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Published in:
Sustainability

Published: 01/02/2023

Document Version:
Final Published version, also known as Publisher's PDF, Publisher's Final version or Version of Record

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Publication record in CityU Scholars:
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Published version (DOI):
[10.3390/su15042913](https://doi.org/10.3390/su15042913)

Publication details:
Zhou, Y., & Herr, C. M. (2023). A Review of Advanced Façade System Technologies to Support Net-Zero Carbon High-Rise Building Design in Subtropical China. *Sustainability*, 15(4), Article 2913.
<https://doi.org/10.3390/su15042913>

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Review

A Review of Advanced Façade System Technologies to Support Net-Zero Carbon High-Rise Building Design in Subtropical China

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Abstract: While net-zero carbon buildings have been the focus of many previous studies, existing research tends to focus on low-rise buildings in temperate climates with cold winters. However, much of current building activity across the world, particularly in China, is located in hot and humid subtropical climates and typically features high-rise buildings. This review article systematically surveys recent literature on advanced façade systems that have been widely used across Europe and North America to determine their suitability for implementation in the subtropical climatic environment of southern China. To support the further research and design of net-zero carbon buildings in this context, this paper reviews existing technologies enabling zero carbon buildings, particularly those related to high-performance building facades, with a focus on South China. To this end, we present a systematic literature review of relevant studies in English conducted in the past 10 years. Following a definition of the scope of zero carbon building and design factors related to such building types, the paper discusses the rationale and mechanisms of key advanced facade technologies and their suitability for high-rise buildings in the hot and humid subtropical climate of South China, including double-skin façades, building integrated photovoltaics, façade greening systems, advanced shading systems, phase-change materials, and smart windows. The results of the review illustrate a shortage of relevant studies as well as a shortage of design tools supporting the integration of key technologies in the early architectural design stages, where decisions will have a significant impact on a building's subsequent performance.

Keywords: zero carbon building; sustainability; building façade system; technology integration; high-rise buildings; subtropical climates



Citation: Zhou, Y.; Herr, C.M. A Review of Advanced Façade System Technologies to Support Net-Zero Carbon High-Rise Building Design in Subtropical China. *Sustainability* **2023**, *15*, 2913. <https://doi.org/10.3390/su15042913>

Academic Editor: Ali Bahadori-Jahromi

Received: 9 October 2022

Revised: 15 December 2022

Accepted: 16 December 2022

Published: 6 February 2023



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1. Introduction

1.1. Zero Carbon Emission Goals in the Context of South China's Megacities

Leading economic bodies have set ambitious goals to achieve carbon neutrality across many developed nations. Among the largest carbon dioxide (CO₂) emitters, the EU aims to be carbon-neutral by 2050, while China has vowed to peak its CO₂ emissions by 2030 and to achieve carbon neutrality by 2060 [1,2]. These plans require the large-scale implementation of a range of clean energy systems affecting a broad range of industries, including, among others, solar energy harvesting systems, wind turbines, and geothermal power.

The building industry plays an important role in global CO₂ emissions. The building sector accounts for 36% of energy consumption and 40% of global greenhouse gas emissions [3]. In China, building operations accounted for 21% of the total primary energy consumption in 2020. Another 10% of the total primary energy consumption is used in the construction of buildings [4]. Information provided by Tsinghua University's Building Energy Research Center (BERC) reveals that the building sector's primary energy consumption accounted for approximately 20% of all commercial energy consumption in 2018

(which refers to sources that are available in the marketplace with a specific price and are used for electricity generation); the total carbon emissions related to building energy use were around 2.2 billion tCO₂. Current research predicts that with further improvements in living standards across China, building-related energy consumption will increase by up to 80% compared to current demand by 2050 [5]. The key factors mitigating the environmental impacts of a building's life cycle include embodied environmental impacts (EEl) and operational environmental impacts (OEI) [6]. The term "EEI" refers to the environmental impacts that a building generates on the environment over the course of its entire life. This includes the energy consumed for building construction, maintenance, and repairs, as well as for raw material extraction, manufacturing, and material and product transportation [7]. End-of-life management and the environmental impact caused by demolition activities are also included in assessments of EEI [8]. The environmental impacts caused by building operations, such as the energy used for lighting, cooling, and heating are excluded from EEI; these impacts are defined as OEI [9]. Accordingly, achieving zero carbon emissions requires minimizing both embodied emissions and operational emissions [10]. With façade systems linked to both the embodied energy and the operating energy of a building [11], innovative façade systems aiming to adapt to varying environment conditions have taken energy-responsible approaches by including an increasing variety of designated functions. For the purpose of this paper, we adopt a building façade definition proposed by Attia et al. [12] in the context of adaptive facades, as building envelope elements with thermal and/or solar, and/or visual properties (e.g., transparency) that change over time, either passively or as a response to an active control. We further include vertical greenery systems as climate regulating façade elements. The aim of such integrated building envelopes is to lower carbon emissions and to improve a building's energy performance while also enhancing indoor comfort under varying outdoor and indoor conditions as well as user demands.

As façade-related design and technologies are a major factor determining carbon emissions of high rise buildings, a significant body of previous research has been directed at this topic. Most of the available literature addresses building façade-related carbon emissions in temperate to cold climates in areas such as northern Europe, the northern United States, and Canada. However, a major part of current urban growth and high-rise building construction takes place in the subtropical areas of Asia, particularly in China [13]. In these different climatic contexts, existing strategies and technologies for lowering CO₂ emissions through high-rise building facades have to be revised and adapted to remain effective. At the same time, design approaches addressing the specific requirements of subtropical climates promise great improvements in energy conservation. As shown by Haase and Amato in a study on façade design for the hot and humid climate of Hong Kong, 55% of the peak cooling load in Hong Kong can be attributed to a lack of energy efficiency in the building envelope design [11]. Most net-zero or near-zero energy buildings are located in Europe, followed by North America, along with the majority of related research on this building type [10,14]. Across both regions, government policy along with a broadly shared sense of urgency to reduce global warming by minimizing building energy usage have supported related research and implementation efforts [15]. In contrast, building envelope design optimization of zero/low-energy buildings without heating or cooling is rarely studied for the subtropical regions.

As of May 2020, 1627 buildings taller than 200 m existed around the globe, according to the CTBUH data. China (758) was the country with the most high-rise buildings. The number of newly constructed high-rise buildings in China is likely to remain high as China's urban population continues to increase [16]. In addition, many areas within existing cities will continue to be reshaped and upgraded. This demonstrates the urgency of addressing façade design strategies and façade technologies in this specific climatic context.

A zero energy building (ZEB) is a building that produces as much energy onsite as it consumes over the course of a year [17]. Typically, the ZEB criteria only include the energy used to operate the building, and they exclude any other carbon emission-related aspects,

such as the fabrication and transportation of building materials and the energy used during construction. However, the scope of zero carbon building can be extended to cover more stages of a building's life cycle, encompassing the carbon emission reduction from the building structure, building materials, equipment, production, transportation, construction process, etc. [18]. China is divided into five major climate zones, each featuring a distinct climate. Analogously to similar building types overseas, about 70% of China's zero energy building projects are located in the northern "cold" zone, with only 12% located in the "hot summer and cold winter" zone, illustrating the unbalanced regional distribution of ZEBs in China [19].

