

Article

Sustainable Urban Planning for High-Rise Residential Complexes Using an Adaptive Facade System

Ho-Soon Choi

Department of Architecture, Gachon University, 1342 Seongnamdaero, Seongnam-si 13120, Republic of Korea; hosoon@gachon.ac.kr

Abstract

This study proposes a sustainable urban planning strategy that enhances building energy self-sufficiency through photovoltaic-based renewable energy generation. This research focused on high-rise residential complexes and introduces an adaptive facade system designed to efficiently utilize the extensive solar-exposed surfaces of building facades. The system was programmed to automatically adjust according to the optimal tilt angle, which reflects monthly variations in solar altitude and azimuth, thereby maximizing energy generation. To further improve the effectiveness of the adaptive facade system, a “bridge-type apartment complex” layout was developed, in which building orientations varied around a south-facing axis to include southeast and southwest orientations. The proposed urban configuration was developed using a parametric design within the building information modeling software Revit 2023, and energy generation simulations were conducted for Seoul, South Korea, using Insight (a Revit plug-in) during 2024. Simulation results revealed that bridge-type apartment complexes achieved higher levels of renewable energy generation than conventional slab-type apartment complexes. These findings suggest that a three-dimensional urban design incorporating diverse facade orientations, combined with a dynamic adaptive facade system, not only enhances energy efficiency but also offers the potential to create creative and flexible urban landscapes that contrast with conventional, uniform cityscapes.

Keywords: sustainable urban planning; adaptive facade system; Building Information Modeling (BIM); parametric design; renewable energy

1. Introduction

Environmental change poses a serious threat to human life and livelihood worldwide. Among the core issues of environmental change, global warming is accelerating each year, leading to an increasing frequency of natural disasters such as sea-level rise, floods, and droughts. In response to this crisis, the United Nations established the goal of limiting the global average temperature increase to within 1.5 °C above pre-industrial levels through the Paris Climate Agreement in 2015. However, in 2024, the World Meteorological Organization reported that the global average surface temperature in 2023 had increased by 1.45 °C compared to pre-industrial levels, marking the highest level ever recorded [1]. This increase in average surface temperature, approaching the critical threshold of 1.5 °C within just a decade, suggests that any further temperature increase

Received: 8 January 2026

Revised: 30 January 2026

Accepted: 3 February 2026

Published: 4 February 2026

Copyright: © 2026 by the author.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

could lead to severe consequences that threaten human survival. Therefore, there is a critical need for a radical global shift in the energy paradigm.

Energy consumption is the primary source of greenhouse gas emissions responsible for global warming, and the building sector accounts for approximately 30% of global energy consumption [2]. Furthermore, the building sector is responsible for approximately 39% of total carbon emissions [3], and this proportion tends to be higher in industrialized nations owing to increased urbanization and associated building emissions. For example, in the case of South Korea, a representative country in Asia, the building sector accounted for 24.7% of the total greenhouse gas emissions as of 2018 [4]. Within the building sector, the residential subsector had the highest share of energy consumption. In 2022, residential buildings accounted for approximately 21% of the total energy consumption in the global building sector [5]. Therefore, reducing energy consumption in the residential building sector is directly linked to reducing greenhouse gas emissions, which in turn contributes to mitigating global warming.

Considering these concerns, this study proposes a sustainable urban planning model targeting collective housing complexes. The objective of this research was not merely to reduce energy consumption in residential buildings, but also to transition their energy sources to clean energy to lower carbon emissions. This study focused on a group of residential buildings, rather than a single structure, to explore the potential for maximizing renewable energy generation at the urban scale. Given that residential planning in major Asian cities is typically based on high-rise, high-density models, the outcomes of this study are expected to make meaningful contributions to enhancing energy self-sufficiency and sustainability at the urban level.

This study focused on high-rise residential building facades as its primary subject. Beyond serving as a mere architectural feature, the facade of a high-rise building plays critical functional roles, such as solar shading. A key contribution of this research was development of an adaptive facade system applicable to the expansive facades of high-rise residential buildings [6–8]. This system was designed based on the solar energy harvesting principle, recognizing the constant exposure of building facades to sunlight. Specifically, it was implemented in the form of a kinetic photovoltaic (PV) facade that actively adjusts its orientation in response to the trajectory of the sun. Unlike conventional fixed PV panels, this dynamic system maximizes energy generation by maintaining an optimal angle throughout the day.

The dynamic facade system was designed using a parametric design. Parametric design utilizes digital design tools to derive optimal architectural solutions by considering various variables and surrounding conditions. These tools have been extensively used in architectural planning and design in recent years [9,10]. This design approach is useful in the planning stage because it digitizes the interactions between the building and surrounding elements within a virtual environment and generates predictable design outcomes through various simulations.

The adaptive facade system proposed in this study offers the following academic contributions. First, architectural planning provides the basis for deriving the optimal renewable energy yield for individual buildings. Second, in the field of urban planning, effective strategies are essential for developing self-sufficient energy master plans. Third, from the perspective of architectural design, it presents the potential to create creative and sustainable urban landscapes by introducing a dynamic facade composition approach, moving beyond the uniformity of conventional cityscapes.

2. Literature Review

2.1. Urban Planning of Collective Housing in South Korea

This study focused on collective housing complexes in South Korea. In major Korean cities, residential development is commonly planned for high-rise buildings, and these housing types are typically organized as large-scale residential complexes rather than as single buildings. Such high-rise, high-density residential development has been a defining feature of urban planning in South Korea since the mid-20th century, paralleling similar trends in other major Asian countries. During this period, many Asian nations experienced rapid economic growth, with industrialization and urbanization centered in metropolitan areas. The resulting population influx into these cities led to large-scale rural-to-urban migration, for which high-rise collective housing has emerged as a practical solution to accommodate the growing urban population.

Since the implementation of the “First Five-Year Economic Development Plan” in 1962, South Korea has established a state-led systematic economic development strategy [11]. This policy accelerated industrialization and population influx into major cities, resulting in a sharp increase in housing demand and necessitating the mass provision of residential space. To address this demand, the government encouraged not only public sector participation, but also private sector involvement in housing supply, leading to the large-scale development of collective housing complexes within urban areas [12].

These collective housing complexes were designed to accommodate the maximum number of residential units within limited land areas and were characterized by low building coverage ratios and high floor area ratios. Consequently, building forms typically emphasize verticality and horizontality, resulting in a standardized rectangular geometry. The layout of buildings was determined based on minimum spacing requirements that considered sunlight access and mutual shading effects, which led to widespread adoption of the “slab-type apartment” form [13,14]. Slab-type apartments, characterized by their tall, narrow, and elongated rectangular form, became a hallmark of modernist residential architecture in the mid-20th century. This typology is considered advantageous because of its cost-effectiveness and construction efficiency, making it suitable for large-scale housing supply and development of new towns [15].

However, this standardized housing model has been criticized for contributing to the physical homogenization of urban spaces, overscaling of residential complexes, and spatial segregation, which exacerbates social stratification [16]. Despite this criticism, apartment housing remained the most prevalent residential type in South Korea from 2015–2023 (Table 1). In particular, the share of apartments in total housing showed a continuous upward trend, accounting for approximately 60% of all residential types by 2023 (Figure 1).

Table 1. Number of housing units by type in South Korea from 2015–2023 [17].

