY 1—Passive solar gain: double layer glass façades.
- STRATEGY 2—Summer overheating control.
- STRATEGY 3—Renewable solar energy—semitransparent PV, bio-adaptive glass.

The purpose is to outline criteria and operational tools to guide and inform the design of innovative envelopes, allowing targeted choices to be made in relation to the foreseen interventions, to obtain the desirable levels of quality.

Finally, a technological multi-criteria matrix is defined, in which the façade solutions are briefly described and compared by crossing the strategies of interventions with the requirements described in **Tables A1–A3**.

3.1 Passive solar heat gain: double layer glass façades

Solar gain holds significant importance in cold and temperate climates, as it plays a crucial role in reducing heat losses and harnessing passive solar incidence, thus contributing to the overall energy balance. Historical solar passive design—e.g., the

"Trombe wall"—can be considered as a precursor to modern double skin systems [24].

A double Skin Façade is an advanced building skin, originally born in Northern Europe, that can dynamically respond to varying ambient conditions, able to:

- maximize daylighting with integral solar heat gain control;
- improve heat exchange by greenhouse effect in the buffer zone; overheating, as a minor problem, is solved by blinds and buffer zone;
- reducing air-conditioning loads;
- allow natural ventilation (**Figure 3**).

A typical double glass envelope system comprises a layer of single glass and a layer of double-glazing, separated by an air space that can incorporate a range of integrated sun-shading, natural ventilation, and thermal insulation devices or strategies. During the winter season, a double skin façade can improve heat gains coming from solar radiation by means of the greenhouse effect and reduce the heat losses due to the slow air flow that can lower the heat transfer from inside to outside. Glass panes maintain a warm surface temperature on the inside, enabling more effective utilization of the space close to the window [14].

In winter, the air cavity, heated by the sun, becomes a warm buffer zone, while in summer the stack effect of fresh air (passive ventilation) removes the exceeding heat [25].

In addition to energy efficiency and the U-value of the glass, other important requirements include acoustic control, water penetration resistance, and daylight control, which are crucial for ensuring office building comfort.

In summer, control of solar heat gain is ensured through shading devices placed within the air cavity. Additionally, the cavity itself can help dissipate some of the incoming solar radiation through the passive ventilation effect. Various configurations for shading devices exist; they can either be fixed elements or, typically, operable units that are either controlled by the occupant or by sensors within the building [26].

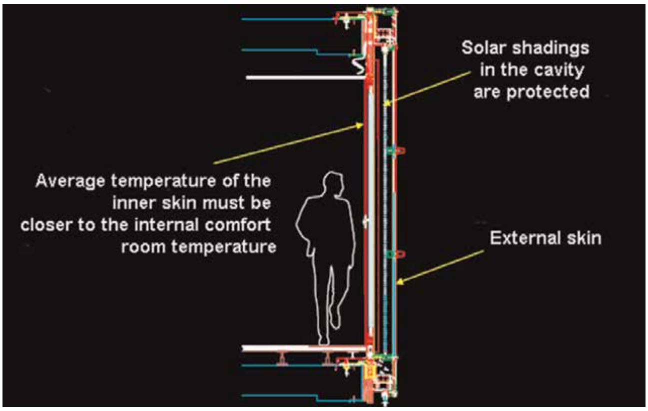

Figure 3.
Conceptual scheme of a double layer glass façade.

In Mediterranean Countries, solar gains control in building design that is relevant; therefore, double skin façades may lead to overheating during summer months if there is no appropriate façade design, ventilation technique building orientation, and provision of shading [27].

The use of improved solar U values for glazing favors the absorption and reflection of heat, to minimize solar heat gain. This can be accomplished using spectrally selective glazing, which can selectively respond to different wavelengths of solar energy. It allows visible light to pass through while rejecting unwanted invisible infrared heat [28]. There are products available on the market that have successfully achieved this characteristic, permitting for much clearer glass than previously available for solar control glazing, as reported in paragraph 3.

In addition, complete glass façades need an accurate daylighting control to avoid excessive glare and heat. This is important primarily for two reasons: firstly, it reduces the amount of electrical lighting required, and secondly, because the quality of light from daylight is preferential to electrical lighting. It is proved that the health and productivity of office personnel are highly influenced by the quality of lighting in the environmental workplace; natural light is particularly relevant for well-being and mental health of the occupants [28].

A classification system to assess and compare different kinds of double skin façades is proposed, by considering their main characteristics regarding building construction and their environmental behavior, related to the ventilation system.

According to these parameters, a categorization can be done by considering different typologies of construction and cavity ventilation [29].

Based on their construction features, façades can be classified by full height, corridors, or cells, depending on the air cavity dimension and division. An appropriate design of the air space is crucial to the double façade.

In full height façades, the façade is undivided from the bottom to the top, creating a unique air cavity that benefits from the stack effect. On warm days, hot air collects at the top of the air space. In certain cases, the undivided air space can be a big atrium, in which people can stay and enjoy this "environmentally dynamic interstitial space" [30] that can be used for spaces with low occupancy (meeting rooms or cafeterias). Sometimes, vegetation is used instead of traditional shading devices, to improve air quality and well-being [31].

Corridors façades are divided by floor, best for fire protection, heat, and sound transmission, or divided vertically into bays to optimize the stack effect.