The Pearl River Delta forms the most densely urbanized region among China's urban agglomerations and is situated in the southern subtropical climate zone, officially labelled as "hot summer and warm winter", or commonly referred to in previous studies as having a hot and humid climate [20–22]. Economic growth across the Pearl River Delta has been driven by high-speed construction and fast urban densification, with design goals in high-rise buildings typically prioritizing large floor areas and exterior aesthetics rather than long-term sustainability considerations. Located in the Pearl River Delta, the city of Shenzhen is one of 36 low-carbon pilot cities in China, and joined the national pilot program during the 12th Five-Year Plan period between 2011 and 2015 [23]. Current efforts to lower carbon emissions in Shenzhen have reportedly reduced CO₂ emissions by approximately 0.5 Mt annually over the past decade. The reductions have however been insufficient and have not offset the rapid rise in emissions during the same time period, which is particularly due to the increase in constructed floor area. The total CO₂ emissions from the public building sector in Shenzhen city increased from 15 Mt in 2005 to 22 Mt CO₂ in 2016 [24]. Across Hong Kong, heating, ventilation and air-conditioning (HVAC) systems consume the highest proportion of energy among all end-user systems. Jing et al. [25] have demonstrated this in a study breaking down the energy consumption of 30 buildings by end-user systems, where HVAC systems consumed 68% of the energy, while lighting and the remaining other systems accounted for a shared 14% and 18%, respectively.

With the increasingly urgent need to prevent significant global climate change caused by CO₂ emissions, this paper reviews and discusses existing research addressing strategies to significantly lower CO₂ emissions in high-rise façade design. The review aims to inform the research and design efforts to develop the much-needed innovative, integrated low-carbon emission building facades located in hot and humid climates, with a particular emphasis on South China.

1.2. Green Building Assessment Tools and Sustainable Goals

To support the architectural design process in making responsible decisions, a variety of green building assessment tools and protocols have been developed which aim to reduce energy consumption and negative environmental impacts for both the construction and the management phases and to support designers in implementing related regulations. The well-known and widely adopted green building rating systems (GBRSs), such as the Building Research Establishment's Environmental Assessment Method (BREEAM), the Leadership in Energy and Environment Design (LEED), the Comprehensive Assessment Systems for Building Environmental Efficiency (CASBEE), GBTOOL, BEAM PLUS, etc., have been broadly reviewed and discussed in previous studies. The GBRSs are typically based on checklists comprising a number of qualitative criteria. It is worth noticing that such rating systems are defined in accordance with local climatic and geographic conditions, such that existing variations are the outcome of local adaptations of the sustainability idea [26]. In other words, the weightings that are key to green building assessment tools cannot be generically applied since they may result in very different results and may not be suitable beyond specific regions and climates. Life cycle analysis (LCA) forces decision makers to base their analyses on scientific data and numerical evidence, which helps in comparing design options. Furthermore, when new technologies allow buildings to use less energy and cleaner off-grid energy sources, the embodied energy impacts arising from

materials are becoming more significant in the overall assessment. This is a factor that should be accounted for in the continued development of nearly zero energy building (NZEB) standards and practices, as Sartori et al. (2021) point out [27]. Although operational energy currently accounts for the majority of a building's life cycle, the focus of the current NZEB approaches may ultimately result in buildings with higher embodied energy and carbon [26,27]. The incorporation of LCA into GBRs would thus provide a more balanced and scientific assessment of sustainable development.

The above-described assessment methods raise designers' awareness of a building's environmental impact by contributing enhanced transparency to the design process. Green Globe and LEED, in particular, recognize the importance of embodied energy in the green building assessment process through evaluation criteria such as reduced material use and the use of locally accessible resources [28]. BREEAM and Green Star have also been incorporating LCA as part of their assessment systems [27].

The two most common rating systems in mainland China are LEED, an international certification originating in the United States, and 3-Star, a domestic Chinese certification [29]. These two GBRs have been tailored to different market segments in order to attract target developers with different motivations to build green. Developers and building owners are more likely to choose LEED to certify their commercial and industrial buildings, while 3-Star certification is more likely to be chosen by residential builders.

In Hong Kong, BEAM Plus is recognized as the leading initiative offering independent and impartial assessments to a building's overall performance over its entire life cycle [30]. BEAM developed its rating system with reference to BREEAM. Accompanied by the continued development of the green building industry, BEAM then introduced new elements from major assessment schemes around the world, including, but not limited to, LEED, GBL, and CASBEE [31]. Building life cycle best practices are rewarded with credits or points depending on either enhanced performance or implemented features. In Hong Kong, a growing number of residential, commercial, and institutional developments have received BEAM and LEED platinum certifications in recent years [32].

However, previous studies have revealed the insufficiencies and challenges of implementation faced by BEAM Plus in Hong Kong. An interview conducted by Chen et al. concludes that BEAM Plus is insufficiently comprehensive for analyzing a building's carbon footprint, according to the majority of interviewees with local (Hong Kong) practice and industry practitioner perceptions [33]. They further conclude that the reasons for this assessment are in part related to a lack of effort regarding the promotion and adoption of low-carbon strategies for buildings, as well as to shortcomings in LCA integration [33]. The most fundamental factor influencing BEAM Plus application is 'high initial cost', according to an investigation employing questionnaire surveys and expert interviews by Yeung et al. [34]. The more recently introduced passive design strategy, on the other hand, has been criticized for its debatable criteria allocation, unjustified weighting system, and incompatibility with current whole-building energy modelling methods [31]. Despite the importance of weighting, the credit system of BEAM PLUS does not always correlate the number of credits with the amount of greenhouse gas emissions that are reduced [35]. Moreover, the current structure does not help with revealing the resources required for meeting the various assessed criteria or the credits to the investors and designers, despite the fact that it is well recognized that resource commitments will normally grow as environmental performance improves [35]. While it is necessary to build measurement and benchmarking systems, the existing range of zero carbon approaches, i.e., from low to near-zero carbon, then to zero carbon, should be clarified with regard to measurement methods [36].

The variability of these factors can also be assumed to apply to cities in South China. With regard to the focus of this review on high-rise building facades, it can be stated that despite the urgency of the need to address concerns regarding energy-efficient, low-carbon emissions in the design of high-rise building facades, there is currently no uniform and

widely accepted method for assigning weighting to the assessment schemes that could be applied to buildings in the hot and humid climate of South China.

1.3. Study Focus and Overview

While urban growth is ongoing in the subtropical high-density cities of China, comparatively little research is available to inform architectural designers. However, decisions made in the architectural design process are known to have a significant impact on energy use and carbon emissions as well as on general occupant comfort and health throughout the building's lifespan. From a design perspective, the currently available partial and specialized research is difficult to integrate with the broader scope of design and the ambition to integrate a range of building technologies.

This review maps a spectrum of key technologies suitable for high-rise building façade design which aim at low-carbon or zero carbon performance in the subtropical regions of South China. The following sections first present a definition of zero carbon building and an outline of the scope of this approach in the context of sustainable building design; secondly, the factors that should be considered at the design stage of a zero carbon building are summarized; and thirdly, promising key façade technologies are analyzed and discussed in terms of their integration and implementation strategies in architectural design. Key challenges of designing zero carbon, high-rise buildings in hot and humid subtropical climates are outlined and discussed with a view to future developments over the next decade, particularly in South China.

2. Publication Selection and Review Method

2.1. Aims of the Study

This article surveys key façade technologies supporting zero carbon performance and identifies those that are the most relevant for high-rise façade system design in the hot and humid subtropical climate of South China in the next decade, with a view to detailing the potential and the challenges of their application as well as their roles within an integrated and performance-oriented low-carbon design strategy.

2.2. Identification of Relevant Publications

This review adopts diverse searching, screening, and selection criteria. The general criteria employed to identify relevant publications are listed as follows. The selected literature should:

1. Be within the scope of the AEC industry, especially with regard to architectural façade system design;
2. Preferably have been published within the last 10 years, with the exception of some early or fundamental papers;
3. Include or explicitly address high-rise buildings;
4. Specifically address hot and humid or subtropical climates, particularly that of South China.

