sustainability

MDPI

Article

Energy and Daylighting Performance of Kinetic Building-Integrated Photovoltaics (BIPV) Façade

Sujan Dev Sureshkumar Jayakumari [1], Samarasinghalage Tharushi Imalka [1], Rebecca Jing Yang [1,*], Chengyang Liu [1], Siliang Yang [2], Max Marschall [3], Pablo Sepulveda Corradini [3], Adolfo Fernandez Benito [3] and Nick Williams [3]

1 School of Property Construction and Project Management, RMIT University, Melbourne, VIC 3000, Australia
2 Mott MacDonald, Leeds LS12 1BE, UK
3 Aurecon Group Pty Ltd., Docklands, VIC 3008, Australia
* Correspondence: rebecca.yang@rmit.edu.au

Abstract: The deployment of renewable energy in the construction industry has emerged as a crucial topic due to the building sector's substantial energy consumption and greenhouse gas emissions. Building Integrated Photovoltaics (BIPV) offers a promising solution, replacing conventional building materials with solar energy-generating components. Moreover, retrofitting commercial buildings with BIPV and kinetic façades present an innovative approach to improve energy efficiency and enhance occupant well-being. Adaptive façades, capable of responding to varying climatic conditions, play a pivotal role in reducing energy consumption while ensuring thermal and visual comfort for occupants. By integrating solar generation and shading capabilities, BIPV kinetic façades deliver dual benefits, optimizing energy performance and reducing lifecycle costs, compared to traditional PV systems. Furthermore, effective daylighting strategies not only contribute to energy savings but also positively impact occupant productivity and comfort. Despite predominant research focusing on energy aspects, there is a notable gap in comprehensive assessments that integrate environmental, economic, and daylighting considerations. Therefore, evaluating Australian commercial buildings' energy and daylighting performance with BIPV kinetic façades provides valuable insights for advancing sustainable building designs and operations in the region. The implementation of kinetic BIPV façades in Melbourne reduced energy consumption by 18% and covered 26% of energy demand, achieving the target daylighting levels.

Keywords: BIPV; building simulation; kinetic façade; daylighting; energy

Citation: Sureshkumar Jayakumari, S.D.; Imalka, S.T.; Yang, R.J.; Liu, C.; Yang, S.; Marschall, M.; Corradini, P.S.; Benito, A.F.; Williams, N. Energy and Daylighting Performance of Kinetic Building-Integrated Photovoltaics (BIPV) Façade. *Sustainability* **2024**, *16*, 9739. https://doi.org/10.3390/su16229739

Academic Editors: Ali Bahadori-Jahromi, Stefano Galassi and Riccardo Liberotti

Received: 31 July 2024
Revised: 25 October 2024
Accepted: 31 October 2024
Published: 8 November 2024

1. Introduction

The deployment of renewable energy in the construction industry has become an emerging topic as the building sector accounts for 40% of the total energy use while accounting for 28% of global greenhouse gas emissions [1]. Building-integrated photovoltaics (BIPV) replace conventional roof and façade building materials while generating energy [2,3]. Thus, BIPV have the potential as an emerging, reliable, renewable, and cost-effective energy source. Retrofitting mitigates buildings' environmental impact, enhancing performance and lowering emissions.

The building envelope can manage interior solar radiation, thereby reducing heating and cooling loads and improving daylighting [4]. Daylighting has been shown to have a significant impact on buildings' energy consumption [5]. A study conducted by the Pacific Northwest National Laboratory [6] found that properly designed daylighting systems can reduce energy consumption for lighting by as much as 50% in office buildings. The study also found that daylighting can improve visual comfort and increase productivity for the building's occupants. Furthermore, it posited that daylighting should be properly controlled and distributed throughout workspaces to maximize the benefit of natural light. Daylighting also has a positive impact on the environment by reducing greenhouse gas emissions associated with the generation of electricity used for lighting. A study conducted by the IEA found that reducing energy consumption for lighting through effective daylighting strategies can reduce greenhouse gas emissions by up to 15% [7].