This kind of construction is commonly used when it is needed to have fresh air and exhaust intakes on every floor, allowing for maximum air changes. When the cavity is divided into vertical corridors, air flows across the façade through openings, allowing for better natural ventilation.

A third typology consists of high prefabrication elements—one floor high—ready to be installed, that are called cells. Double layer glass cell façades have a floor-by-floor divisions that allow a construction speed by a simple repeating unit, which can maximize ventilation thanks to fresh air and exhaust intakes on every floor. Moreover, the compartmentalization of the air cavity divided into small zones improves fire security, noise requirements, and heat transfer from one section to another (**Figure 4**).

Another classification can be made according to ventilation.

When ventilation is natural, the air entered from the bottom, warms thanks to the sun radiation across the glass panes. Hot air rises according to natural physics principals until openings at the top of the cavity allowing expelling it out and replacing it by

Figure 4.
Different types of double glass skin. From left to right: full height, corridors, cells.

cooler air drawn in from the outside. Sometimes, especially in hot climates—when there is the risk of low pressure and lack of stack effect—the offices on the top floors can suffer from overheating due to the accumulation of hot air in the cavity adjacent to their space. For this reason, it is a good practice to insert mechanical air vents to assure the hot air will be discharged [32].

In this configuration, the single-glazed outer skin is used primarily for moderate to extreme temperature within the façade and for the protection of the air cavity contents (e.g., shading devices). External single glass is generally safety or laminated glass, while the internal skin offers the insulating properties to minimize heat loss (double or triple glass) [33].

Natural ventilation includes the necessity of openings in the outer skin (moveable glass panes or grids), while windows on the interior façade can be opened or not. Ventilation openings in the inner skin allow the building's users access to airflow that can be used to cool and ventilate the space.

The exterior glazing of the double skin creates a layer that in most case can be accessible by the inhabitants for natural ventilation: This buffer zone is a key component of the naturally ventilated double skin façade, typically 60-90 cm of thickness, and can include plants and vegetation to mitigate the temperature.

Furthermore, the use of internal moveable windows can allow for night-time cooling of the interior thereby lessening cooling loads of the building's HVAC system.

In double layer glass façades with forced ventilation, the air space between the two layers of glazing becomes part of the HVAC system. In this configuration, the thermopane units (optimal U-value) are placed on the external of the main façade of double glazing. In winter, the heated air between the glazing layers flows through the cavity and the outer layer of insulating glass minimizes heat-transmission loss. In summer, fresh air is supplied by HVAC through the cavity and contributes to the façade cooling.

Numerous studies prove that double skin façade presents many advantages over a conventional—single skin—façade [34–36]. A double skin dynamic envelope in a cold temperate climate, like the United Kingdom, can reduce energy consumptions by 65%, running costs by 65%, and cut CO_2 emissions by 50%, compared to a single skin building. The same study reports that cost exercises of buildings employing a double skin façade may cost as little as 2.5% based on gross internal floor area [37].

Regarding sustainable design, the double layer façade offers strategies of solar heat gain control, increased daylight, moderation of temperature, and natural ventilation strategies to improve the thermal behaviour of the building. The ability to engage and control these environmental aspects inevitably leads to increased energy efficiency and improved occupants' comfort.

Significant studies in sustainable architectural design have shown that construction cost of double layer glass façades can be two or three times higher than a traditional curtain wall, anyway double skin buildings can significantly reduce overall long-term operating/energy costs making the increased initial capital costs justifiable (affordable). The goal of these systems is not only to be environmentally responsible but also to greatly improve working conditions for the occupants of these buildings through access to day lighting, natural ventilation, and greater control over the workplace atmosphere. Moreover, a double skin system also offers a choice for renovation of existing building façades to transform into more energy efficiency buildings and improve the architectural value.

3.2 Strategies to control summer overheating

Over time, glass, a material that once performed only the function to allow the entrance of light, has evolved into a dynamic filter, capable of assuming a more interactive role in managing the internal environment of buildings.

Various experimental and groundbreaking glazed systems, encompassing a broad array of functions and applications, are currently accessible in the market or, at the very least, in the developmental phase, having different features from many points of view.

This group includes what is referred to as "dynamic glazing," fenestration products capable of altering their performance attributes by modifying their characteristics of transparency, gloss, coloration, and solar radiation screen while maintaining the structural properties of the glass [38].

Dynamic glasses, otherwise defined as "smart windows," can be controlled through a variety of means, enabling end-users to govern the interactions between external conditions and the internal environment. This capability results in the creation of a smart, adaptive building envelope that contributes to cost savings related to heating, cooling, and lighting.

Therefore, the massive adoption of these innovations holds the potential for substantial decreases in energy usage and, by obviating the need for supplementary devices to regulate incoming solar radiation, also in costs, maximizing at his best natural daylight while minimizing issues like glare and heating/cooling demands.

To fully understand the potential of these glazing components, a brief description of the most promising glazing technologies has been compiled, drawing from recent literature on the subject. These technologies have been categorized based on their performance characteristics, whether they are equipped with static or active features.

3.2.1 Static performance glazed components

Static performance glazed components are technologies that act passively on the control of incident solar radiation, thus meaning without varying their performance feature over time.