Three databases were considered: Scopus, Web of Science, and Google Scholar. The selection criteria for each specific part of the review vary. In Section 3, in order to define the zero carbon building and its scope, the related terms of 'Zero Carbon Dwellings', '(Net) Zero Energy', '(Net) Zero Carbon', and 'Zero Emission', were also included to better distinguish and contextualize the scope of zero carbon building. Nine papers are included in this section.

In Section 4, 10 papers are included to define the factors to be considered in zero carbon building design. Literature on sustainable building design is reviewed for a broad initial search and further narrowed down to the specific scope of zero carbon buildings. To this end, literature analyzing the design factors and design parameters by employing scientific methods is selected, concluding with selected relevant case studies.

Each core review sub-section focusing on key technologies and integration strategies employs a similar sequence, proceeding from first defining key terminology and subse-

quently addressing the environmental impact of key façade system technologies. Studies employing simulation, examination, and investigation are included for a rigorous validation of their effectiveness and suitability with regard to high-rise buildings in South China. We included 55 papers in this section.

The snowball method was employed as a supplementary search method, utilizing a website-based search through ‘Connected Papers’ to better explore the relevance of publications in the broader context of the field through visual graphs [37].

2.3. Analysis and Synthesis

Section 3 reviews definitions of zero carbon building, as well as the scope of this design approach, to offer a broad perspective on the background of carbon neutrality goals. In Section 4, we conduct a brief literature review of design factors that have to be considered in sustainable architectural design, narrowing down the scope to subtropical and hot and humid climates. The section focuses primarily on façade design parameters determining environmental impact and on examining publications on design factors and parameters for zero carbon buildings in hot and humid climates, specifically that of South China.

Section 5 offers an in-depth review of literature on key façade technologies, taking into account integration strategies with a view to architectural design strategies for zero carbon buildings. Each sub-section starts with a brief review of the rationale and mechanism of the selected key technology, then narrows this down to the high-rise building typology and subtropical climate of South China.

2.4. Scope and Limitations

The scope of this paper focuses specifically on technologies relevant to building facade design that are widely acknowledged and supported by previous research, indicating their viability for achieving low-energy building in hot and humid subtropical China. Although sustainable building design for low-carbon or zero carbon performance involves the integration of systems throughout the whole building, façade systems have a significant impact on energy management and are also of particular interest from an architectural design perspective. Furthermore, the proper design and optimization of the envelope has been shown to be a powerful and effective approach in subtropical regions [38]. This review thus addresses façade technologies, with other fundamental technical systems for NZCBs such as heating, ventilation and air-conditioning (HVAC), lighting, plug load equipment, and renewable energy technologies covered only where necessary as supplementary aspects.

EU and North American regulations and policies have driven a push towards lowering carbon emissions in various climates, which has produced much research and new knowledge on related building types. However, many large urban clusters in the world, particularly those in China, are situated in hot and humid climates. The dominant building type for these megacities is the high-rise building, within a unique and developing urban context and thus requiring flexible and context-specific design strategies. For the purpose of this study, the broad field of sustainable facades lowering carbon emissions is narrowed down to façade technologies deemed relevant to hot and humid climates, with established energy-saving performance documented in previous research.

While the surveyed façade system technologies also offer ecological and social benefits, this paper focuses mainly on energy performance with a view to achieving zero carbon building goals. Accordingly, our discussion of green facades, for example, is not focused on vertical greenery systems that help to improve biodiversity and air quality of outdoor environments that people and animals live in, but on the role of vertical greenery systems in lowering temperatures and reducing solar radiation through shading.

Aiming to inform architects and façade design professionals, the study offers a survey and a comparison of the current state-of-the-art research on advanced facade system technologies at the early design stage to support more integrated decision making as well as design workflows. It also potentially informs policy makers as well as educators working on strategies to develop future integrated high-rise building visions.

3. Definition and Scope of Zero Carbon Building

Generally, the terms '(Net) Zero Energy,' '(Net) Zero Carbon,' and 'Zero Emission' are used to describe buildings that use renewable energy sources onsite to produce energy for their operation, with the net amount of energy generated onsite equaling the net amount of energy required by the building over the course of a year [39]. A zero energy building (ZEB) is a building that generates as much energy onsite as it consumes over the course of the year [17]. Typically, ZEB criteria only include the energy used to operate the building, while the scope of a zero carbon building (ZCB) may also include carbon emissions.

The definition of zero carbon dwellings, according to the Department for Communities and Local Government (DCLG) [40] was aimed at encouraging high energy efficiency, onsite carbon reduction methods, and a list of allowable solutions (mostly offsite) for dealing with the remaining emissions. Within that scenario, zero carbon means that the net carbon emissions from the total energy use in the dwelling would amount to zero over the course of a year. Allowable options, according to a related study by the Department for Communities and Local Government (DCLG), could include large-scale offsite (and potentially unconnected) renewable energy installations, local energy efficiency investments, and the installation of energy-efficient white goods (major appliances used for routine housekeeping tasks) or building control systems [40]. Furthermore, as suggested in the UK Green Building Council (UK-GBC) report 2008 'on- or near-site' recommendation, Fulcrum [17] argued that the metrics employed should be outcome-based and that the criteria should be broadened to include new renewable energy generation installations near the development. The Australian Sustainable Built Environment Council (ASBEC) created a definition for ZCB in order to enable stakeholders to realize their efforts to achieve zero emissions, according to a greenhouse gas reporting standard established by the World Business Council on Sustainable Development and the World Resources Institute [39,41]. The resulting definition proposes that a zero carbon building should produce no net annual emissions from direct greenhouse gas emissions from sources that the occupant owns or controls and from the generation of power utilized in the building. According to this definition, all energy demands or sources that are part of the building fabric at the time of delivery, such as the thermal envelope, water heater, built-in kitchen appliances, fixed lighting, shared infrastructure, and installed renewable energy generation, are included in the building-incorporated services.

'Zero Carbon Building' is a relatively broad concept relevant to each stage of a building's life cycle. Accordingly, the ASBEC suggested variations of the standard terminology for zero carbon building delivery. These variations provide specific goals at certain stages, including the following terms: 'Zero Carbon Occupied Building', focusing on the occupant emissions during the use period of the building; 'Zero Carbon Embodied Building', mainly focusing on the significance of embodied emissions related to early design decision making; 'Zero Life-cycle Building', including all emission sources in the overall building life cycle; 'Autonomous Zero Carbon Building', focusing on electricity use without power grid connection during the operation stages; and 'Carbon Positive Building' or 'Carbon Positive Occupied Building', achieving less than zero emissions and calling for energy generation strategies.

While the topic of the zero energy building has led to extensive publications on energy conservation, more recent studies have also addressed the significance and impact of embodied energy or embodied carbon emissions. Definitions of zero carbon buildings also encompass the carbon embodied in a building's structure, building materials and equipment, as well as carbon emissions generated by a building's production, transportation, construction process, etc. [18]. In a more stringent and broader definition, all emissions would be considered as part of the life cycle of a building, from planning and design to the manufacturing of building materials, the transportation of materials, the construction process, the regular building operations, the renovation and maintenance, and the waste disposal.

In an effort to provide a comprehensive definition, Pan (2014) defined eight system boundaries that are important for an effective understanding of a zero carbon building; these include the policy time frame and the building's life cycle and the geographical, climatic, stakeholder, sector, density, and institutional boundaries [42]. The model's application to five examined zero carbon building case studies in the study demonstrated the boundary dimensions of ZCBs in terms of their significant diversity and complexity, as well as insights into their comparative profiles. The incorporation of multiple boundaries to further elaborate the concept and define future research is becoming more urgent as the awareness of life cycle approaches for reducing carbon emission and energy consumption is rising.