As per Bui et al. [8], the design of a façade for energy efficiency is an optimization problem aimed at minimizing energy consumption in varying outdoor conditions. Thus, static façade systems, which are irresponsive to changes in climatic conditions, fail to fully address this problem. Adaptive or kinetic façades can help preserve the thermal and visual comfort of occupants while contributing to significant reductions in building energy use and carbon emissions [9]. By adjusting the orientation and opening angle of the shading devices in response to changes in weather and solar exposure, adaptive façades can effectively regulate the amount of light entering a building. Furthermore, they can help regulate the amount of solar heat gain, reducing the need for cooling and improving the overall energy efficiency of the building. Thus, responsive or kinetic façades have become an emerging area concerning energy-efficient buildings [10]. BIPV façades provide two benefits, namely, solar gains reduction and energy generation. However, kinetic BIPV façades can further enhance the overall energy performance of a building by adapting their geometry according to the sun's movement and thereby further reducing cooling loads [11]. Incorporating photovoltaics into the building envelope reduces the extra cost of PV installation and lowers the structure's life-cycle cost by eliminating the need for conventional materials at the construction site. This approach is more cost-effective in the long run compared to PV systems that require specialized mounting solutions, as it saves on materials, labor, and energy costs. The cost of these integrated systems is also less expensive over time, and the additional monetary savings are significant [12].

Aelenei et al. [9] found that solar radiation and outdoor air temperature are the most common external factors considered in the design of adaptive façades, while occupant comfort is their primary objective. Although there are assessment studies related to BIPV envelopes, not many have focused on the kinetic aspect of solar envelopes. Salah and Kayili [13] studied the potential of the kinetic façade reinforcement strategy to reduce the energy consumption of existing buildings by lowering the cooling load with a mobile solar control system and effective solar control. The study by Koukelli et al. [14] explored the possibility of a kinetic solar envelope for urban heat island mitigation in Athens, Greece. Some studies focused on the design of kinetic façade systems with conventional building materials [15]. Bui et al. [8] proposed a computational optimization approach to design and assess the viability of adaptive façades systems. They showed that the proposed adaptive façade system can reduce energy consumption by 14.9–29.0% and 14.2–22.3% for their first and second case studies, respectively, compared to a static façade. However, not many studies have focused on the assessment of the energy aspect of kinetic BIPV façades. Bacha and Bourbia [16] used parametric design to analyze the impact of kinetic façades on energy efficiency in office buildings in hot, dry climates demonstrated that the use of kinetic façades with PV (photovoltaic) modules can significantly improve indoor air temperature, thermal and visual comfort levels, and overall environmental conditions for the occupants. Most studies only considered the energy consumption aspect but not the daylighting aspect related to adaptive façades. Tabadkani et al. [17] investigated the development process of an adaptive solar façade for a building in Tehran, Iran, with a focus on its visual comfort. Tabadkani et al. [18] proposed a new approach for the parametric analysis of daylighting and visual comfort, through a sun-responsive shading system. These studies do not provide a comprehensive assessment of different aspects such as environmental, economic, and daylighting features related to an adaptive façade system. Jayathissa et al. [19] conducted a life cycle assessment of an adaptive BIPV system considering its environmental performance, and showed that adaptive systems outperform static PV systems. Jayathissa et al. [20] presented a simulation method to evaluate an adaptive PV shading system combining both the energy consumption of the building and the PV electricity generation. However, it only considered a single room. Kensek and Hansanuwat [21] studied the energy efficiency, daylighting, ventilation, and thermal aspects of a kinetic BIPV setup in place of windows in a vertical setting. They have shown that the kinetic façade achieves a 30% decrease in energy consumption for both heating and cooling situations while keeping the recommended daylighting levels. Research and adoption of kinetic façade systems are popular in Europe and the United States but not in Australia [15]. A comprehensive assessment of an adaptive BIPV system, considering different aspects, is therefore timely. The aim of this study is to evaluate Australian buildings' energy efficiency and daylighting via BIPV kinetic façades. This study targets commercial sector retrofitting to improve both building efficiency and occupant well-being. Section 2 outlines assessment methodology, data collection, and parametric modeling. Section 3 showcases results. Discussion and conclusion follow.

2. Materials and Methods

The assessment of the case study building's performance was conducted by analyzing three primary criteria: building energy consumption (kilowatt–hours, kWh), daylighting (lux), and photovoltaic (PV) energy output (kilowatt-hours, kWh). The existing case study building serves as the baseline for comparison, as it currently has no Building Integrated Photovoltaics (BIPV) installed. This study aims to evaluate the potential impacts of integrating BIPV panels through a detailed comparison of the following four distinct scenarios.