Category	Year								
	2015	2016	2017	2018	2019	2020	2021	2022	2023
Apartment housing	9806	10,375	10,375	10,826	11,287	11,662	11,949	12,269	12,632
Individual housing	3974	3963	3963	3949	3918	3898	3871	3861	3861
Collective housing	1898	2073	2073	2140	2195	2231	2253	2283	2303
Intermediate housing	485	503	503	509	514	522	526	531	539
Empty house	1069	1265	1265	1420	1518	1511	1395	1452	1535

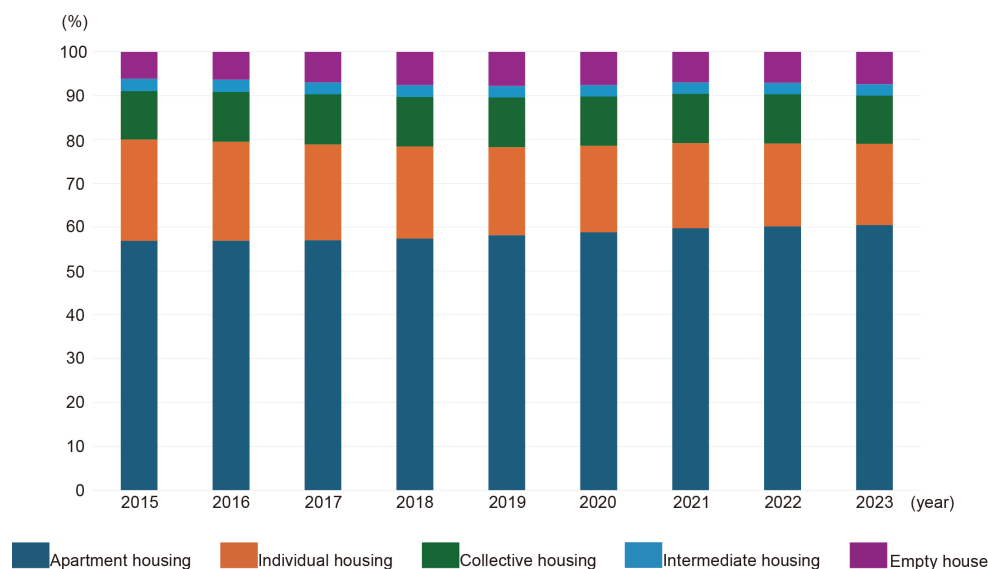


Figure 1. Proportion of housing stock by type in South Korea from 2015–2023.

2.2. Zero Energy Buildings and Solar-Based Active Strategy Technologies

The concept of zero-energy buildings (ZEBs) was developed as a strategic model to minimize energy consumption in the residential sector [18–20]. The oil crisis of the 1970s was a turning point that raised awareness in the architectural field of energy conservation and efficiency. Since then, development of renewable energy technologies as alternatives to fossil fuels (e.g., coal and oil) has accelerated globally. Alternative energy technologies have been introduced to the built environment, leading to the emergence of ZEBs as energy-autonomous building models.

In the 2000s, the institutional frameworks for ZEBs began to develop, particularly in European countries. In the United States, the U.S. Green Building Council introduced Leadership in Energy and Environmental Design, a green building certification system aimed at promoting sustainable building practices, including zero-energy strategies [21].

ZEBs rely on two primary strategies to achieve energy independence. The first is a passive strategy, which aims to minimize energy losses within the building. This approach focuses on enhancing energy efficiency using high-performance insulation materials and advanced window systems that reduce thermal losses [22]. The second is an active strategy that involves generating energy onsite by harnessing natural energy sources in the environment of the building. Prominent examples of active technologies include the use of geothermal, wind, and solar power systems to supply building energy needs [23–25].

Passive technologies gained significant momentum in the 1980s and 1990s with development of advanced materials, which led to the introduction of high-performance insulation and window systems that enhanced the feasibility of ZEBs [26]. Technological advancements in passive energy strategies have catalyzed the development and adoption of active energy strategies. Among the various active technologies, solar energy-based systems are the most widely utilized in the architectural sector, owing to several key advantages. Solar energy is a clean and inexhaustible resource that does not emit greenhouse gases during its generation. Second, it enables on-site energy generation at the building level, reduces reliance on centralized power grids, and contributes to long-term energy cost savings. Third, PV panels are available in a range of sizes and forms, making them easily attachable to roofs or building facades; they can also be retrofitted onto existing buildings with relative ease. Fourth, with annual improvements in panel efficiency, solar technology is now being integrated not only into facades but also into architectural

elements such as shading devices and canopies, further enhancing the energy autonomy of buildings [27–29].

Technological advancements in the materials and forms of PV panels have created creative opportunities in architectural design. Panels with varied colors, translucency levels, and geometries are now available, enabling designs that balance aesthetic facade articulation with energy performance. As a core strategy for realization of ZEBs, solar-based active technologies continue to exhibit strong potential for further development. Recent research has focused on maximizing renewable energy efficiency by integrating multifunctional materials and convergent technologies. For example, a novel system was developed by combining PV panels with salt hydrate crystal-based modules that feature thermal storage capabilities. The system absorbs solar heat during the day and radiates it indoors when the internal temperature decreases, thereby contributing to thermal comfort [30].

Moreover, PV panels can serve a dual function by acting as shading devices. In summer, they block direct solar radiation, whereas, in winter, changes in the angle of the sun allow solar gain into the interior, aiding indoor temperature regulation. Consequently, solar-based active technologies offer comprehensive benefits, including sustainability, ease of installation and maintenance, high energy productivity, and design flexibility, and are considered key drivers in advancement of ZEBs.

2.3. Adaptive Facade Systems and Energy Simulation Based on Parametric Design

In recent architectural discourse, the importance of building envelope systems that can respond in real time to environmental factors such as climate change, seasonal variation, and solar radiation has gained increasing attention. In response to these demands, an adaptive facade system has emerged as a key strategy. This approach involves integration of prefabricated components into the building envelope to optimize energy performance. These systems are designed to dynamically interact with the surrounding environment and respond to various climatic conditions, including solar exposure, temperature, and wind speed, in real time.

The primary objective of implementing an adaptive facade system is to enhance energy efficiency. Specifically, these systems aim to reduce heating and cooling loads, maximize the use of natural daylight, and maintain a comfortable indoor environment, thereby supporting the visual comfort of the occupants. By maintaining a balance between daylighting and exterior views, adaptive facades contribute to improving the overall energy autonomy of a building.

Previous studies have predominantly focused on analyzing the thermal and energy performance of adaptive facade systems in buildings. These systems are typically designed and evaluated in virtual environments through digital simulations using parametric design tools that enable performance assessments under various conditions. EnergyPlus is a commonly used simulation tool that allows quantitative evaluation of solar radiation, thermal loads, and energy consumption [31,32].

With advancement of digital design techniques, tools such as Honeybee and Ladybug (i.e., plugins for Rhino) as well as Insight for Revit, have been increasingly adopted for parametric design and energy analysis [33–36]. These tools incorporate a wide range of key variables necessary for evaluating the performance of adaptive facade systems. First, site-related parameters include geometric data such as simulation dates, latitude, and longitude of the project site, as well as the position, height, and spatial interference of surrounding buildings. Secondly, climate-related variables include meteorological data for the target location, such as solar radiation, global irradiation, air temperature, and sky illuminance, which are input into the parametric model [37]. Third, the physical properties of facade materials are critical for simulation accuracy. For example, parameters such

as transparency, thermal transmittance, and in the case of PV panels, electricity generation efficiency are comprehensively considered.