In the long term, considering ZCB in a broader manner will benefit several pillars of sustainability in urban development, especially given the urgency of achieving carbon neutrality across the world. However, in the short term, the attention of researchers and practitioners revolves as much around building energy consumption as around embodied carbon. The scope of the (net)-zero carbon/energy aim, the parameters addressed, and the value-based (the manner in which design teams reflect local conditions) and context-specific features of ZCBs must all be considered when developing a systemic understanding of ZCB. Once this more holistic understanding of ZCBs is established, it will lead to a more coherent sustainable vision of building construction. At this time, however, the scope of 'Zero Carbon' has not been defined in a unified manner, and is therefore more of a general notion than a practical approach [36].

4. Factors to Be Considered at the Design Stage of Zero Carbon Buildings

As the decisions made during the design phase will determine a building's performance for the entirety of its life cycle, involving roughly 80% of the building's energy consumption, it is critical that architects think about sustainability principles as they develop design proposals. This is accomplished by prioritizing less energy-intensive, preventive, and passive design strategies over active ones in a linked and weighted approach [43,44]. Architectural professionals also play a significant role in future low-energy, sustainable buildings, as they are responsible for most crucial decisions during the design phase of a building. With nearly 80% of a building's usage patterns established during the design process, there is a considerable opportunity to avoid negative impacts [43,45]. This seems especially relevant as, despite most architects' positive attitude to incorporating sustainability concepts into the architectural design process, only a handful will follow through on these principles on closer examination.

A significant number of previous studies focused on determining key factors for sustainable design that should be considered early on in the architectural design process. Li presented 10 categories of sustainable design factors, covering a broad scope of sustainable development, including economy, society, natural environment, and the architecture itself [46]. The categorization reveals the complexity and functions of a sustainable building in a broad view, considering energy and CO₂ emissions, water, materials, surface water run-off, waste, pollution, health and well-being, management, land use and ecology, microclimate, and society. Another set of design guidelines for sustainable projects based on key sustainability indicators was developed by Fera and Amado [43]; these guidelines mostly follow the traditional design process while enhancing sustainability strategies.

The energy performance of buildings in hot and humid climates has received some attention, such as in the sensitivity analysis performed by Yildiz and Arsan [47] to determine the most significant performance parameters for buildings in hot and humid climates; the analysis focuses on an existing apartment building in Izmir, Turkey. The findings derived from this study show that the sensitivity of parameters in apartment buildings vary, depending on the energy load's purpose and the building's location. The study demonstrated that in hot and humid conditions the total window area, the heat transfer coefficient (U), and the solar heat gain coefficient (SHGC) of the glazing depending on orientation are shown to have the greatest impact on the energy performance of apartment buildings.

A multi-stage sensitivity analysis for zero/low-energy buildings without heating provision in subtropical regions was conducted by Li et al. [15]; the analysis identified the key design parameters as being the building's orientation, roof solar absorption, window-to-wall ratio, wall solar absorption, the window solar heat gain coefficient, and the overhang projection ratio. From these parameters, the window-to-wall ratio, the wall solar absorption, the window solar heat gain coefficient, and the overhang projection ratio were shown to be the parameters with the most significant impact on the energy performance of zero energy buildings in subtropical climates. All factors identified in the study by Li et al. [15] are directly related to architectural façade design.

Several studies specifically addressed parameters particularly relevant in façade design. From an environmental perspective, Tabadkani et al. [15] suggest that the key parameters for façade design in hot and humid climates are solar gain control, natural ventilation, daylighting rather than artificial lighting, view out, heat control, and moisture control. Design strategies and energy-conservation strategies of zero carbon building design for Hong Kong (hot and humid subtropical climate) were outlined by Ng et al. [48]. These include a high-performance facade with a low overall thermal transmittance value, excellent air tightness, and optimized window design that allows natural ventilation and daylighting to operate.

The above outlined studies give different emphasis to aspects such as climate, building type, and the goal of sustainable architecture or zero carbon goals. However, in the context of zero energy, high-rise buildings in hot and humid subtropical regions there is still little existing research examining and consolidating the performance parameters that could inform the related architectural design strategies.

5. Key Technologies, Materials, and Integration Strategies for Façade Systems of High-Rise Buildings

Façade systems are widely recognized as viable and effective means to achieve carbon emission reductions by energy conservation and/or energy generation. Several advanced façade technologies have been found to be particularly effective in reducing energy consumption, such as double-skin façades (DSFs), building integrated photovoltaics (BIPV), building greenery, and advanced shading systems. This section reviews these four key technologies with a view to their viability in the context of high-rise buildings in hot and humid subtropical climates, specifically in the context of South China. Each core review sub-section concentrates on key technologies as well as integration strategies and follows a similar sequence, proceeding from defining key terms to an outline of these key façade system technologies' effects on the environment. For a thorough evaluation of their effectiveness and applicability to high-rise buildings in South China, this review mainly included studies utilizing simulation, examination, and investigation.

From a holistic sustainable design perspective, the buildings should be designed to sustain people as well as nature in urban contexts in order to support and improve the health of urban inhabitants in a broader urban ecological setting. Accordingly, the buildings should be designed in a systemic manner, integrating various advanced technologies, to achieve functional as well as sustainable buildings. Advanced building façade technologies thus aim to achieve multiple goals, including performance contributions towards zero energy buildings, carbon emission reduction, and more generally sustainable urban environments.

In hot and humid climates, the essential principle to consider for realizing NZEB targets should be the integration of multiple energy-saving and renewable energy technologies at the lowest cost [49]. To achieve these design goals, the integration of active and passive strategies becomes particularly crucial. The following sections offer more detailed reviews of the status quo of the above outlined key technologies, their integration strategies, applications, and operational experience in architectural design.

5.1. Double-Skin Façades

Double-skin façades (DSFs) are among the most promising sustainable façade technologies and have been discussed in detail in previous studies. The double-skin facade is a building system consisting of an outer skin and an inner skin, typically consisting of glass assemblies, and the intermediate cavity in between. The glass skins can be single- or double-glazing units at distances from 20 cm to 2 m [50]. The intermediate space is typically used for controlled ventilation and solar protection. For solar protection and heat extraction reasons during the seasonal cooling period, solar shading devices are often placed inside the cavity [51]. Ventilation of the cavity can be natural, mechanical, or hybrid, depending mostly on climatic conditions, use, location, occupational hours of the building, and the HVAC strategy [52]. In practice, DSFs are usually applied in combination with other façade technologies, including the vertical greening system, active and passive shading systems, and PV systems.

With the promotion of sustainable building codes in South China, the DSF has caught the attention of architects and engineers alike in both new and retrofit building projects aiming to achieve zero energy and zero carbon buildings. However, existing studies have reported insufficient details on the application and operation of DSFs in the hot and humid subtropical climate of South China. Although DSFs have been widely studied in different climates in the past decades, the application of the DSF as a building system is complicated and requires adaptations to suit hot and humid subtropical climates. As Zhou and Chen [19] argued, double-skin façades function less efficiently in the summer, with disadvantages such as intense solar radiation, high external temperatures, and the required constant low wind speed all limiting the efficiency of natural ventilation when employed in subtropical climates.

Chan et al. [50] conducted an investigation of the optimal selection of glazing types for application in DSFs, based on the climate of Hong Kong. The study indicated that buildings with a DSF can save up to 26% of annual cooling energy if well configured, compared to conventional buildings with external walls and single absorptive window glazing. Haase and Amato [11] conducted a simulation study calculating the reduction in cooling energy for different DSF systems, illustrating considerable cooling savings of up to 17%, including during the three hottest months, indicating a 25% lowered peak cooling load compared to a conventional curtain wall system. Wong et al. [52] developed a new type of double-skin façade configuration employing a natural ventilation strategy in high-rise buildings in hot and humid climates, in order to provide better indoor thermal comfort.