Case Study Building Without BIPV: In this scenario, the performance metrics for the existing building are recorded, serving as the reference point. The energy consumption is measured without any contributions from solar energy generation, and daylight levels are assessed based on the current façade design.

Case Study Building With BIPV: This scenario simulates the installation of BIPV panels on the existing building. The expected improvements in energy consumption and daylight levels are calculated based on the addition of BIPV, which captures solar energy and converts it into usable electricity. The anticipated benefits are quantified by comparing the energy savings and daylighting improvements against the baseline scenario, highlighting the reductions in both heating and cooling loads due to the enhanced energy efficiency.

Kinetic Façade Without BIPV: This scenario evaluates the performance of a kinetic façade installed on the case study building, but without any BIPV integration. The analysis focuses on the dynamic properties of the kinetic façade, which can modulate daylight entry and reduce glare while enhancing aesthetic appeal. Energy consumption data in this scenario are collected to assess the improvements in comfort levels, even without the energy-generating capabilities of BIPV.

Kinetic Façade With BIPV: This scenario combines the benefits of a kinetic façade with the energy-generating potential of BIPV. Here, both the dynamic performance of the façade and the solar energy production are considered. The analysis quantitatively measures improvements in energy consumption due to reduced reliance on artificial lighting and heating, ventilation, and air conditioning (HVAC) systems as well as the additional energy produced by the BIPV panels. Daylight levels in occupied spaces are assessed to determine whether the kinetic design effectively maintains adequate illuminance while maximizing energy generation.

2.1. Case Study Building

The case study building (Figure 1) selected for this research is an eleven-story institutional structure in Melbourne with a gross floor area (GFA) of 13,000 square meters. The Design Hub is renowned for its innovative architectural and environmental design, making it an ideal candidate for evaluating the performance of a kinetic photovoltaic (PV) façade. The layout of the building is designed to be modular and adaptable, allowing spaces to be reconfigured based on changing needs. The flexible interiors serve as studios, research spaces, and exhibition areas, offering a highly adaptable environment for various design disciplines. The building's façade is composed of a double-glazed inner skin, offering thermal insulation, while a second skin shading system, consisting of 17,000 circular glass panels mounted in aluminum frames that dynamically adjust to control solar gain and optimize interior comfort. From the ground floor to the roof plant level, the whole building is surrounded by the second skin shading layer. This kinetic façade enables the panels to rotate in response to sunlight, regulating natural light and heat ingress. The building's primary structural material is reinforced concrete, providing strength and durability, with exposed concrete surfaces contributing to a minimalist, industrial aesthetic. Internally, steel, glass, and timber are used to create functional and flexible spaces that foster collaboration and creativity. From the ground floor to the roof plant level, the entire building is surrounded by the second skin shading layer, which balances daylight penetration with solar protection. In addition, the building integrates advanced passive design principles alongside active environmental systems, such as natural ventilation and mechanized solar shading, to reduce energy consumption. Detailed information about the building's floor plans, HVAC specifications, and energy usage has been collected from the University Property Services. This combination of innovative construction techniques and sustainable design makes the building an exemplary case for showcasing the performance and benefits of a kinetic PV façade, particularly in commercial and institutional settings where energy efficiency is critical.

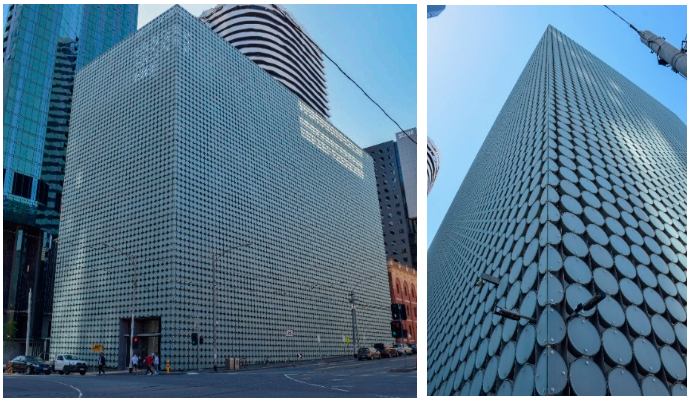


Figure 1. Case study building.