An example of passive solar control is provided in glass treated with metal oxides, during the production process. This is the case of tinted glasses, in which the applied oxides allow to vary color and optical properties of glass, conferring to it the ability to absorb certain sections of incident solar radiation, thereby reducing the amount that passes through them. Normally, the coloring is achieved using ionic or phase-dispersed color substances, formed by particles' aggregates that affect the level of transparency as they lead to light diffraction and reflection due to the particles dispersed throughout the glass material. A colored glass with discrete properties should block solar energy wavelengths ranging from 800 to 2000 nm, still maintaining a reasonable level of visible transmission. Thermal transmission in a room with tinted glass can be reduced by more than 20% [39].

The application of metallic oxides in the form of coating can generate also reflective glasses, in which the pane's reflection toward near IR is increased; they are characterized by a predetermined selective reflection toward solar radiation and by a low SHGC. Compared to tinted glazing, reflective glasses have significant effects on diminishing solar transmission; this attribute makes them a favorable choice for regions characterized by climates where the reduction of solar heat gain is crucial, particularly in cooling-dominant environments.

Acting on the emissivity of the glazed panes allows to reduce heat exchanges through them, without compromising their transparency. This is the case of low-emissive glasses (Low-E), transparent toward solar thermal radiation but reflecting regarding IR radiations. A weak point of Low-E is that they multiply the effect of thermal solar radiation, increasing overheating as well; for this reason, they are particularly suitable to be applied in heating-dominate climates (rigid climatic contexts) where high solar factor (SHGC) is required, as well as a low thermal transmittance coefficient (U-factor). Employing Low-E in Insulated Glass Units (IGUs) allows to obtain thermal transmittance values between 1.7 and 1.0 W/m^2K, for double glazing, and lower than 0.7 W/m^2K for triple glazing, reducing solar heat gain through windows up to the 48% [40].

Combining the thermal insulation property of Low-E with the sun-blocking features of reflecting glasses results in selective glasses. These glasses utilize coatings to hinder the entry of infrared radiation, while maintaining controlled levels of light transmission and simultaneously restricting the solar factor's impact. These selective coatings filter the electromagnetic waves, admitting most of the incoming solar radiation in both visible and near-infrared spectra. However, they reflect long-wave radiations (far-IR) emitted by warm objects inside rooms. This approach has the effect that during the winter season, when solar rays are inclined—typically parallel to the slender glazed element—the radiations can permeate the system, triggering the greenhouse effect, exploited in passive thermal energy strategies to decrease heating demands (**Figure 5**).

Other static-performance glazing technologies are Vacuum Insulated Glasses (VIG) and TIM (Transparent Insulating Material) glasses. Both are fully available on the market but still with a quite high cost.

Figure 5.
From left to right: tinted glass at Miami International Airport; reflective glass at Mann Island Development Building; selective glass at the Blue Pavilion, Fiera del Mare, Genova.

Standard VIGs consist of two glass panes, generally of low emissive, set apart by a vacuum cavity. The benefit of this technology is the combination of an exceedingly thin profile with highly effective thermal insulation characteristics[1], due to the vacuum in the space between the glass panes, which prevents convective exchanges between them. However, they still present some shortcomings; these encompass vulnerabilities to pressures originating from wind and vibrations that could impact the glass surface, as well as the challenge of maintaining an airtight seal along the edges to prevent the reestablishment of conduction to its normal level.

TIM glazing systems instead comprise in the space between two glass' panes a transparent or translucent insulating material [19], combining diffused lighting features with very limited thermal losses[2] [43].

With their translucency (typically having a SHGC equivalent to that of a standard IGU), these materials enable the dispersion of natural light, encompassing both direct and diffused illuminations. This feature proves advantageous in spaces where there's no necessity for complete visual transparency to the external environment, effectively averting instances of glare.

TIMs are generally classified under four categories, according to the structure of the TIM layer; TIM glazing systems generally employ plastic capillaries or honeycomb structures insulating materials that can be made of polycarbonate, poly-methyl-methacrylate, or aerogel [44]. Nonetheless, a limited number of investigations have delved into the thermal and optical capabilities of glazed systems incorporating Transparent Insulation Materials (TIMs), as the majority of prior research has primarily focused on their usage within solar collectors and solar walls [45].

Another worth-mentioning technology is the one employed in Heating Glasses (HG) where an electrically connected metallic coating is introduced to the inner pane of an IGU; upon applying a low voltage, this coating heats up and directs warmth toward the interior, effectively minimizing heat loss through the transparent surface. These systems completely remove the risk of condensation between glass' panes, contributing also to the heating system of the entire building, as they generate about 0.42 Kw/m^2 of heat. Typically, heating glasses require 100–300 W/m^2 to operate, resulting in a pane temperature of roughly 40°C. If used solely for preventing condensation, their operational power can be reduced by half.

Appeared on the market in 1980, now heating glasses are produced by several companies all over the world; among the others, significant is the device produced by Vitrius Technology since it can re-calibrate and re-program itself in real time, improving its performance based on end-user needs.

3.2.2 Dynamic performance glazed components

Contrary to static performance components, dynamic performance systems, otherwise called "smart glazing," can modulate their optical characteristics according to different inputs of various natures. Smart glazing technologies can be active if they change using external signals (such as electrical direct currents) or passive if they automatically respond to environmental variations, such as air temperatures or solar radiation.