The advantages of the DSF need to be balanced against the challenges of the technology, which include higher investment costs and a long payback compared to conventional single-skin façades, the risk of overheating on warm sunny days, and acoustics, moisture, and fire safety issues. Among the downsides of a double-skin facade are much greater initial investment and maintenance costs compared to a standard single-skin façade. The long-term payback strategy might make DSF less attractive in the short term, but it has also been widely agreed by experts to be beneficial for building construction in the long run due to its emphasis on quality and durability [53]. The risk of overheating on hot sunny days is another technical challenge of the DSF, which could potentially be minimized through the integration of phase-change materials, shading systems, and mechanical ventilation strategies [54,55]. Acoustics, moisture, and fire safety design difficulties, due a lack of industry standards, are also challenges that have been discussed in the context of the implementation of DSFs in China, with ongoing related research that is supported by the recent strengthening of China's efforts to reduce carbon emissions [55].

Among the most promising DSF-related technologies is the integration of phase-change materials (PCMs). The term is used to characterize materials that absorb or release substantial amounts of latent heat at a constant temperature through state shifts (e.g., solidifying/liquifying). The process of the state change releasing or storing thermal energy can help to regulate temperatures in façade assemblies without requiring much thermal mass. PCM applications can be a powerful tool in designing net-zero energy

buildings as innovative thermal storage systems since they can absorb and/or release heat energy without temperature fluctuation during the process of physical property transformation [56,57]. Chan [58] assessed the energy and environmental performance of a typical residential flat under subtropical climate conditions in Hong Kong with PCMs installed in the external walls of the living room and bedroom. The living room of a residential flat with a west-facing wall integrated with PCMs was found to perform better in terms of lowering the interior surface temperature by up to 4.14%. A corresponding annual energy saving of 2.9% in the air-conditioning system was realized for the west-facing case. Chan also stated that building facades incorporating PCM wallboards can be a cost-effective way to apply PCMs across large surface areas of building façades and can lead to significant energy emission reductions.

Located in the central business district of Bao'an, the new Shenzhen Rural Commercial Bank headquarters, designed by Skidmore, Owings & Merrill LLP (SOM) is a new landmark development of a 158 m tall, 33-story tower. Sustainable strategies such as the double-skin façade concept were integrated with the structural design. The diagrid supporting superstructure outside the glass curtain wall functions as a static shading system which can reduce more than 30% of the solar gain. Automated louvers in the full-height vertical atria and the mechanized window vents on each office floor together constitute a 'breathing' façade that can provide fresh air and enhance energy efficiency in Shenzhen's subtropical climate [59].

5.2. Building Integrated Photovoltaics

Building integrated photovoltaics (BIPV) provides an aesthetical, economical, and technically feasible method for integrating solar cells that capture solar radiation to generate electricity within building envelopes designed to support a carbon-neutral built environment [60]. As such, BIPV has been widely acknowledged as an effective approach contributing to achieving global greenhouse gas (GHG) emission reduction objectives [61]. For the decarbonization of the energy system, a significant expansion of photovoltaic (PV) areas is required, which must often be accomplished with minimal additional land use [62]; PVs can be installed on the roofs and facades of existing and new buildings. In high-rise buildings, where the roof is frequently required for the installation of heating, ventilation, and air-conditioning systems, the roof area is typically very limited, such that façade areas become more significant. Accordingly, cities dominated by high-rise buildings, such as Hong Kong and Shenzhen, along with other dense megacities in the Pearl River Delta, require a façade-focused consideration of PV application to buildings. The challenges and opportunities of PV deployment in these types of urban contexts are acknowledged and reviewed in the following sections. In this paper, we focus on BIPV as a technology with the capacity to integrate with various façade systems, and we exclude the well-established research area of BIPV in the form of roof panels. We aim to facilitate the versatility of building façades, with potential benefits to both indoor environmental quality and overall building performance, and further support the long-term achievement of a zero energy and zero carbon building.

BIPV systems, on the other hand, replace the exterior building envelope skin, i.e., the climate screen, which serves as both a climate screen and a power source generating energy. As a result, in addition to lowering electricity costs, BIPV can also generate savings on materials and labor [63]. BIPV systems can also be integrated with other key technologies such as shading systems. The analysis of examples in different climates has shown that up to 42% of annual building energy consumption could be reduced by BIPV systems when combined with appropriate shading configuration implementation [64]. Happle et al. argued that BIPV installation can reduce carbon emissions by 15% to 50% in Southeast Asian cities [65]. Feng et al. conducted studies of 34 NZEB cases in hot and humid climates, and most of them applied onsite solar PVs as key renewable energy technology [14]. They highlighted that BIPV design is important for achieving the NZEB targets and increasing renewable energy penetration in high-rise buildings. Lou et al. studied school buildings in

Hong Kong and concluded that 97.5% of annual electricity generation can be supplied by the vertical BIPV facades [66].

Previous research also identifies several technical barriers of BIPV systems. The main problem consists of heat transfer issues due to the inherent design of BIPV, leading to the façade system overheating and heat transfer to the building itself. A second set of barriers is identified by Agathokleous and Kalogirou as a lack of standards, performance monitoring systems, and modelling studies prior to system installation [67]. Maintenance and the possibility of replacement also need to be considered, as external fixing and wiring can present issues when replacements are needed. As PV cells are part of building envelopes, they can be considered as a substitute for façade materials and accordingly have to fulfil various requirements, including noise control, proper positioning regarding inclination, orientation, and shadows as well as allowance for extra loads under extreme weather conditions [67,68]. The disadvantages of BIPV over solar modules were discussed by Shukla et al. [69]. In their comparative analysis, the biggest disadvantages of BIPV over normal crystalline PV modules involve higher cost as, normally, BIPV modules are made of thin film, leading to lower efficiency. Moreover, the installation of BIPV is more complex than that of conventional PV modules. In high-density environments, the performance of BIPV furthermore depends on the buildings' urban context, which could sometimes be a disadvantage in high-density cities since shading from surrounding buildings or objects can be a serious concern to solar collecting and renewable energy generation through PVs [70].

Energy-saving measures, including building orientation, natural ventilation rate, external surface solar absorptance, envelope U value, window solar heat gain, building airtightness, cooling COP, lighting efficiency, and cooling set point, all have an impact on energy performance [71]. These energy-saving measures have been studied to achieve better energy efficiency and to provide engineers with a solid scientific knowledge base for technical design. However, BIPV is a technology that involves new materials and technologies that feature prominently on building facades, which leads to a significantly different appearance compared to conventional façades. While the suitability of BIPV has been shown to be effective in terms of energy conservation, other design factors are considered similarly important for implementation success, such as the aesthetics of solar modules in urban contexts. While this aspect of BIPV is rarely studied, it is acknowledged as crucial for achieving a higher aesthetic scores and broader acceptance among architects [72].

A survey by Farkas et al. [73] examined the barriers to BIPV adoption encountered in architectural design through an international survey. The study points out that from the perspective of architectural designers, deploying commercially available products and integrating them directly into façade design is challenging. On the one hand, BIPV product development does not give much attention to aesthetics. On the other hand, architectural designers lack knowledge and find the information on BIPV products difficult to access, while clients are not familiar with the benefits of BIPV integration into facades. Overall, this leads to a broad lack of interest in BIPV implementation.

Generally, architectural design options in BIPV applications to building facades include their front and rear materials, PV cell patterns, the positioning of modules in the façade context, and the use of color to conceal the PV cells [62]. A pervasive lack of architecturally oriented literature and readily understandable data for architects, including guidelines and criteria, consequently creates challenges for architects interested in integrate BIPV into their design proposals. As a result, only a few BIPV products support high-quality building integration or complement the construction components [73]. A further compounding factor is a lack of architecture-friendly design tools providing data on the BIPV energy output based on size and orientation. With building technologies often considered only late in conventional architectural workflows, insufficient time and resources are dedicated to integrating such technologies. To adopt BIPV in the early architectural design stages, new cross-disciplinary workflows as well as simple design tools could help to broaden the designers' knowledge with architecturally accessible data on the products, which could benefit the integration and adaption of BIPV in building façades from an early design stage.