2.2. Parametric Modeling

The building geometry mainly consists of two layers. The first layer has double-glazed windows integrated along with the building; the second layer consists of frames and frosted glass panels which are modeled using the grasshopper, which is a plugin included within Rhino v7. The building's unique façade design features 17,000 circular glass disks that act as both windows and shades. This façade contributes to controlling daylight and heat, leading to a highly dynamic WWR. The adjustable disks and their density suggest a significant balance of solid-to-glass coverage, with 30% window-to-wall coverage in many areas. These disks allow for adaptive shading and daylight control based on the environmental conditions. The shape coefficient refers to the ratio of the building's surface area to its volume, influencing its thermal efficiency. It is considered to be 0.14 for this building. The major focus of the study is to improve the performance of the second layer, which is the external façade, by changing the frosted glass into BIPV panels. Finally, the modeled building has carried out energy simulations through different scenarios with and without BIPV to determine the potential to reduce energy demand and generate energy with the integrated PV panels. The point-in-time simulation has been carried out instead of dynamic shading due to the software's limitation in performing annual simulation. Since the kinetic BIPV panels tilt their angle based on the sun's movement, it is a tedious process to specify the sun's path and energy analysis period simultaneously. Therefore, the point-in-time approach, which considers particular times of day, has been used to compare the different cases. Figure 2 shows the different components of an existing building façade in a single room.

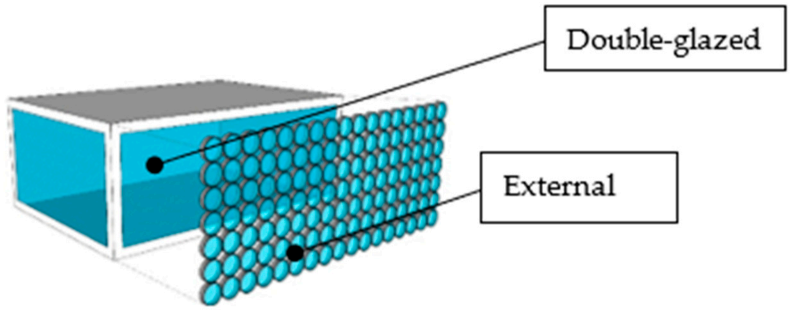


Figure 2. Existing façade layers of a single room.

2.2.1. Modelling Stage-Case Study Building

Initially, the case study building was modeled to determine the baseline performance and later modeled with BIPV panels to determine the impact. The floor plan was imported into the Rhino and each floor has been traced to the appropriate dimensions. After the initial modeling of the case study building using Rhino 7, the program and construction set of the building were assigned using Grasshopper for further modelling according to the material specifications. Table 1 shows the thermal properties of the walls, roof, floors, and glass panels on the façade allotted in the construction set of Grasshopper based on the minimum standards from the National Construction Code (NCC) [22]. The panel used for kinetic BIPV façade is an amorphous silicon (a-Si) PV glass.

Table 1. Construction set for the case study building and retrofitted building.

Building Elements	Materials Used (Outside to Inside)	Thickness (mm)	Conductivity U-Value (W/mK)	Density (kg/m^3)	Specific Heat (J/kg-K)	SHGC
External Walls	Brick Work Polyurethane Board Plaster Brickwork	250	0.840 0.025 0.500 0.620	1700 30 1300 1700	800 1400 1000 800	-
Floor	Lightweight Concrete Block-Concrete Filled	150	0.380	1200	1000	-
Roof	Fiber Board Insulation Board Concrete Block (Heavy Weight)	150	0.060 0.043 1.630	2300 48 2300	1130 1381 1000	-
Internal Glazing (Case Study Building)	Double Glazed, aluminum frame, Visible Light Transmittance (VLT) of 70%	24 mm glass	1.6	-	-	0.4
Case study and Kinetic Building without BIPV	Frosted Single Glazed	6 mm glass	5.5	-	-	0.4
Case study and Kinetic Building with BIPV	Onyx Solar Panel	4 mm	2.7	-	-	0.14

2.2.2. Modeling Stage–Kinetic Façade

The retrofitting is carried out by replacing the glass disk façade of the case study building with kinetic PVs. The modeling process includes three phases: deciding the optimum PV layout, deciding the PV placement surfaces, and the parametric modeling. As the first step, the prototype of the kinetic and photovoltaic panels is developed and the digital mockup of the prototype model is created using the Rhino. The prototype of the kinetic PV panel has been modeled using Rhino, which has a panel area of 0.203 square meters and then implemented BIPV panel for the retrofitting building. The tilting of the kinetic PV panels is based on the sun's movement during different seasons; excessive solar exposure to the building can be blocked by these panels and generate energy at the same time. This study investigated the vertical tilting of the kinetic PVs according to the sun's movement, as indicated in Figure 3.