By developing a parametric design-based framework that integrates these diverse variables, it is possible to design adaptive facade systems optimized for specific sites and climate conditions. This framework can serve as an effective strategy for realizing ZEBs. Consequently, the establishment of a simulation-driven design methodology that integrates various environmental variables and material characteristics can significantly enhance the feasibility of energy-autonomous architecture.

2.4. Additional Variables to Consider in Implementing Solar-Based Active Technologies

Compared with other renewable energy sources, PV systems have been widely adopted in the building sector owing to their relatively high energy conversion efficiency. In most cases, PV modules are installed on building rooftops; however, their application has increasingly expanded to building facades as part of building-integrated photovoltaic (BIPV) strategies. When PV systems are installed on exterior building envelopes, the development of appropriate construction and mounting methods and careful material selection are critically important. Facade-mounted PV panels are directly associated with pedestrian safety concerns and significantly affect the architectural appearance of buildings. More importantly, as the primary objective of PV installation is renewable energy generation, economic assessment is an indispensable step in the implementation process. The installation and maintenance costs of PV-integrated facade construction systems must be evaluated in relation to the energy generation efficiency and overall renewable energy yield. In addition, from an architectural design perspective, further development of PV modules with diverse materials and aesthetic properties should be encouraged to enhance their broader applicability in building facades.

3. Methodology

This study was structured into four main stages. First, two types of collective housing development models were planned within a designated site. The first model reflected the current slab-type apartments on the site. It was designed to maximize the residential floor area ratio and incorporate the urban planning and architectural regulations applicable to the site as comprehensively as possible. The second model aimed to enhance the energy autonomy of buildings and maximize the generation of solar-based renewable energy. To this end, building masses were arranged in various forms to ensure maximum exposure of their facades to sunlight.

Second, two residential models were developed in a virtual environment using building information modeling (BIM). BIM digitally represents the physical and functional characteristics of a building through three-dimensional modeling. It enhances design accuracy and efficiency while enabling the early detection and resolution of potential design issues. In this study, Autodesk Revit 2023 was used as the BIM tool [38]. Revit is a widely adopted BIM software capable of integrating the entire building life cycle from design and planning to construction and operation [39].

Third, a parametric design was applied to BIM-based residential models. The objective of this parametric approach was to implement a solar-powered active architectural design, which was realized in the form of a kinetic PV facade applied to the building envelope. The facade was designed to respond and adapt according to a set of defined variables. Parametric functions provided in Revit were used to construct the algorithms, allowing iterative design experiments under varying conditions.

Fourth, energy generation simulations were performed for the kinetic PV facades implemented through a parametric design. Simulations were conducted for both an urban planning model composed of slab-type apartments and an alternative model comprising

various residential buildings designed to optimize renewable energy generation. These simulations evaluated the amount of solar energy generated on building facades. Insight, a plug-in software package for Revit, was used to calculate and compare the energy performance of each model [40]. Ultimately, by analyzing the energy output of the two urban planning strategies, this study assessed the impact of urban design approaches on building energy autonomy (Figure 2).

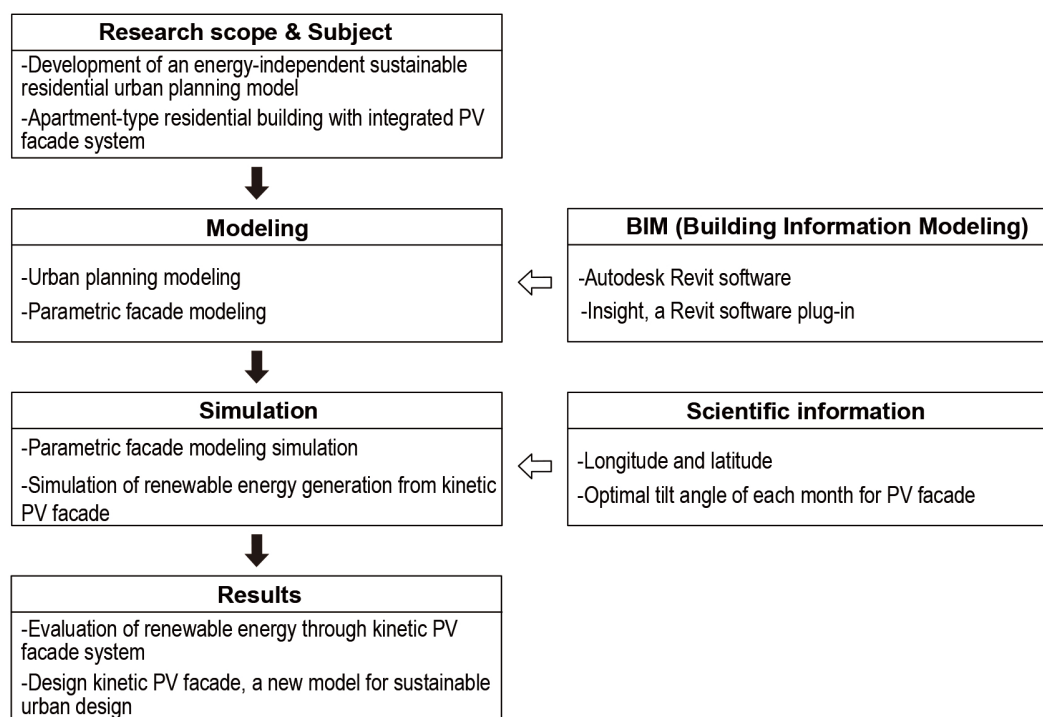


Figure 2. Methodology flow chart.

4. Design

4.1. Site Description and Urban Planning Regulations

To plan a collective housing complex model, this study selected a multi-family residential site as the case study area. The goal was to enable a comparative analysis between the proposed urban planning model and the existing conventional model using a slab-type apartment complex commonly implemented across urban areas in South Korea as a representative typology to support the generalization of findings. The selected site is located in Seoul, South Korea (latitude 37.5°, longitude 126.9°), and is approximately 90 m wide and 70 m long. The land is designated for multi-family residential use under the urban planning regulations of the city, and accommodated two slab-type apartments, comprising a total of 414 dwelling units, at the time of this study. Regarding the surrounding context, high-rise collective housing structures of the apartment typology were densely arranged to the south, east, and north of the site, whereas elementary schools were situated directly to the west (Figure 3A).

Detailed urban planning regulations were applied to the site to ensure a comfortable residential environment, and the main criteria were as follows: First, if a building was oriented south of the lot, it must be set back to a minimum distance equivalent to at least half its height (h) from the site boundary. Second, for two buildings in the same lot, a minimum spacing equal to the full height (h) of the southern building must be secured between them. This regulation ensured sufficient solar access for all floors of a building located to the north. Third, a setback of at least 3 m from the site boundary must be maintained considering pedestrian circulation and emergency vehicle access. Fourth, the

maximum building height was limited to 15 stories. Finally, the building coverage ratio must remain $< 50\%$ and the floor area ratio must not exceed 200% [41] (Figure 3B).