In terms of BIPV performance, Aelenei et al. [74] conducted research through simulations and experiments using phase-changing material (PCM) as a rapid stabilization of the PV module temperature, decreasing its operating temperature and increasing overall electricity production. The study presented a maximum electrical efficiency of a new BIPV–PCM integrated system of up to 10% and a maximum thermal efficiency of 12%. In the context of the hot and humid climate of China, the R&D building of Zhuhai Xingye New Energy Industrial Park can be drawn on as a successful case study using BIPV in façades to achieve NZEB performance [14]. In this building, PVs were integrated into the southern façades, while natural ventilation strategies were employed to cool the PV panels and achieve the desired efficiency through circulating air at the back of the PV system. Yet another local example, the façade of the Pearl River Tower in Guangzhou combines BIPV with façade shading. The PV systems are integrated with the exterior horizontal shading systems on the eastern and western façades and can generate around 200,000 kWh of electricity per year while reducing excessive solar radiation [75].

5.3. Vertical Greenery Systems

Green systems, such as vertical vegetation systems and green roofs, have been employed as a sustainable solution for preventing the building envelope from receiving excessive solar radiation. In addition, greenery systems have many advantages for urban environment, such as absorbing incident solar radiation and thus lowering the ambient air temperature, reducing urban heat islands, and generally improving the building's aesthetic value [76]. By reducing the surface temperature of walls and roofs, the greenery systems achieve a reduction in building thermal load and, as a result, a reduction in building power consumption. In this paper, as we aim to focus on the potential of façade system technologies development, we specifically discuss the suitability of vertical green systems (VGSs) as a technology for improving façade performance.

Many types of vertical green systems have been developed and studied, including green facades, modular living walls, vegetated mat walls, cable and wire-rope net systems, balcony gardens, and various combinations of these types [77]. Green facades are defined as facades covered by plants to lower temperatures through acting as shading systems, in addition to insulating occupants from noise. Vertical greenery systems can be differentiated in terms of their approach to integrating plants on building surfaces. Modular living walls as well as vegetated mat walls for example are typically connected to the structural frame of the building and can potentially support a greater variety of plant species. Cable and wire-rope net systems are more efficient in terms of their lower weight and lower requirement for maintenance, with their separation from building walls potentially reducing the damage caused by climbing plants. Balcony gardens can be combined with living wall systems and can allow the planting of larger tree species. However, the increased weight introduced by heavier plants and soil mass typically requires the integration of such balconies into the main load-bearing structure of the building. Greater plant variety in these vertical greening systems also has the benefit of marked seasonal changes which may be employed for aesthetic effects.

A number of visionary projects in Singapore have applied vertical greenery in innovative ways. Over the past two decades, Singapore has conducted many research projects and small-scale experiments that investigate the integration of greenery in buildings. Several policies and initiatives were generated from these programs, including the GFA exemption for communal sky terraces, the GFA exemption for communal planter boxes, the Skyrise Greenery Incentive Scheme, and the Landscape for Urban Spaces and High-Rises (LUSH), as well as the Landscape Excellence Assessment Framework (LEAF) [78]. To achieve its goal of becoming a “City in a Garden”, Singapore currently focuses on three main strategies: employing extensive greenery from the ground through building facades up to rooftops, incorporating biodiversity into urban landscapes, and encouraging community involvement as active participation. The “City in a Garden” idea is expected to be sustained by social engagement such as community ownership and pride [78]. These strategies are well

practiced in building projects. WOHA's PARKROYAL for example incorporates intensive greenery on roof and terraced façades (balconies) [79]. In their design of the School of the Arts, green façades function as an environment filter to block glare and dust and to regulate temperature and traffic noise [80]. The residential, 36-story Newton Suites includes a continuous vertical green wall as well as cantilevered sky gardens projecting off the elevator lobbies every four floors [80]. All the described projects support high population density, high environmental sustainability standards, and greater livability for the city of Singapore as a whole. The pioneering ideas demonstrated in these projects provide inspiration for many other cities in Asia seeking new approaches to integrating the requirements of density and sustainability.

Among the green building technologies tested as part of Singapore's zero energy buildings, the greenery systems were monitored for their thermal performance. A study conducted by Hien et al. [81] conducted field measurements of the surface temperatures and ambient air temperatures and observed that the surface temperatures of the walls/roofs covered by the vertical greenery systems on the west- and south-facing facades and rooftop were reduced by up to 11 °C, 6.6 °C, and 24.5 °C, respectively; the ambient air temperature was reduced for the west- and south-facing facades and rooftop greenery by 3 °C, 2 °C, and 24.5 °C, respectively. This performance of reducing surface temperature and ambient air temperature is indicative of the energy conservation potential of green facades.

In cities with limited green and ground space, living walls and green walls, as well as green roofs, have been proposed as a promising strategy for greening cities [82]. In hot and humid climates, with plants growing year round, the application of green façades and green roofs is a common design strategy in net-zero energy buildings [14].

Lin et al. [83] used computational fluid dynamics, to simulate the thermal effect of green façade foliage in the climate conditions of Guangzhou China [84]. In three scenarios with south, east, and west orientations, seven green façade typologies and one unshaded reference model were utilized for simulations and compared to analyze the effects of green facades on the thermal environment of the transitional area. The results show the remarkable effectiveness of the three typologies of green facades in adjusting temperature [84]. Yet another study on the thermal behavior of living wall systems in hot and humid climates by Chen et al. [83] has shown a notable cooling performance. Compared to the bare wall situation, the exterior wall surface temperature is reduced by a maximum of 20.8 °C, the interior wall surface temperature is reduced by a maximum of 7.7 °C, and the interior space temperature is reduced by a maximum of 1.1 °C. Thermal simulation results presented by Stav and Lawson [83] show that the annual cooling energy savings derived from the use of living wall systems can reach 25% with realistic design decisions in subtropical environments. Wong and Baldwin conducted an investigation concluding that substantial energy could be saved by applying a double-skin green façade to high-rise residential buildings in Hong Kong, thereby reducing cooling energy consumption in the hot and humid summer [85]. Pan and Chu [86] examined the thermal performance and potential energy savings achieved through vertical greenery systems (VGSs) in Hong Kong and found that VGSs can significantly reduce heat transfer in building facades during the summer months. VGSs not only help to reduce global warming through conserving energy and mitigating urban heat island effects (UHI), but functionally provide effective external shading by reducing air-conditioning load and increasing thermal comfort in hot and humid regions. However, Dahanayake and Chow, as well as Pan and Chu, also pointed out that VGSs were less cost-effective in the winter months since electricity savings from reduced air-conditioning usage were closely tied to the daily average temperature [86,87].

Manso and Castro-Gomes offered a broad categorization of the different types of green wall system into several groups while summarizing their advantages and disadvantages [88]. The advantages and disadvantages are discussed in relation to specific application methods, including aspects of plant selection/climate adaptability, surface coverage of growth, complexity of implementation, maintenance problems, environmental impact of the required materials, and cost of installation and maintenance. There is a

significant evolution in this field that is concluded comprehensively as the green wall system could be developed in several aspects, including lightness for building rehabilitation, modularity for rapid installation, maintenance simplification, disassembly and replacement, new strategies for performance and durability, and design innovation for adapting to surface forms and inclinations [88]. Several studies point out that vertical greenery systems (VGSs) require high installation costs and maintenance [89]. Radic et al. [77] identified 13 VGS types in their publication, which include four types of green façades and nine types of living wall. The cost of the panels and diverse plant species and the irrigation and installation cost lead to living walls generally being regarded as the most expensive type of vertical greening system. In addition, disposal, taxes, and cladding renewal contribute to living wall system expenses, limiting the wider applications of such systems [90]. Green façades may generally result in the loosening of masonry; so, their employment is often limited to concrete building façades. However, with an average payback time of 20 years, green façades are economically sustainable in longer-term planning models.