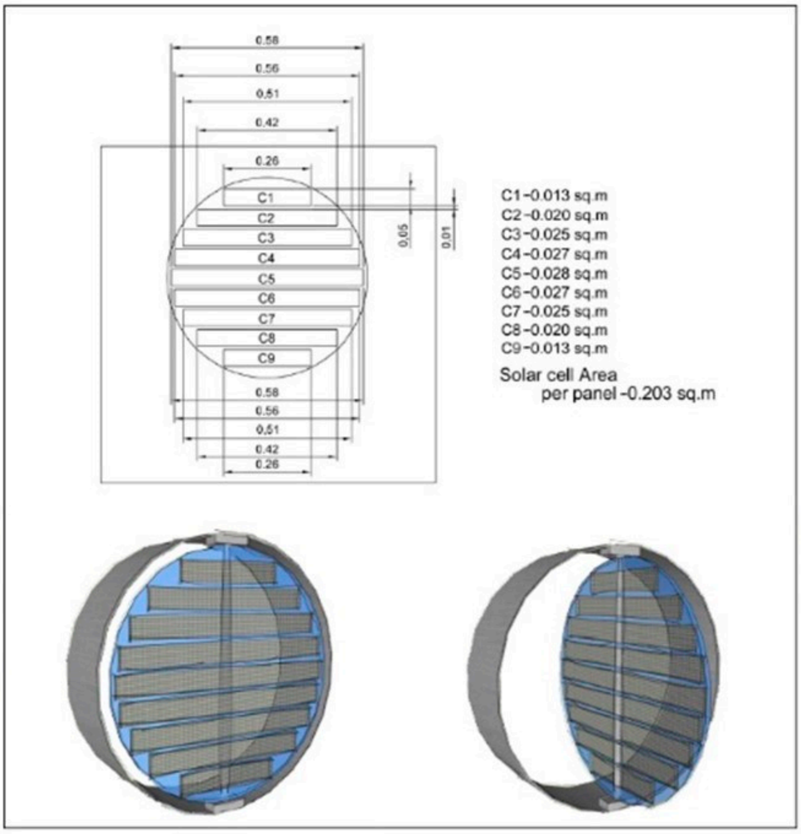


Figure 3. Prototype showing the opening and closing of kinetic PVs.

The second step involves deciding on which surface to place BIPV panels. The annual incident radiation calculation of the case study building is carried out using Ladybug tools to determine the available solar irradiance on each façade. According to the irradiance simulation displayed in Figure 4, the south façade has less incident radiation throughout the year. Therefore, the placement of the kinetic PV façade on the south façade has been eliminated, and the north, east, and west façades are considered for installing the kinetic PV panel.

Based on the BIPV layout and the placement surfaces, parametric modeling was performed for the movement of the circular element that has a vertical rotation axis eliminating the south façade. The parametric modeling was performed using Rhino for the kinetic façade and provided various parameters to determine the façades with more solar exposure. The grasshopper plugin has been used on Rhino to determine the opening of the kinetic façade according to the sun's movement. The movement of the BIPV panel is designed so that the tilt angle of each panel is perpendicular to the solar altitude [11]. Thus, the position of the sun was considered as a point in which the kinetic panels are provided with a tilt angle of 90°. The tilt angle of the kinetic BIPV panel varies based on the sun's position during different seasons. It was designed using various scripting to input the solar data into the kinetic PV panels. Figure 5 demonstrates the tilting of kinetic panels according to solar exposure. The dynamic nature of the kinetic façade means that the panels continuously respond to the sun's movement throughout the day. They are designed to balance solar radiation, allowing for maximum solar exposure during cooler periods while minimizing excessive heat gain in hotter conditions. The closing percentage of the kinetic BIPV panel varies between 0% (fully opened), 50%, 60%, 70% (Semi-closed) and 100% (fully closed), differing during each season. The impact of openings will be discussed in the later stages of this study.