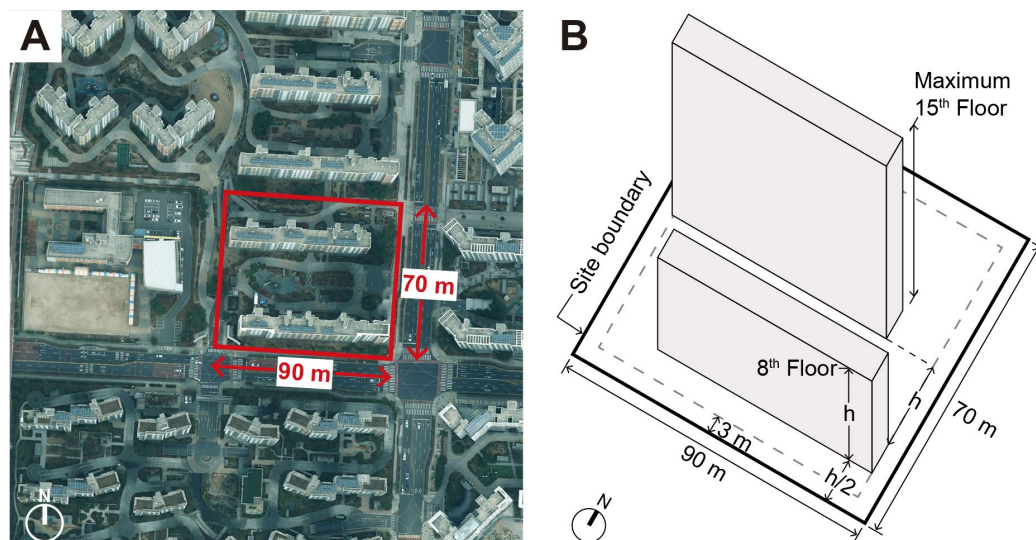


Figure 3. Mater plan of the study site, 6300 m² (A) [42]. Axonometric view of the slab-type apartment complex within the study site (B).

4.2. Concept and Design Principles of “Bridge-Type Apartment Complex” Through Diversified Residential Building Layouts

At the time of this study, the study site contained two slab-type apartments aligned along the north–south axis and arranged in a parallel formation. This urban planning approach limits solar exposure to south-facing facades, resulting in a structural constraint that allows for high PV efficiency only during a narrow time window around solar noon. To address this limitation, this study aimed to enhance solar-based energy self-sufficiency through an alternative urban configuration. Accordingly, a new urban form that can actively respond to the trajectory of the sun throughout the day was proposed.

From an urban planning perspective, designing in response to movement of the sun involves maximizing the solar gain potential by exposing building facades to a variety of solar incidence angles. Conventional slab-type apartments, which are oriented solely toward the south, can efficiently harvest solar energy only during a limited timeframe around midday. In contrast, buildings with facades facing south, east, and west can receive sunlight from multiple angles, thereby maximizing energy generation efficiency throughout the day. Based on this concept, the study reconfigured the massing of the two existing slab-type apartments to propose a “bridge-type apartment complex” model. Figure 4A shows the floor plan of the eighth level of the bridge-type apartment complex. The vertical circulation core, composed of an elevator and stairwell, was centrally located within the building. This central placement was intended to enhance the convenience of resident movement and minimize evacuation distances in the event of a fire. According to building code regulations, the maximum allowable evacuation distance from any interior point to a vertical stairwell was limited to 40 m. In this study, the longest evacuation route to a direct stairwell was designed as 39 m, thereby complying with the relevant standards.

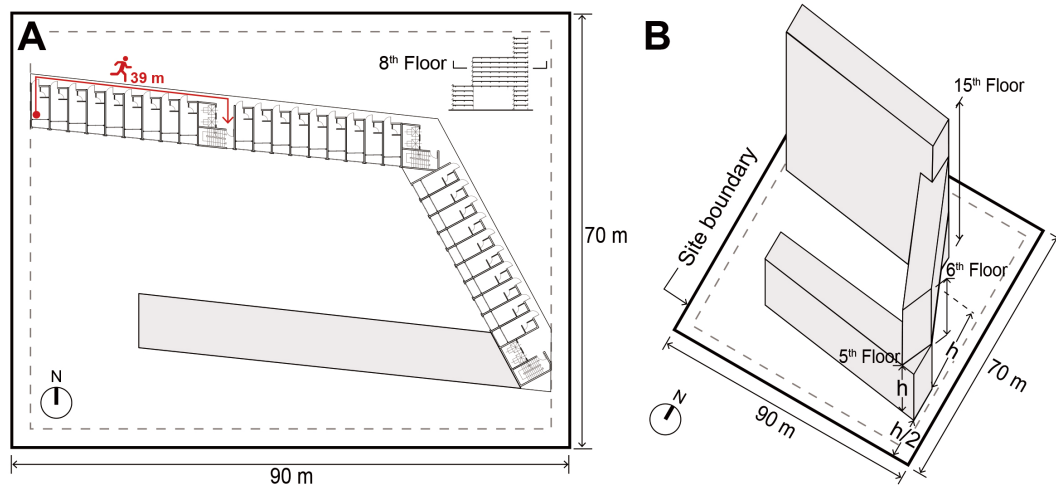


Figure 4. Floor plan of the 8th level in the bridge-type apartment complex (A). Axonometric view of the overall “bridge-type apartment complex” (B).

The design principles of bridge-type apartment complexes are as follows. First, while maintaining the traditional south-oriented alignment of conventional slab-type apartments, the building located on the southern side of the site was limited to 5 stories in height to ensure adequate solar access for the northern buildings. Second, on the northern edge of the site, a 15-story apartment—the maximum height permitted by local regulations—was planned to maximize both solar efficiency and residential density within the complex. Third, a 6-story building was positioned at the center of the site, oriented southeast and southwest to accommodate diverse solar incidence angles according to the path of the sun. This central structure was designed in a “bridge” form, physically connecting the northern and southern buildings, thereby enhancing the spatial integration and cohesion of the complex (Figure 4B).

The bridge-type apartment complex utilized 1422 m² of the total 6300 m² site area as the building footprint, resulting in a building coverage ratio of 22.5%, which is well below the legal maximum of 50%. The number of residential units remained consistent with that of conventional slab-type apartments, totaling 414 households. The total floor area was 13,118.4 m², achieving a floor area ratio of 200%, conforming to the maximum floor area ratio allowed under applicable urban planning regulations, thus representing an optimal planning proposal for the site.

4.3. Design of Adaptive Facade System

Both the existing slab-type apartment complex located at the study site and the newly developed bridge-type apartment complex proposed in this research incorporated an adaptive facade system. This system was based on the principle of on-site renewable energy generation through solar power and serves as a core technology for realizing energy-self-sufficient buildings. To maximize PV energy generation, the adaptive facade system was designed to automatically adjust the tilt angle of the solar panels according to the optimal tilt angle calculated monthly. This dynamic adjustment function optimizes the angle of solar incidence in response to seasonal variations in solar altitude and azimuth throughout the year, thereby achieving superior energy productivity compared with conventional fixed-type solar panels.

Additionally, the adaptive facade system was implemented as a “kinetic facade” on the building envelope, providing not only enhanced energy performance but also a visually dynamic architectural expression. This flexible facade design introduces a distinctive aesthetic character that sets it apart from traditional static facade systems.

The adaptive facade system proposed in this study was planned based on the following design assumptions: First, the system was installed on all building facades except for the north-facing elevations, which were not directly exposed to sunlight. Second, because the study focused exclusively on the performance of facade-mounted PV systems, rooftop installations were excluded from the analysis. Third, the PV panels applied to the adaptive facade system were Hanwha Q.TRON XL-G2 modules, each measuring 1.134 m in width and 2.465 m in length (Table 2). As of the first half of 2022, this high-efficiency module held the largest market share in the U.S. residential and commercial solar markets [43]. Importantly, the system was designed based on the exact dimensions of a single Q. TRON XL-G2 module, which aligned with the typical facade size of an individual residential unit. This alignment allowed the system to be constructed without cutting the panels, thereby minimizing construction waste and maximizing installation efficiency.