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[1] VIG systems reach for a U-value of about 0.4 W/m^{2}K [41].

[2] A study [42] reveals that the presence of a TIM structure can suppress convective heat transfer through the windowpanes and cause a significant reduction in radiative heat transfer.

Active systems comprise of technologies based on Electrochromic (EC), Gasochromic (GC), Suspended Particles Devices (SPD), and Liquid Crystal Devices (LCD), while Thermochromic (TC) and Photochromic (PC) technologies are examples of passive smart glazing types.

Electrochromic glasses are systems capable of altering their light transmission characteristics, usually achieved by modifying their color and optical attributes after the application of an electric field. ECs are obtained by introducing a layer of micro-liquid crystals between two glass panes within the gap. These liquid crystals facilitate reversible electrolytic reactions that, when exposed to a potential difference, can change their coloration to the extent of becoming transparent [46].

During the transition, light transmission of the system modifies from about 1-4% (in the opaque state) to 60–63% (in the transparent state); the SHGC instead stays between 0.63 and 0.26 for the clearest state and between the 0.31 and 0.04 for the darkest state.

Once the change has occurred, no electricity is needed for maintaining the shade that has been reached.

The speed at which EC devices switch can range from a few seconds to several minutes, according to the type of technology used and the size of the window.

Most of today's available devices function in either on- or off-states only, although technologies enabling adjustable degrees of transparency can be readily implemented [47].

Recent progresses in EC materials, particularly those based on transition-metal hydrides, have resulted in the creation of hybrid systems with reflective properties. These systems shift from being absorbent to reflective, allowing them to alternate between transparent and mirror-like states. While these materials adhere to the foundational concept of conventional EC, they approach the issue differently: transitioning from a transparent state (when inactive) to a reflective state upon the application of voltage.

Additionally, the exploration of self-powered EC glazed components activated by photovoltaics (PVs) has been undertaken [48]. However, their transparency is substantially limited due to the presence of the PV layer. These devices employ sputtered titanium and tungsten oxide films as the electrochromic layer, combined with a photoactive layer composed of dye solar cells, often constructed using dye-sensitized titanium oxide (TiO2) [49].

Gasochromic glasses are obtained by introducing a gasochromic layer between two transparent panes. This layer reacts with a mixture of diluted hydrogen gas (usually combined with Argon), resulting in a color change and alteration of the system's transparency due to a catalytic reaction with the glass composition. The degree of transparency in these devices depends on the quantity of hydrogen the gasochromic layer has been exposed to. GC glasses maintain unobstructed visibility from the interior to the exterior in all operational states.

Tungsten oxide is the most used material for GC applications [50], often accompanied by a thin catalyst layer, although devices employing a thin layer of Wolfram are also accessible.

The alteration in the transmission characteristics of glass enables a reduction in both visible and overall solar energy transmittance rates of an IGU, reducing them from 0.63 and 0.49 to 0.20 and 0.17, respectively (when the interior pane is coated with a conventional low-E coating). By introducing a solar-control coating, even lower SHGC values can be achieved.

In contrast to other passive smart glazing systems, GCs require additional control equipment, such as a gas supply unit and a control unit. The gas supply unit encompasses an electrolyzer and a pump, linked *via* pipes to the glazing system in a closed-loop arrangement. Ideally, this gas supply unit is integrated within the external façade of the building. A single gas supply unit has the capacity to furnish sufficient gas to activate gasochromic glazing covering an area of 10 m^2 [51]. On the other hand, the control unit facilitates both manual and automatic regulations. When integrated into a bus system, this unit allows the glazing to be switched, optimizing lighting conditions, thermal comfort, and/or overall building energy consumption.

SPDs are electroactive devices in which the application of an AC voltage prompts particles to transition from a random arrangement to an aligned one, becoming the glazed components transparent. In the absence of an electric charge, SP windows absorb light, leading to a reduction in light transmission. The typical ranges of light transmission and SHGC—when transitioning between transparent and opaque states—are approximately 60–0.5% for VLT and 0.57–0.06% for SHGC, with switching times of some seconds.

Simulation outcomes have demonstrated that switchable SPD smart windows, when in the off and automated states, can result in a net energy reduction of up to 58% compared to double-glazing low emissive IGUs [52].

Conversely, LCDs employ materials with a bars-molecular structure that, under the influence of an applied voltage, can alter the light transmission characteristics of the systems; most of the LCDs tend to disperse light, leading to their becoming white and semi-transparent [51].

Typically, LCDs consist of a layer containing droplets dispersed within a polymer matrix. When the voltage is off, these droplets scatter light due to the disparity in refractive indices between the matrix and the droplets.

In the active state, the light transmittance of liquid crystal glazing does not exceed 70%, whereas in the inactive state, it remains around 50%. These systems diffuse direct incident solar radiation without effectively blocking it, which results in a SHGC usually ranging from 0.69 to 0.55.

In contrast to SPDs, these systems are primarily used for privacy applications [53] and need of a continuous supply of electrical energy to remain operational.

Thermochromic are glazed systems in which a temperature variation triggers a response in the material. This reaction enhances its reflective capability, making it particularly responsive to IR. Consequently, there is a modification in light absorption related to the external surface temperature, making these devices opaque when reaching a critical temperature (specific for each product).