The building 18 Kowloon East, designed by Aedas, can be viewed as a good exemplar of a well-integrated vertical greening system which achieved pleasing architectural effects [77]. Located in the former industrial area of Kowloon Bay, the tower is a 28-storey mixed-use building which includes housing, offices, retail spaces, and a car park. Extensive façade plantings were introduced in the lower portion of the tower, transforming the unattractive car park area into a visually attractive city garden for the neighborhood. This strategy demonstrates a broader purpose of VGSs and an important role of these systems in sustainable ecological urban rejuvenation.

5.4. Advanced Shading System (Passive and Active)

Shading systems play an important role in sustainable architectural practices in subtropical climates, where the demands for cooling and the reduction in unwanted direct sunlight are high. Advanced shading systems can be categorized into passive and active types according to their design strategies. Passive shading systems include overhangs, external roller shades, and venetian blinds, as well as internal shading, and they are applied globally as typical passive strategies to protect buildings from intense solar radiation while provide the potential to reduce energy consumption [91–93].

In Hong Kong, horizontal overhangs and vertical side fins are widely applied as passive shading devices to block direct solar radiation from certain angles [94]. A study by Liu et al. has shown that, with optimal shading panel configuration design, an up to 8% overall energy saving can be achieved for residential tall buildings in Hong Kong's climate [95]. However, one of the key disadvantages of passive shading is a lack of flexibility in response to the daily and annual dynamics of the outdoor climate.

Active shading systems which can respond to changing external and internal environments are increasingly applied to building façades. They can be categorized into three sub-groups: smart glazing, kinetic shading, and integrated renewable energy shading [92]. Smart glazing such as electrochromic glazing (EC) can save up to 50% of the air-conditioning energy consumption in warm and hot climates [96]. As novel façade devices composed of moveable elements that are operated algorithmically [97], kinetic shadings have demonstrated the potential to optimize dynamic interior daylight and to benefit the occupants' visual comfort with the support of parametric design [98,99]. Increasing research and application interest is currently directed to integrated renewable energy shadings, such as active shading with photovoltaics, due to their dual benefits in reducing unwanted direct sunlight while generating electricity [100]. In terms of energy considerations, Zhang et al. [101] investigate the optimum design of solar PV shadings with various tilt angles and orientations in Hong Kong. A numerical simulation approach demonstrated that fixed horizontal solar PV shadings on the south facade can be beneficial for buildings in Hong Kong, with recommended tilt angles of around 20° to obtain optimal electrical productivity. Zhang et al. [101] also compared PV shadings and interior blinds in terms of their annual overall electricity balance and found that interior blinds cannot

compare to the annual overall electricity savings that well-designed solar PV shadings can produce. When the solar PV shadings are movable, there is a potential to provide even better building efficiency compared with fixed solar PV shading [102].

Despite numerous previous studies investigating the opportunities and challenges of different advanced shading systems, only a few studies of advanced shading systems consider a more holistic sustainability perspective, covering aspects of energy, interior climate, daylight, façade aesthetics and carbon footprint aspects, especially in the subtropical climate context.

The application of advanced shading systems integrating such technology in real-life building projects in the Pearl River Delta is already starting to attract the attention of design teams. Liu et al. [95] presented a case study of typical Concord-type public rental housing (PRH) high-rises in Hong Kong, which could be a reference for energy optimization strategies for architects. In the study, a simplified three-floor part of the high-rise was optimized, and the vertical and horizontal shading panels were applied separately on the external opaque walls for computer simulation through DesignBuilder V5 software. A series of design parameters were set for simulation: tilt angle of the shading panels, length of the shading panels, and the number of shading panels per wall surface [95]. Another high-rise case study in the Greater Bay Area—the Shenzhen Energy Mansion designed by BIG—demonstrated a successful design strategy for integrating a façade shading system design with the aesthetic concept from the start. The folded and undulated curtain walls and façade shadings control the solar load and unwanted glare elegantly, while enabling iconic architectural expression and clear views for the interior office spaces [103].

6. Discussion

This article presents a broad survey of contemporary advances in high-rise façade technologies applicable to hot and humid climates in support of the overall goal of achieving zero carbon buildings. The review of relevant recent literature shows that previous studies, as well as some building case studies in hot and humid climates, have made recent progress in employing advanced technologies to their façade systems for energy conservation and carbon emission reduction purposes. Most of these technologies are derived and adapted from earlier instances of these technologies found in Europe and North America. Only few studies on advanced façade systems focus on high-rise buildings in the context of subtropical China, despite the urgent need to lower the energy and carbon emissions generated by this locally prevalent building type. In addition, the sample of literature examined for this review shows that previous studies on promising technologies tend to discuss such technologies in great depth but also often in isolation from each other. In addition, advanced research often does not account for the practicalities of local implementation.

Our review of publications on double-skin façades (DSFs) shows that despite a plethora of studies examining the DSF over the last few decades, its implementation as a building system remains challenging and requires further adaptation to hot and humid subtropical climates [11,50,52]. While technical barriers might be overcome through the integration of DSF with other technologies and materials, this also requires consideration of various factors, including geometric parameters, glass selection, ventilation strategy, shading, daylighting, aesthetics, and wind loads, as well as the maintenance and cleaning cost expectations already implied in the design of DSFs [104,105]. With regard to this integration of various and sometimes conflicting parameters, research on implementing DSFs in high-rise buildings in South China remains underdeveloped. Designers aiming to apply DSFs to building projects can only rely on a few studies providing informative research results and principles to inform applied façade design supporting zero carbon building goals in high-rise buildings in subtropical China.

Section 5.2 reviewed recent publications on building integrated photovoltaics (BIPV) as a technology for the building façade system. As demonstrated in recent studies, BIPV design is critical for meeting NZEB targets and improving the utilization of renewable energy in high-rise buildings, where BIPV serves as a climate screen as well as a power

source that generates electricity [14,60,65,66]. As BIPV mainly relies on solar radiation, its application is not limited to certain climates but can be used in all areas offering sufficient solar energy sources [64]. In other words, BIPV is a key zero carbon façade technology for high-rise buildings in subtropical China. However, in the very dense urban contexts of the Pearl River Delta, shading from neighboring buildings or objects presents a considerable challenge for solar energy collection and renewable energy generation [70]. Further barriers to BIPV documented in previous research include aesthetic issues and designers' lack of knowledge, as well as a lack of architecturally oriented literature and understandable data tailored for architects, along with specific design guidelines and criteria, installation, and maintenance of BIPV [62,67,69,73]. Most previous publications focus on detailed technical aspects, offering data on the performance of PV products [71] and their integration with other technologies and materials; yet, they lack consideration of a broader integration with the architectural aspects of building façades [72–74].

Section 5.3 mainly focused on vertical greenery systems (VGSs), where most previous publications are found to classify and examine different general types of vertical greenery systems and their benefits, including lowering surface temperatures and providing shading functions. Only a few studies on vertical greenery used in high-rise buildings in subtropical China could be found. Most closely related studies on greenery systems address tropical climates, particularly in Singapore, which may serve as a broad reference to the hot and humid climates found in the Pearl River Delta of southern China. While related technologies and design approaches may be suitable for subtropical China, many design factors also differ between applications in tropical and subtropical climates, including plant selection/climate adaptation, growth and surface coverage, implementation complexity, maintenance issues, environmental impacts, and installation and maintenance costs.