Table 2. Hanwha Q. TRON XL-G2 solar module [44].

Type	Parameter	Value
Solar panel module	Model	Q.TRON XL-G2
	Length (mm)	2465
	Width (mm)	1134
	Power capacity (kW/unit)	630 Wp
	Efficiency (%)	22.7

The adaptive facade system was designed as an integrated modular unit incorporating PV panels. Each module was 1.10 m in width and 2.40 m in length. All modules were oriented south to maximize the efficiency of solar energy collection. Additionally, to enhance renewable energy generation, the tilt angle of the modules was adjusted monthly based on the optimal tilt angle (β). The modules of the adaptive facade system were structurally integrated with the exterior railings of individual residential units. In South Korea, the standard floor-to-floor height of an apartment units is regulated at 2.85 m. The adaptive facade system, installed on the exterior railings of each unit, maintained a vertical spacing of 1.75 m between modules on successive floors. This spacing ensured that mutual shading did not occur between modules (Figure 5).

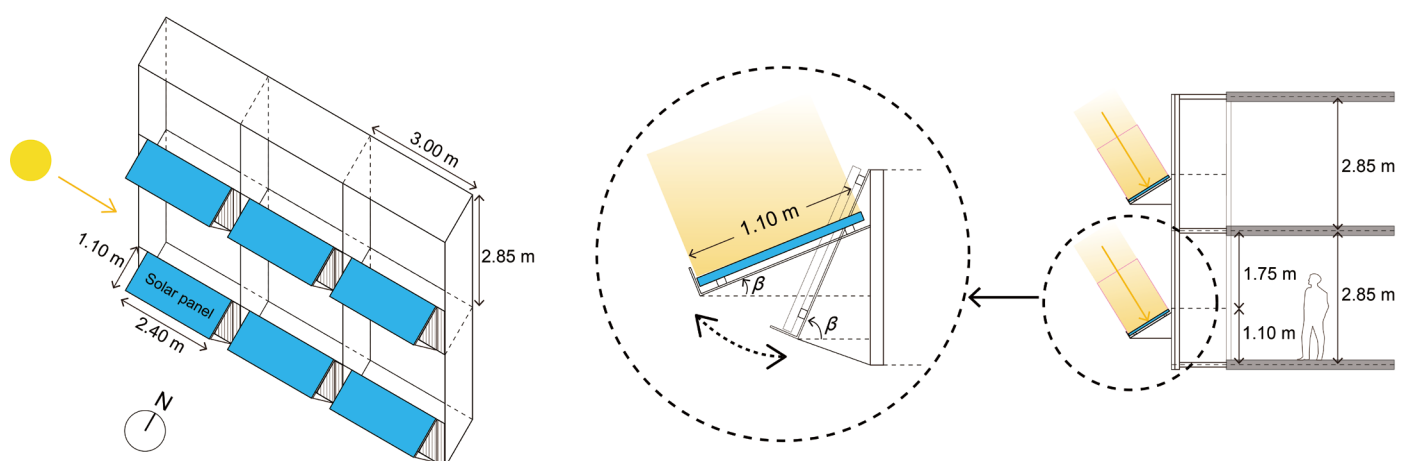


Figure 5. Principle of adaptive facade system.

Unlike conventional fixed PV panels, the PV modules integrated into the adaptive facade system were adjusted monthly according to the optimal tilt angle. The monthly optimal tilt angle was calculated using the Calabrò function (1) [45]. In Equation (1), β represents the optimal tilt angle, a_1 and a_2 are coefficients derived from the solar

declination, and φ denotes the latitude of the location where the adaptive facade system is installed.

$$\beta = a_1 + a_2 \times \varphi \quad (1)$$

This study was conducted in Seoul, South Korea (37.5° N; 126.9° E). By substituting the latitude of Seoul ($\varphi = 37.5$) along with the monthly coefficients a_1 and a_2 into Equation (1), the optimal tilt angles (β) for each month in Seoul were obtained (Table 3).

Table 3. Optimal tilt angles from January–December for the study location of Seoul (37.5° N; 126.9° E).

Month	Solar Declination (°)	Coefficient		Optimal Tilt Angle (°)
		a_1	a_2	β
January	−21.269	31.33	0.68	56.8
February	−13.289	16.25	0.86	48.5
March	−2.819	6.80	0.84	38.3
April	9.415	−6.07	0.87	26.6
May	18.792	−14.95	0.87	17.7
June	23.314	−19.27	0.87	13.4
July	21.517	−15.65	0.83	15.5
August	13.784	−4.23	0.75	23.9
September	2.217	6.42	0.77	35.3
October	−9.599	15.84	0.83	47.0
November	−19.148	23.61	0.84	55.1
December	−23.335	30.56	0.76	59.1

5. Modeling and Simulation

Parametric Modeling and Renewable Energy Generation Simulations

The parametric modeling in this study was performed in two stages. The first stage involved facade composition modeling of the adaptive facade system under varying installation angles. The monthly optimal tilt angles derived in Section 4.3 were applied as key design parameters for the adaptive facade system, enabling generation of various facade configurations based on the arrangement of PV panel modules. The second stage focused on modeling renewable energy generation based on the geographical and climatic characteristics of the study area. Seoul was selected as the study location, and monthly geographic data from January–December, 2024 were used as the simulation inputs. The existing slab-type apartment complex described in Section 4.1, the proposed bridge-type apartment complex described in Section 4.2, and adaptive facade systems applied to the facades of each building, were all implemented in a digital virtual environment. To maximize solar energy harvesting efficiency, an adaptive facade system was installed on the south, east, and west facades of each building according to the monthly optimal tilt angles. Both urban models employed an identical total installation area of 1520 m² for the adaptive facade system, which was evenly distributed across the south-facing facades of individual units and the east and west facades of the buildings. As the focus of this study was analysis of building facades, no PV panels were installed on rooftops.

Three-dimensional architectural modeling was conducted using Autodesk Revit 2023. Renewable energy generation simulation was performed using Insight, a plug-in program integrated with Revit. Insight is a simulation tool capable of quantitatively analyzing solar energy generation based on PV systems applied to digital building models developed within the Revit environment.

The key input variables used for the simulation were as follows: First, the actual site information of the building under simulation was entered. By specifying the city name of the study location, the latitude and longitude were automatically recognized by the

software. Second, PV-panel related information was configured. In this study, the Hanwha Q. TRON XL-G2 model was selected, with panels installed across the entire facade of each building. Third, the simulation period was from January–December, 2024. During this period, PV modules configured according to the monthly optimal tilt angles were simulated to estimate the solar energy generation during daylight hours from sunrise to sunset (Figure 6).