In general, the most employed TC technology is the one that uses tungsten trioxide or vanadium dioxide (VO_2) coatings to obtain this reversible behavior [54]. VO_2 is the most common material, despite its many shortcomings as the high transition temperature, comprised between 10°C and 65°C, so much higher than indoor temperatures [55]. To address these limitations, alternative approaches involve incorporating additional substances like W and F into VO_2 to lower its transition temperature, or utilizing specialized gels placed between the two layers of plastic film.

Nevertheless, this leads to a reduction in the VLT of these systems. To counteract this effect, anti-reflective coatings are applied to increase it [46]. Another notable limitation of traditional fully passive thermochromic technology is its inability to adequately adapt transparency based on outdoor climate conditions. While it does regulate solar radiation, it overlooks the indoor temperature rise due to heat entering per convection [17]. However, these systems maintain a relatively low cost in comparison with more complex alternatives [56].

Photochromic glasses can vary their optical properties due to external light-intensity variations by means of the presence of organic or inorganic compounds that act as optical sensitizers [57]. Their conduction becomes reversible once the exposure to radiation stops; this reversibility is allowed by the breakdown of micro-silver halide crystals (chlorides, bromides, iodides), responsive to UV rays and contained in the glass mixture.

The transparency of these systems is related to the level of light striking the glass surface, as they adjust their transmission characteristics in response to intensity, duration, and type of incoming solar radiation. The more global solar radiation hits the glass pane, the darker it tints. The specific configuration of the system's response to varying global solar radiation levels can differ based on manufacturing methods, and it can be tailored to align with the preferences and requirements of users (**Figure 6**).

Generally, SHGC of PC systems varies between 0.48 and 0.31 (for the clearest state) and 0.41 and 0.22 (for the darkest state), while VLT varies between 0.78 and 0.13 (for the clearest state) and 0.73 and 0.09 (for the darkest state) [58].

Due to the ambient temperature's influence on the coloring process of photochromic glasses, with more pronounced effects at lower temperatures and minimal effects at higher temperatures, their applicability in building contexts is significantly limited [59].

Other relevant technologies are PCM systems, which incorporate Phase Change Materials to manage and reduce the energy demands of buildings during peak hours and mitigate fluctuations in building temperatures[3]. These systems leverage the concept of latent heat thermal storage (LHTS) to absorb energy and subsequently release it at different times.

Variable substances are viable to be used as PCMs, enabling the regulation of temperatures within a particular range, determined by the chosen material. PCM glasses typically enable the soft dispersion of natural light within spaces: In their solid state, PCMs allow around 28% of visible light to pass through, whereas in their liquid state, VLT rises to more than 40% [61]. Despite the existence of translucent PCMs [62], the effectiveness of these technologies in terms of transmitting high-quality light remains a drawback. Furthermore, PCMs still have limitations, including challenges associated with selecting the appropriate melting temperature, concerning about the

Figure 6.
Transition phase in a thermochromic glazed façade.

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[3] In a study [60], it was found that wall and indoor air temperature fluctuation is decreased by 2.7°C and 1.4°C, respectively, in a building that incorporates PCM; moreover, also energy demand was reduced by 57% during winter.

flammability of paraffin, and the complexity of efficiently dissipating thermal energy from the material following extended periods of elevated temperature exposure.

3.3 Renewable solar energy

By considering that around 40% of the worldwide energy demand is consumed by buildings, "solar Architecture is not about fashion, but about survival," as Architect Norman Foster said, becomes a reality. Anyway, the planning of buildings with multifunctional, integrated façade elements capable of fulfilling the technical demands becomes an essential part of the architectonic mainstream and can contribute to an esthetic valorization.

3.3.1 Semi-transparent PV

The goal of energy change linked to greater use of renewables is successfully achieved when visual appeal and energy efficiency merge together: This architectonic feature finds its optimum in the semi-transparent photovoltaic systems. At the basis of the photovoltaic panel functionality, there is its ability to absorb solar energy and convert it into electricity, transforming photons into electrons (**Figure 7**).

The phenomenon is very similar to selective glass: In the case of transparent photovoltaic panels, a transparent luminescent solar concentrator (TLSC) is used to make the panels completely transparent like glass and, on the other hand, to allow them to absorb wavelengths of light nonvisible to the human eye, such as infrared and ultraviolet light [63].

Today, Building Integrated Photovoltaic (BIPV) can provide optimum U-value (ranging from 0.5 in triple glass glazing to 1.1 W/m^{2}K in double glass), with optimum

Figure 7.
The Hauptbahnhof, Berlin (Germany): Detail of the 1700 m^2 curved surface covered with 780 semi-transparent c-Si panels (Energy output: 180 kWp, Architect: Meinhard von Gerkan; System provider: Optisol, 2003).

solar factor (G value) and light transmission (TL value) and in the main time to produce solar energy.

Semitransparent PV is formed by Solar PV Cells placed between two panels of glass.

The light transmission and the level of shading inside the building can be controlled and regulated by adjusting the distance between solar PV cells. The panels become transparent when solar PV Cells are positioned far apart; instead, when the cells are positioned closely together, they become semi-transparent and produce a shading effect. Apart from generating electricity, modules can be customized in different dimension, thickness, shape, and color.