Section 5.4 reviewed key publications on advanced shading systems. Compared to the other technologies surveyed in this paper, shading systems are a well-developed technology that has been implemented widely. However, despite the extensive number of studies examining shading systems over the last few decades the adaptation of shading systems to changing climate conditions remains a challenge. Advanced shading systems should be considered part of a broader sustainable strategy, taking into account factors such as energy, indoor climate, daylight, façade aesthetics, and the carbon footprint.

As early decision making in the architectural design process has a strong impact on the later energy and carbon emission performance of buildings, this article offers architects and façade system professionals an overview of promising contemporary façade technologies supporting zero carbon goals in façade design for high-rise buildings in hot and humid climates. It is important to note that zero carbon façade design should be addressed from a broader perspective, taking into account the context of a building's life cycle as well as locally specific regulatory, economic, and technical developments.

Energy conservation and energy generation measures are difficult to discuss in isolation. To realize zero carbon buildings in China, the bigger picture needs to be considered. Due to the highly fragmented nature of the design and construction process, which comprises different stakeholders with varying viewpoints and project goals that are affected by several professional practice codes, interdisciplinary collaboration is difficult to perform during the early stages of design [106]. Building construction is often disconnected from later maintenance and operation. As a result, building life cycle and operational implications do not play a significant role when the cost and quality of design and construction are discussed. Similarly, environmental certification systems still place too little emphasis on the long-term implications and management of construction. The accumulation of savings in maintenance and operation offered by energy-efficient buildings thus do not play a major role in real estate development, which is a major driver of the Chinese economy. This disjunction continues to limit the scope and innovative capacity of zero carbon building construction practices and technologies.

As a fundamental technology of integrating building related information, building information modelling (BIM) is already well established in many developed economies

and is expected to eventually drive the broad implementation of a common data environment and BIM collaboration format to improve project teams' operational efficiency. The implementation of BIM reflects the development of building industrialization and also reveals the level of data integration between the information model and related business processes. From this perspective, the disconnect between stakeholders can be investigated by examining current barriers to BIM deployment [66]. According to Wu et al. [60], the primary barriers to BIM deployment for industrialized buildings were capital-related issues and a lack of owner support. Further development of the comprehensive integration of advanced façade system technologies with BIM as a platform for information synchronization and built environment management throughout a building's life cycle may support the increased transparency and availability of data among stakeholders who intend to adopt net-zero carbon building strategies in China.

Other studies on the development of green building in China also reflect on the challenges of zero carbon building development. Unlike most green building evaluation systems in other developed countries, no well-developed specific evaluation criteria system for each stage of the design and construction process is available yet, with current recommendations focusing mainly on design guidance. Unsurprisingly, the number of green buildings that have been certified in the operational phase is substantially lower than those that have been certified in the design phase. Moreover, as a result of differences in government oversight, incremental costs, property management expertise, and a lack of awareness of environmental protection opportunities through green buildings across different cities, China's development of this building type is also unevenly spread [14]. To become effective at promoting zero carbon buildings, current green building standards need to provide additional evaluation criteria for each stage of the building life cycle while considering different regional conditions.

Despite a broad variety of promising technologies becoming available to contemporary zero carbon integrated façade design, the reasons for their current limited use can be explained by economic as well as practical implementation factors. Once regulatory and economic issues are addressed, the wider application of these technologies will also require new types of digital tools capable of integrating these technologies for planning purposes and to better support the architectural design phase. In the early design stages, various digital tools are available for designers to develop advanced facades. Ochoa and Capeluto (2009), for example, presented a digital design support tool named NewFacades. The tool assists designers in the translation of ideas to articulated architectural concepts by using climate and visual comfort strategies that comply with an energy code [65]. In addition to custom-developed tools for specific demands, there are several visual programming environments in CAD tools, such as Bentley Generative Components and Grasshopper for McNeel Rhinoceros. Within the software ecosystem of Rhinoceros, Grasshopper-based custom plugins facilitate parametric design based on the creation of a script from geometric commands that allow for modifications according to sustainable architectural design considerations. This enables architects to easily experiment with different design alternatives without the need for professional programming or scripting knowledge [64]. Moreover, the capacity of Rhino-based Grasshopper plugins can promote zero carbon building design by parameter adjustment [64]. To be specific, Rhino-based Grasshopper plugins can be employed systematically together and can work with other environmental simulation tools to support multi-agent system strategies for façade design [70]. Grasshopper and its plugins, such as Ladybug and Honeybee, are frequently used tools for developing and assessing adaptive or interactive facades in the design process [107–109]. The parametric design process can thus embed a broad variety of design knowledge-related activities for design concerns, including zero carbon facades [71]. Accordingly, parametric design environments constitute a promising design platform to integrate data, knowledge, technologies, and designers' concerns for zero carbon building façade design.

While stakeholders' interests can vary significantly, clear information regarding the positive impact of such technologies on a building's life cycle and operation cost can

provide a more solid basis for decision making, particularly once more long-term strategies are sought and agreed on.

7. Conclusions

This review surveys and discusses the suitability of key façade system technologies for the design of zero carbon high-rise buildings in hot and humid climates, specifically focusing on South China. While net-zero carbon buildings and related façade systems have attracted considerable recent research efforts, previous studies were primarily conducted in developed countries across Europe and North America and mostly addressed temperate climates with cold winters as well as low-density urban environments. However, the technologies and design approaches developed for these specific contexts and building types have limited applicability beyond this relatively narrow scope. In contrast, the Pearl River Delta in southern China is one of the world's most densely populated regions and continues to experience rapid increases in the number of high-rise buildings, which are key contributors to local carbon emissions. Despite the need for integrated zero carbon technologies and design strategies tailored to high-rise buildings in hot and humid climates, few existing studies address this issue. This study offers a systematic literature review, mainly based on relevant literature in English language published over the past ten years, to identify and discuss a spectrum of key façade technologies supporting the architectural design of net-zero carbon tall buildings in South China. We focus on technologies pertinent to building facade design that are widely accepted and supported by previous research, indicating their viability for achieving low-energy buildings in China's hot and humid subtropical climate. We aim to contribute to this field of zero carbon building by focusing on the under-researched sub-topic of high-rise building facades in hot and humid subtropical China.

The paper identifies the scope of zero carbon building and its design factors and subsequently discusses the rationale and mechanisms of advanced technologies and their suitability for high-rise buildings in South China. Recent research on four promising key technologies is analyzed, including double-skin façades, building integrated photovoltaics, façade greening systems, and advanced shading systems. The conclusion drawn from the literature review of these key technologies is that building integrated photovoltaics (BIPV) and advanced shading systems are the most suitable and promising façade system technologies for high-rise buildings in the hot and humid climate of South China. While the preliminary results are presented in previous studies, vertical greenery systems and double-skin façades still require more research to determine their suitability and effective application in the context of hot and humid climates. The review of previous studies further indicates that the four discussed façade technologies all offer energy savings in the climate conditions of subtropical South China, in support of zero carbon building goals. In terms of implementation, the review result also reflects a severe lack of comprehensive tools supporting the integration of key technologies to support the application of these technologies during early architectural design decision making. In particular, the holistic considerations deriving from a life cycle perspective are not yet part of design decisions.

Based on the findings presented in this paper, further research on façade system design as part of zero carbon building goals in the context of hot and humid climates in South China will require:

- More reliable data, including measurement and benchmarking systems to support more rigorous zero carbon building concept implementations;
- Digital tools supporting the integrated application of advanced facade system technologies in preliminary design for zero carbon buildings;
- Research on how cross-disciplinary workflows can be enabled, with a view to building life cycle modelling;
- Research extending the current focus on energy conservation, embodied energy, and embodied carbon in zero carbon building literature, with an integrated and implementation-oriented perspective on façade technologies.

Author Contributions: Conceptualization, C.M.H. and Y.Z.; methodology, Y.Z.; writing: Y.Z. and C.M.H. 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 no conflict of interest.

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