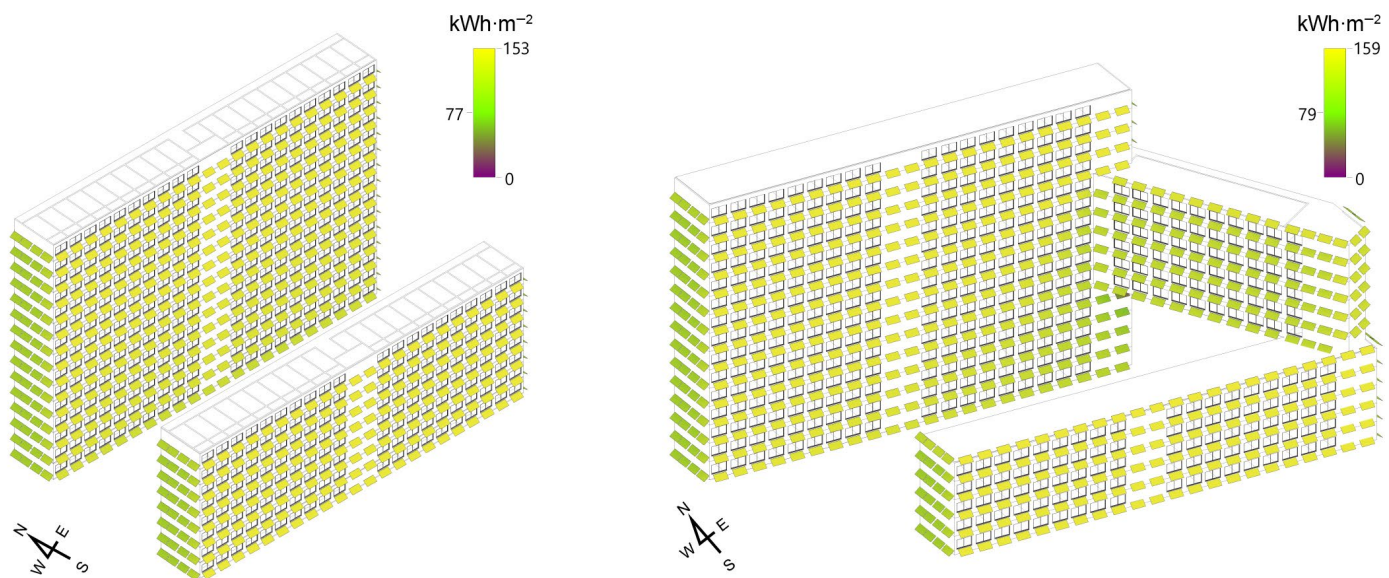


Figure 6. Energy simulation of the adaptive facade system implemented using Insight software for the slab-type apartment complex (**left**) and the bridge-type apartment complex (**right**) in March, 2024.

Table 4 presents the energy generation results from the adaptive facade system installed on the facades of slab-type apartments. According to the energy simulation results, the highest and lowest monthly solar energy outputs occurred in March and July, respectively. In March, PV panels were installed at an optimal tilt angle of 38.3° , producing a total of $199,174 \text{ kWh}\cdot\text{month}^{-1}$. In contrast, in July, the panels installed at an optimal tilt angle of 15.5° generated a total of $103,478 \text{ kWh}\cdot\text{month}^{-1}$. Over the course of the year (January–December 2024), the total energy produced by the adaptive facade system on the slab-type apartment facades was $1,818,162 \text{ kWh}\cdot\text{year}^{-1}$.

Table 4. Renewable energy generation from the adaptive facade system installed according to monthly optimal tilt angles in the slab-type apartment complex from January–December 2024.

Month	Total Area of Solar Modules (m^2)	Optimal Tilt Angle ($^\circ$) (β)	Energy Generation ($\text{kWh}\cdot\text{month}^{-1}$)
January	1520	56.8	118,498
February	1520	48.5	152,375
March	1520	38.3	199,174
April	1520	26.6	173,899
May	1520	17.7	170,724
June	1520	13.4	147,667
July	1520	15.5	103,478
August	1520	23.9	175,142
September	1520	35.3	180,829
October	1520	47.0	171,900
November	1520	55.1	119,507
December	1520	59.1	104,969
Total energy generation			$1,818,162 \text{ kWh}\cdot\text{year}^{-1}$

Table 5 shows the energy generation from the adaptive facade system (with the same total PV panel area of 1520 m²) applied to the facades of bridge-type apartments. As in the previous case, the highest and lowest monthly energy outputs were recorded in March and July, respectively. In March, with the panels tilted at 38.3°, the system generated a total of 207,973 kWh·month⁻¹. In July, at a tilt angle of 15.5°, the energy output was 110,414 kWh·month⁻¹. Total annual energy generation from the adaptive facade system installed on the facades of the bridge-type apartments was 1,948,641 kWh·year⁻¹.

Table 5. Renewable energy generation from the adaptive facade system installed according to monthly optimal tilt angles in the bridge-type apartment complexes from January–December 2024.

Month	Total Area of Solar Modules (m ²)	Optimal Tilt Angle (°) (β)	Energy Generation (kWh·month ⁻¹)
January	1520	56.8	134,981
February	1520	48.5	168,345
March	1520	38.3	207,973
April	1520	26.6	174,654
May	1520	17.7	181,704
June	1520	13.4	155,889
July	1520	15.5	110,414
August	1520	23.9	182,918
September	1520	35.3	187,575
October	1520	47.0	185,050
November	1520	55.1	136,621
December	1520	59.1	122,517
Total energy generation			1,948,641 kWh·year ⁻¹

6. Results and Discussion

This study was an empirical investigation aimed at supporting sustainable urban planning with a particular focus on the energy self-sufficiency of buildings as a key evaluation metric. The primary objective was to propose facade development strategies for PV-based renewable energy generation in high-rise collective housing buildings. These building types were selected for three reasons. First, residential buildings account for the largest share of energy consumption in the architectural sector; therefore, improvements in their energy self-sufficiency are expected to have a significant impact. Second, the adaptive facade system with integrated PV panels proposed in this study was designed in a modular form, making it easily applicable to standardized facades typical of residential buildings. Third, from an urban design perspective, this study proposes new forms of sustainable residential urban planning. The conventional layout approach, characterized by front-facing, south-oriented, slab-type apartment complexes, has led to monotonous and rigid urban landscapes. In response, this study explored creative and flexible urban design possibilities by presenting alternative building layout strategies that enhance the energy generation efficiency of the adaptive facade system.

An adaptive facade system was developed using a parametric design process. Parametric design is a methodology in which predefined algorithms generate design outcomes based on limited sets of input data defined by the designers. In recent years, advancement of various parametric design software tools has evolved this design approach further, significantly enhancing both the efficiency and precision of architectural design. In this study, an adaptive facade system was modeled in a virtual environment using Autodesk Revit, a BIM-based software that allows for real-time three-dimensional visualization of

parametric designs based on variable inputs. Parameters such as the PV module type, dimensions, and installation angles were entered into Revit to design the adaptive facade system.

The parametric design was driven by the monthly optimal tilt angle data for the period from January–December 2024. Once the design of the adaptive facade system was completed, energy simulations were conducted using Insight, a plug-in software integrated with Revit. Insight uses geographic information and simulation timeframes as input variables to analyze the renewable energy generation of a system based on solar radiation.

To maximize the efficiency of renewable energy generation, this study strategically positioned residential buildings equipped with an adaptive facade system to ensure maximum solar exposure. Consequently, the proposed urban planning layout favors a bridge-type apartment complex configuration, with building orientations predominantly facing south, southwest, and southeast. Energy simulations were conducted for both the bridge-type apartment complex developed in this study and a conventional slab-type apartment complex with adaptive facade systems installed on building facades. The study area was Seoul, and simulations were conducted over a 1-year period from January–December 2024. For the slab-type apartment complex, the highest monthly energy generation occurred in March ($199,174 \text{ kWh}\cdot\text{month}^{-1}$) and the lowest was in July ($103,478 \text{ kWh}\cdot\text{month}^{-1}$). The total annual energy output from the adaptive facade system applied to the slab-type apartment façades was $1,818,162 \text{ kWh}\cdot\text{year}^{-1}$.