Efficiency is quite lower comparing to traditional polycrystalline PV panels.

The average efficiency in intermediate seasons reaches values of about 7.5%, while the conversion efficiency is always calculated as the ratio between generated power and incident radiation, it reaches values equal to 15.5% [64].

Anyway, as this technology is widespread and can be used on a large scale, for example, to cover entire façades of buildings, its lower efficiency is destined to be overcompensated with greater surface development [65].

Semitransparent PV can reduce the carbon footprint of a building, improve thermal insulation, acoustic insulation, and comfort increase, and in general increase the environmental and sustainable value of a building, being a solution that joins functionality, utility, and design.

3.3.2 Bio-adaptive glasses

A novel emerging category of energy-generating glazed systems are bio-adaptive glasses, realized employing photobioreactors, commonly featuring algae as their main component.

Photobioreactors are transparent structures housing a "culture medium" that contains nutrients (typically water), in which microalgae circulate in accordance with the intensity of direct sunlight exposure [66]. These microalgae are consistently supplied with nutrients, and sunlight facilitates photosynthesis, leading to a responsive adaptation of solar shading levels.

Microalgae are often favored over other plant varieties due to their remarkable growth rates and their ability to sequester more CO_2 as they can even double their volume within a week. Moreover, their capability to grow vertically makes them an ideal choice for integration of photobioreactors into building components.

The biomasses produced by bioreactors (the algae) can subsequently be collected for energy-generating purposes (i.e., as biogas to heat water); at the same time, they can capture solar-thermal heat, providing an energy source used to power the building.

This technology has been installed in buildings for the first time in the BIQ house, during the International Building Exhibition in Hamburg in 2013. SolarLeaf's bioreactors, conceived and developed by Arup in cooperation with SSC (Strategic Science Consult of Germany), have four glass layers. The two inner panes are designed with a cavity capacity of 24 liters to facilitate the circulation of the growth medium. Insulating argon-filled gaps flank these panes, contributing to the reduction of heat loss. The front glass panel is composed of white anti-reflective glass, while the rear glass panel offers the option for incorporating decorative glass treatments. A total of 129 modules of photobioreactors, each measuring 70 cm in width, 270 cm in height, and 8 cm in thickness, have been integrated into the façade of this building. With a cultivation area spanning 200 m^2, this system produces 900 kg of biomass annually and generates

Figure 8.
SolarLeaf bioreactor installed in the BIQ House in Hamburg (2013, Arup and Splitterwerk Architects).

around 6000 kWh/year of energy. This energy output is sufficient to cater to the heating requirements of 4 units within the building [67]. For comparison, photovoltaic systems have an efficiency of 12–15% and solar thermal systems of 60–65% (**Figure 8**).

3.3.3 Emerging technologies

Strategies to improve glazing performance can be grouped into four family approaches: The first is the most "traditional one," which acts on the interspace of multilayer glazing assembly (IGU) by using films, low-conductance gases of thermally improved edge spacers, to improve insulation capacity of the system; the second is aimed at altering material composition (e.g., tinted glazing); the third approach involves the application of coatings onto the glass surface to alter hoe it reflects light (such as selective, reflective of low-e coatings). Finally, the fourth resorts to external inputs (whether they are passive or active) to modify the optical characteristics of the glass.

Despite their validity, these approaches still have some limitations; to overcome such issues, researches aimed at discovering new emerging solutions are existing. Some investigate the development of self-regulating window materials as an alternative to glass, such as the reversible thermochromic transparent bamboo smart windows [68], prepared by impregnating delignified bamboo (DB) with epoxy resin containing thermochromic microcapsule powders (TMP), which is colorless at high temperatures and purple at low temperatures, or the air-sandwich glazing systems [69], based on the idea of a set of plastic films, with spacers and air trapped in-between, used as insulation.

Other promising technologies are those resorting to energy storage strategies. One such example is the High Thermal Energy Storage Thermoresponsive (HTEST) smart window [70], which encloses a hydrogel-derived liquid within glass panels. These panels exhibit impressive thermoresponsive optical attributes, boasting 90% luminous transmittance and 68.1% solar modulation. Additionally, the hydrogel-based liquid possesses remarkable specific heat capacity, contributing to the exceptional energy conservation performance of the HTEST smart window.

Unconventional types of smart windows also exist, including humidity-triggered smart windows, that alter light transmittance or window color based on humidity variations. This adaptation influences the transmission of both luminous and near-infrared (IR) light, leading to modifications in transparency or coloration. There are also mechanochromic smart windows, constructed from optically responsive materials that undergo reversible structural adjustments, such as modifications in surface morphology and configuration, in reaction to basic mechanical strain. Consequently, these changes influence optical transmittance through scattering or diffraction of visible light. Moreover, magnetochromic smart windows operate by responding to magnetic field intensity. Changes in magnetic field strength cause nanoparticles to move closer together or farther apart, thereby controlling the smart window's behavior [71].