In contrast, for the bridge-type apartment complex, the highest energy generation was also in March ($207,973 \text{ kWh}\cdot\text{month}^{-1}$) and the lowest was in July ($110,414 \text{ kWh}\cdot\text{month}^{-1}$). Total energy generation over the year from the adaptive facade system on the bridge-type façades was $1,948,641 \text{ kWh}\cdot\text{year}^{-1}$.

7. Conclusions and Limitation

This study aimed to contribute to advancement of sustainable urban planning by enhancing energy self-sufficiency in the building sector. To achieve this, a solar energy-based renewable energy generation strategy utilizing building facades was proposed, with a focus on high-rise multi-family residential buildings. The proposed solution involved the application of a modular adaptive facade system integrated with PV panels on a building facade.

The technological novelty of the adaptive facade system developed in this study lies in its ability to actively adjust the tilt angle of the PV panels in response to the optimal solar altitude and azimuth, which vary monthly. This differs from conventional PV systems, which are passively installed at fixed angles on rooftops or facades. The introduction of such “kinetic PV panels” enables improved optimization of solar energy generation compared to that of static systems.

In a case study conducted in Seoul, the optimal tilt angle for fixed PV panels was determined as approximately 25° [46]. Based on this, an energy simulation scenario was created with PV panels installed on the facade of a conventional slab-type apartment complex at a fixed angle of 25° . Using Insight software, a year-long simulation for 2024 estimated the annual energy generation to be $1,762,003 \text{ kWh}\cdot\text{year}^{-1}$. In contrast, under the same conditions, application of the adaptive facade system resulted in an estimated annual energy output of $1,818,162 \text{ kWh}\cdot\text{year}^{-1}$. This represents an approximately 3.2% increase in energy generation compared with that of the fixed system, exceeding 96% of the fixed system output.

These results demonstrated that the adaptive facade system offered superior energy generation performance compared to that of conventional fixed PV panel systems, thereby

underscoring its potential contribution to sustainable and energy-efficient building designs.

This study was conducted based on an urban planning approach aimed at maximizing the energy-generation efficiency of an adaptive facade system. By analyzing the solar irradiation path, the spatial layout of the urban environment and the building orientation were strategically planned to ensure that the adaptive facade systems installed on building facades would receive maximum solar exposure. Consequently, an apartment complex was designed with a three-dimensional architectural massing that incorporated diverse orientations, including south, southeast, and southwest, centered around a predominantly southern orientation.

In this study, the energy performances of two apartment complexes were comparatively analyzed: one designed with newly developed three-dimensional building facades and varied orientations, and the other following a conventional layout with buildings primarily oriented to the south. In both scenarios, an adaptive facade system was installed, and annual energy generation was evaluated.

The analysis revealed that apartment complexes with diverse facade orientations exhibited relatively higher energy production efficiencies. This urban planning strategy, based on three-dimensional facade configurations, not only enhances energy performance, but also contributes to the diversification and usability of rooftop spaces, offering resident-enriched public areas. Furthermore, from an architectural design perspective, such volumetric and flexible arrangements of building forms present opportunities to create a creative and dynamic urban landscape, differentiating it from the monotonous appearance of conventional urban environments.

This study was conducted based on a parametric design that utilized digital design tools. Although the proposed urban planning and architectural strategies offer promising results, the practical implementation of the adaptive facade system in real-world architectural settings still faces several technical limitations. In particular, the current proposal lacks a detailed technical plan for the mechanical systems required to install and operate an adaptive facade system on building facades.

Development of an appropriate mechanical and control infrastructure is essential to enable the system to autonomously adjust the tilt angle of PV panels according to the monthly optimal solar angles. Moreover, a quantitative analysis of the power consumption of the system is crucial. Among these considerations, the amount of energy consumed to operate the moving mechanisms is particularly critical because it directly affects the net energy efficiency of the entire renewable energy system. Further studies are required to address this issue. As part of future work, the present study will be extended through collaboration with a PV-based architectural design company to conduct an empirical economic evaluation of the practical implementation of the proposed adaptive facade system. Furthermore, the system will be implemented on an actual building facade to enable long-term evaluation of its operational performance, adaptability, and overall applicability under real-world conditions.

This research holds strong potential for interdisciplinary expansion beyond the field of sustainable urban and architectural design. Future work may integrate disciplines such as computer science—for the design and control of mobile solar panel systems—and electrical engineering—for energy management and optimization. Through such multidisciplinary collaboration, the practical viability and technological maturity of the adaptive facade system can be significantly enhanced.

Funding: This work was supported by the Gachon University research fund of 2025 (GCU-202503370001).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. World Meteorological Organization. State of the Global Climate 2023. Available online: <https://wmo.int/publication-series/state-of-global-climate-2023> (accessed on 5 August 2025).
2. International Energy Agency. Available online: <https://www.iea.org/energy-system/buildings> (accessed on 11 August 2024).
3. Ali, K.A.; Ahmad, M.I.; Yusup, Y. Issues, impacts, and mitigations of carbon dioxide emissions in the building sector. *Sustainability* **2020**, *12*, 7427.
4. Choi, S.Y.; Choi, J.M. A Study on the Energy Usage and EUI Characteristics by Residential Buildings. *J. Archit. Inst. Korea* **2023**, *39*, 193–200.
5. International Energy Agency. Final Energy Consumption of Buildings Relative to Other Sectors, 2022. Available online: <https://www.iea.org/data-and-statistics/charts/final-energy-consumption-of-buildings-relative-to-other-sectors-2022> (accessed on 25 November 2024).
6. Attia, S.; Bilir, S.; Safy, T.; Struck, C.; Loonen, R.; Goia, F. Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy Build.* **2018**, *179*, 165–182.
7. Čekon, M.; Slávik, R.; Čurpek, J.; Cottone, R.; Bevilacqua, P. An integrated adaptive façade system using a glass block filled with phase change material: Cooling energy load and performance enhancement. *Build. Environ.* **2025**, *273*, 112724.
8. Voigt, M.P.; Roth, D.; Blandini, L.; Kreimeyer, M. An integrated design methodology for extrinsic adaptive façades—Process model, standards, and case study. *J. Build. Eng.* **2024**, *94*, 109810.
9. Jabi, W. *Parametric Design for Architecture*; Hachette: London, UK, 2013; pp. 10–11.
10. Di Paola, F.; Mercurio, A. *Parametric Experiments in Architecture*; Springer: Cham, Switzerland, 2023; pp. 1–3.
11. Chaudhuri, S. Government and economic development in South Korea, 1961–1979. *Soc. Sci.* **1996**, *24*, 18–35.
12. Choi, H.S. How a high-modernism project in South Korea failed: Sewoon Sangga (1966–1972), the first experimental modern planning. *Archnet-IJAR Int. J. Archit. Res.* **2024**, *18*, 972–986.
13. Jang, N.; Ham, S. A study on courtyard apartment types in South Korea from the 1960s to 1970s. *Front. Archit. Res.* **2017**, *6*, 149–156.
14. Yang, H.J.; Choi, M.J. Apartment complexes in the Korean housing market: What are the benefits of agglomeration? *J. Hous. Built Environ.* **2019**, *34*, 987–1004.
15. Seo, J.K. Housing policy and urban sustainable development: Evaluating the process of high-rise apartment development in Korea. *Urban Policy Res.* **2016**, *34*, 330–342.
16. Gu, N. Korean apartment complexes and social relationships of the residents. *Hous. Stud.* **2020**, *35*, 1362–1389.
17. Statistics Korea. Current Status of Housing Stock by Type. Available online: https://www.in-dex.go.kr/unity/potal/main/EachDtlPageDetail.do?idx_cd=1242 (accessed on 2 January 2025).
18. Aljashaami, B.A.; Ali, B.M.; Salih, S.A.; Alwan, N.T.; Majeed, M.H.; Ali, O.M.; Alomar, O.R.; Velkin, V.I.; Shcheklein, S.E. Recent improvements to heating, ventilation, and cooling technologies for buildings based on renewable energy to achieve zero-energy buildings: A systematic review. *Results Eng.* **2024**, *23*, 102769.
19. Belussi, L.; Barozzi, B.; Bellazzi, A.; Danza, L.; Devitofrancesco, A.; Fanciulli, C.; Ghellere, M.; Guazzi, G.; Meroni, I.; Salamone, F.; et al. A review of performance of zero energy buildings and energy efficiency solutions. *J. Build. Eng.* **2019**, *25*, 100772.
20. Sadat, S.Z.H.; Ledari, M.B.; Dehvari, H.; Moghaddam, M.S.; Hosseini, M.R. Aligning Net zero energy, carbon Neutrality, and regenerative concepts: An exemplary study of sustainable architectural practices. *J. Build. Eng.* **2024**, *90*, 109414.
21. Council, U.G.B. *The LEED Green Building Rating System™*, 2nd ed.; US Green Building Council: Washington, DC, USA, 2000; p. 2.
22. Xie, X.; Xu, B.; Fei, Y.; Chen, X.-N.; Pei, G.; Ji, J. Passive energy-saving design strategy and realization on high window-wall ratio buildings in subtropical regions. *Renew. Energy* **2024**, *229*, 120709.
23. Li, X.; Shen, C.; Yu, C.W. *Building Energy Efficiency: Passive Technology or Active Technology?* SAGE Publications Sage UK: London, UK, 2017; pp. 729–732.