Again, some concepts concerning emerging glazing technologies are present in literature even if, to the authors' knowledge, they still do not find real development of market applications. Some of them are the Vacuum Tube Window Technology [72], described as a combination of evacuated glass tubes and a glazed frame with Argon in the air gap between them, the Water-flow window [39], originated from the concept of removing the heat stored inside IGU's air-gap thanks to water flooding; the Solar-pond window [69] aimed at integrating into fenestration functions of lighting, heat collection, heat storage, heat preservation and photoperiod control, and the self-sufficient smart window [73] able to regulate the amount of light entering the buildings, varying its color from a transparent state to a blue state without adding energy electricity.

4. Conclusions

This study has allowed defining a synthetic but comprehensive set of requirements concerning several complementary aspects of glazed building components, ranging from architectural to technological, energetic, and economic features of innovative products for advanced glazed skins.

The relationship of façade systems with other building construction technologies has led to emphasizing and underlining the general opportunities for smart materials and solutions in the construction process as a technological and architectural chance, in a sustainable and affordable way.

To summarize the most relevant factors for each category of intervention, a multi-criteria matrix has been defined, in which the façade solutions are briefly described and compared qualitatively by crossing the strategies of interventions with the main requirement set in **Table 1**, Paragraph 3.

The comparison between the strategies identified can be found in the tables included in Appendix A.

This can become a useful tool to define, at first glance, and design criteria and operational tools to guide the design of innovative envelopes, allowing targeted choices to be made about the foreseen interventions, to obtain the desirable levels of quality.

However, it has to be said that despite their potential to reduce energy consumption in buildings while increasing user's comfort[4], the general application of smart

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[4] Compared with traditional static windows, smart windows reduce total building energy consumption by approximately 10% [71].

glazed façades is currently hampered by economic and technological factors. Although some of the technologies presented are already in the market, their widespread application is limited because of their elevated price and relatively low fatigue resistance; the main driver for building owners to install smart windows is the desire to eliminate the need for attached shades to allow full access to the outdoor views [74] even if very limited analyses are available on assessing their energy efficiency potential when deployed for residential buildings.

Besides this general overview, the real suitability of each component must be specifically evaluated for each single requirement in each context depending on the design needs.

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Valentina Frighi writes the whole section “2. The role of glazed components,” and sections: “3.2 Strategies to control summer overheating,” “3.3.2. Bio-adaptive glasses,” and “3.3.3. Emerging technologies.”

Conclusions are attributable to both the authors, so as the final revision of the work and the approval of the manuscript version to be published.

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Conflict of interest

The authors declare no conflict of interest.

Appendix

See **Tables A1–A3.**

Glass building systems for façades	
	STRATEGY 1 – Passive solar gain
Criteria for glass façades building components	Double layer glass façades
Architecture	
Transparent	X
Semitransparent	—

Glass building systems for façades	
	STRATEGY 1 – Passive solar gain
Independent structure	X
Integrate in façade	—
Architectural and smart media properties (e.g., multimedia)	—
Energy properties and comfort	
Visual Lighting transmission VLT (%)	50–70
Solar factor SHGC (%)	10–40
Thermal insulation U value (W/m^{2}K)	0.8–1.5*
Greenhouse effect (solar gain)	X
Thermal inertia	X
Acoustic insulation (Db)	3–10
Natural ventilation	X
Solar devices integration	X
Renewable energy integration	—
Environmental properties	
Recyclability	—
Green eco label products	X
Pollution adsorption (e.g., photocatalytic)	—
Economic features	—
Construction cost (€/m^2)	1200–2000

**The "thermal insulation" values (*U-value*) are referred to a technical situation of a single IGU (6 mm + 12 mm + 4 mm) Air-filled.*

Table A1.
Matrix of the main features of façade solution systems for comparison: STRATEGY 1 – Passive solar gain.

Glass building systems for façades													
	STRATEGY 2 – Summer overheating control												
Criteria for glass façades building components	TINT.	REFL.	LOW-E	SEL.	VIG	TIM	HG	EC	GC	LCD	TC	PC	PCM
Architecture													
Transparent	X	one side view	X	X	X	—	X	X	—	X	X	X	X
Semitransparent	—	—	—	—	—	X	—	—	X	X	—	—	X
Independent structure	—	—	—	—	—	—	—	—	—	—	—	—	—
Integrate in façade	X	X	X	X	X	X	X	X	X	X	X	X	X
Architectural and smart media properties (e.g., multimedia)	—	—	—	—	—	—	X	X	—	X	—	—	—
Energy properties and comfort													
Visual Lighting transmission VLT (%)	30–70	30	70–80	60	78	68	70–75	0/60	10–60	50/70	8/55	6/60	8–28/12–44
Solar factor SHGC (%)	45–70	45–55	50–60	40–45	67	64	50	9/40	10–50	0/60	15/35	10/35	33/4–37
Thermal insulation U value (W/m^{2}K)	2.8	2.8	1.6	2.7	0.4	0.80–1.3	1.4–2.8	1.80	0.9	1.50	1.36	1.20	0.48
Greenhouse effect (solar gain)	X	X	X	X	X	—	X	X	—	—	—	—	—
Thermal inertia	—	—	—	—	—	X	—	—	—	—	—	—	X
Acoustic insulation (Db)	—	—	—	—	36	—	—	35	—	—	—	—	—
Natural ventilation	—	X	—	—	—	—	—	—	—	—	—	—	—
Solar devices integration	X	—	X	X	X	—	X	X	—	—	—	—	—
Renewable energy integration	—	—	—	—	—	—	—	—	—	—	—	—	—
Environmental properties													
Recyclability	X	X	X	X	N.A.	N.A.	X	N.A.	N.A.	—	N.A.	N.A.	N.A.
Green eco label products	X	X	X	X	N.A.	N.A.	X	N.A.	N.A.	—	N.A.	N.A.	N.A.
Pollution adsorption (e.g., photocatalytic)	—	—	—	—	N.A.	N.A.	—	N.A.	N.A.	—	N.A.	N.A.	—
Economic features													
Construction cost (€/m^2)	20–100	50–90	30–70	50–130	250–500	N.A.	~150	~100	N.A.	85–130	~100	~100	500–1000

***N.A.** = Not applicable, thus meaning considered non-relevant for the state of development of the technologies explained (i.e., technologies still at a prototypal state or not on-the-market available).*
All the "thermal insulation" values (U-value) are referred to a technical situation of a single IGU (6 mm + 12 mm + 4 mm) Air-filled, except for VIG (Vacuum Insulated Glass), considered as "monolithic", and for GC (Gasochromic), for which available data are related to a double IGU gas-filled.
All the values related to VLT and SHGC of chromogenic windows technologies are referred to the two states of the systems (opaque/transparent); for PCM glasses, the values are referred to the two phases of the PCM: from left to right, first numbers reflect the situation when the PCM is crystalized while second numbers refer to PCM at liquid state.
Construction cost is approximate and related to single glass pane, thus means non-referred to a IGU technical solution.

Table A2.
Matrix of the main features of façade solution systems for comparison: STRATEGY 2 – Summer overheating control.

	Glass building systems for façades											
	STRATEGY 3 – Renewable solar energy											
Criteria for glass façades building components	ST PV	BAG	RTTB	ASGS	HTEST	HTSW	MCSW(a)	MCSW(b)	VTWT	WFW	SPW	SSSW
Architecture												
Transparent	—	—	—	—	X	—	X	X	—	—	X	X
Semitransparent	X	X	X	X	—	X	X	X	X	X	—	—
Independent structure	—	X	X	X	X	X	X	—	X	X	X	—
Integrate in façade	X	—	—	—	—	—	—	X	—	—	—	X
Architectural and smart media properties (e.g., multimedia)	—	X	X	—	X	X	X	X	—	—	X	X
Energy properties and comfort												
Visual Lighting transmission VLT (%)	30–50	8–50	60–80	50–60	~ 90	6/65	9/92	—	—	0.24–0.67	—	—
Solar factor SHGC (%)	40–60	10–80	—	—	68	—	—	—	—	—	—	—
Thermal insulation U value (W/m^{2}K)	—	~5	—	1.80–3.40	—	—	—	—	0.30–2	0.40	0.40–2	—
Greenhouse effect (solar gain)	—	—	X	—	X	X	X	X	—	X	X	X
Thermal inertia	—	X	—	X	X	—	—	—	X	—	X	—
Acoustic insulation (Db)	—	X	—	X	X	—	—	—	X	X	—	—
Natural ventilation	—	—	—	—	—	—	—	—	—	—	—	—
Solar devices integration	X	—	X	—	—	—	—	—	—	—	—	—
Renewable energy integration	X	X	—	—	X	—	—	X	—	—	—	X
Environmental properties												
Recyclability	X	X	—	—	—	—	—	—	—	—	—	—
Green eco label products	X	—	—	—	—	—	—	—	—	—	—	—
Pollution adsorption (e.g., photocatalytic)	—	X	—	—	—	—	—	—	—	—	—	—
Economic features												
Construction cost (€/m^2)	176–325 €/module	—	—	—	—	—	—	—	130	—	120	—

ST PV *= Semitransparent photovoltaic;* ***BAG*** *= Bio Adaptive Glass;* ***RTTB*** *= Reversible Thermochromic Transparent Bamboo;* ***ASGS*** *= Air-Sandwich Glazing System;* ***HTEST*** *= High Thermal Energy Storage Thermoresponsive smart window;* ***HTSW*** *= Humidity Triggered Smart Window;* ***MCSW(a)*** *= Mechanochomic Smart Window;* ***MCSW(b)*** *= Magnetochomic Smart Window;* ***VTWT*** *= Vacuum Tube Window Technology;* ***WFW*** *= Water-flow window;* ***SPW*** *= Solar Pond Window;* ***SSSW*** *= Self-Sufficient Smart Window.*

Given the extremely innovative nature of the technologies presented in this table, it was not possible to find some data. Therefore, the cells filled with "-" are to be considered empty due to the difficulty or impossibility of finding this information.

Table A3.
Matrix of the main features of façade solution systems for comparison: STRATEGY 3 – Renewable solar energy.

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Façade design is a challenging task, in which multidisciplinary issues and aspects should be optimally considered and addressed. This is especially the case of building façades exposed to seismic events, impacts, or fire. Special attention and major efforts are required for the detection and application of new technologies in the generation of modern, adaptive façade systems. This book presents a selection of research contributions to provide a comprehensive overview of façade design. It discusses the experimental analysis and numerical investigation of existing or traditional façades, as well as the development and optimal application of new technologies for modern adaptive façades and building envelopes.

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