24. Bradshaw, V. *The Building Environment: Active and Passive Control Systems*, 3rd ed.; John Wiley & Sons: New York, NY, USA, 2010; pp. 35–37.
25. Lachheb, M.; Younsi, Z.; Youssef, N.; Bouadila, S. Enhancing building energy efficiency and thermal performance with PCM-Integrated brick walls: A comprehensive review. *Build. Environ.* **2024**, *256*, 111476.
26. Sadineni, S.B.; Madala, S.; Boehm, R.F. Passive building energy savings: A review of building envelope components. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3617–3631.
27. Vassiliades, C.; Agathokleous, R.; Barone, G.; Forzano, C.; Giuzio, G.; Palombo, A.; Buonomano, A.; Kalogirou, S. Building integration of active solar energy systems: A review of geometrical and architectural characteristics. *Renew. Sustain. Energy Rev.* **2022**, *164*, 112482.
28. Bosu, I.; Mahmoud, H.; Ookawara, S.; Hassan, H. Applied single and hybrid solar energy techniques for building energy consumption and thermal comfort: A comprehensive review. *Sol. Energy* **2023**, *259*, 188–228.
29. Senyonyi, B.; Mahmoud, H.; Hassan, H. Systematic review of solar techniques in zero energy buildings. *Clean Technol. Environ. Policy* **2024**, *27*, 727–772.
30. Choo, Y.M.; Wei, W. Salt hydrates as phase change materials for photovoltaics thermal management. *Energy Sci. Eng.* **2022**, *10*, 1630–1642.
31. Tabadkani, A.; Banihashemi, S.; Hosseini, M.R. Daylighting and visual comfort of oriental sun responsive skins: A parametric analysis. *Build. Simul.* **2018**, *11*, 663–676.
32. Ramos, J.S.; Domínguez, S.Á.; Moreno, M.P.; Delgado, M.G.; Rodríguez, L.R.; Ríos, J.A.T. Design of the refurbishment of historic buildings with a cost-optimal methodology: A case study. *Appl. Sci.* **2019**, *9*, 3104.
33. Hosseini, S.M.; Mohammadi, M.; Schröder, T.; Guerra-Santin, O. Integrating interactive kinetic façade design with colored glass to improve daylight performance based on occupants' position. *J. Build. Eng.* **2020**, *31*, 101404.
34. Waibel, C.; Thomas, D.; Elesawy, A.; Hischer, I.; Walker, L.; Schlueter, A. Integrating energy systems into building design with Hive: Features, user survey and comparison with Ladybug and Honeybee tools. In Proceedings of the Building Simulation 2021 Conference, Bruges, Belgium, 1–3 September 2021.
35. de Sousa Freitas, J.; Cronemberger, J.; Soares, R.M.; Amorim, C.N.D. Modeling and assessing BIPV envelopes using parametric Rhinoceros plugins Grasshopper and Ladybug. *Renew. Energy* **2020**, *160*, 1468–1479.
36. Veerendra, G.; Dey, S.; Mantle, E.J.; Manoj, A.V.P.; Kumaravel, B.; Babu, P.S.S.A.; Rao, P.K.R. Material estimation and energy analysis for a domestic building using Revit architecture and insight: A sustainable approach. *Asian J. Civ. Eng.* **2024**, *25*, 3431–3447.
37. Shi, X.; Abel, T.; Wang, L. Influence of two motion types on solar transmittance and daylight performance of dynamic façades. *Sol. Energy* **2020**, *201*, 561–580.
38. Revit Software. Available online: <https://www.autodesk.com/products/revit/overview?plc=RVT&term=1-YEAR&support=ADVANCED&quantity=1> (accessed on 2 March 2024).
39. Smith, P. BIM implementation—global strategies. *Procedia Eng.* **2014**, *85*, 482–492.
40. Insight Software. Available online: <https://www.autodesk.com/products/insight/overview> (accessed on 30 March 2024).
41. Wirye District Unit Plan and Implementation Guidelines. Available online: <https://www.seongnam.go.kr/city/1000611/30246/bbsView.do?idx=212751> (accessed on 14 May 2024).
42. Google Maps. Available online: <https://maps.app.goo.gl/DTyj8LFGqbmSRjyt8> (accessed on 11 August 2024).
43. Hanwha. Available online: <https://www.hanwha.com/newsroom/news/press-releases/hanwha-qcells-retains-top-market-share-in-the-us-residential-and-commercial-solar-module-segments-for-2022.do> (accessed on 8 April 2025).
44. Hanwha Q CELLS. Available online: https://qcells.com/kr/static/files/solar-panel/Qcells_Data_sheet_Q.TRON_XL-G2.13-BFG_series_620-635_2024-07_Rev03....pdf (accessed on 15 April 2025).
45. Calabrò, E. An algorithm to determine the optimum tilt angle of a solar panel from global horizontal solar radiation. *J. Renew. Energy* **2013**, *2013*, 307547.
46. Energyinfo. Available online: <https://energyinfo.seoul.go.kr/solarmapManual?menu-id=Z080600> (accessed on 3 May 2025).

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