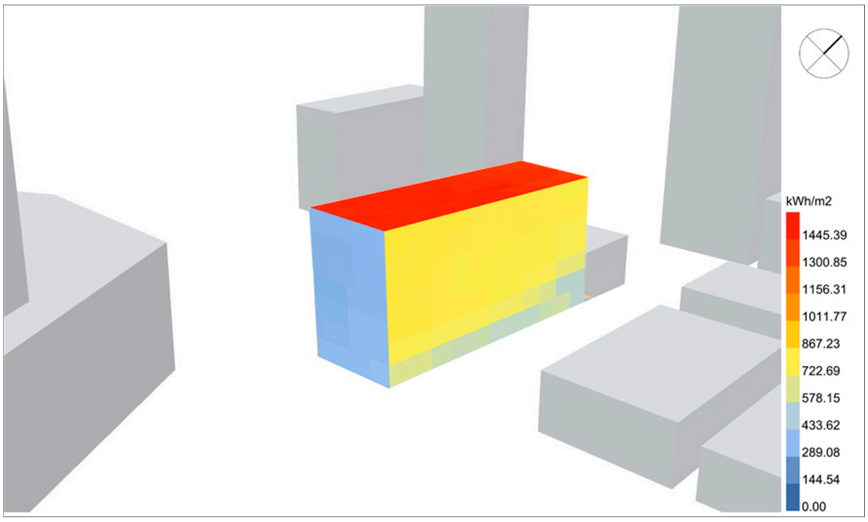


Figure 4. Incident radiation in the case study building.

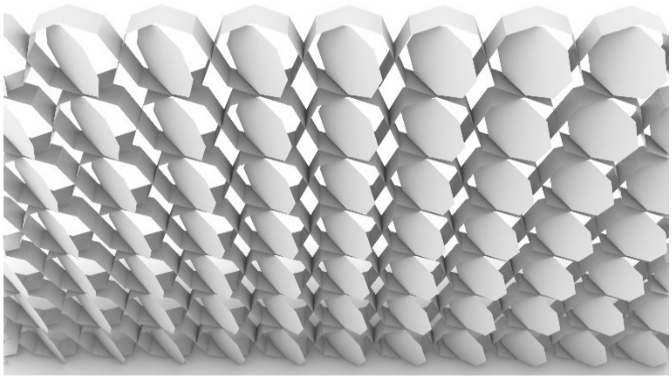


Figure 5. Modelling of a kinetic PV panel using Rhino.

The energy simulation was performed following the parametric modelling process to evaluate the performance of the retrofitted building.

2.3. Assessment Metrics

2.3.1. Energy Consumption

The energy consumption assessment evaluates the differences in energy use between the baseline case study building and the kinetic BIPV façade-integrated building across different seasons in Melbourne. The months chosen for the analysis represent key periods of each season: summer (January), autumn (April), winter (July), and spring (October). These months allow a comprehensive understanding of how the building responds to varying climatic conditions. Initially, the solar incident radiation analysis was carried out using the ladybug tool to determine the amount of solar radiation received inside the building. This allows for determining the heat gain through the façades and how it impacts the energy consumption in the building. The main goal is to analyze the energy performance improvement after implementing the kinetic BIPV façade. This includes determining how the kinetic system affects heat gain, cooling and heating demand, and overall energy consumption, particularly in terms of HVAC (Heating, Ventilation, and Air Conditioning) loads.

Energy Consumption (kWh): Case Study Without BIPV: X kWh, Case Study With BIPV: Y kWh, Kinetic Façade Without BIPV: A kWh, Kinetic Façade With BIPV: B kWh.

The differences in energy consumption between each scenario can be expressed as the following:

Improvement from Case Study Without BIPV to With BIPV: $(X - Y)$ kWh

Improvement from Kinetic Façade Without BIPV to With BIPV: (A − B) kWh

Step 1: Specify Energy Parameters:

The key energy parameters were set for different building spaces (common spaces, office spaces, and teaching spaces) for both the case study building and the kinetic BIPV building. These are shown in Table 2.

Table 2. Program Set for the case study and kinetic building.

Program Type	Common Spaces	Office Spaces	Teaching
people per sqm of floor area		0.05	
Lighting -watts per sqm of floor area	15	16	15
Baseline (W/m^2)		11.84	
Equipment -watts per sqm of floor area		5	
Infiltration -flow per exterior surface (m^3/s per m^2 of exterior surface area) (area (m^3/s))		0.0003	
Heating Setpoint		20 °C	
Cooling Setpoint		24 °C	

Occupancy: 0.05 people per square meter of floor area.

Lighting Loads: Common and teaching spaces were assigned a lighting power density of 15 W/m^2, while office spaces were assigned 16 W/m^2. The baseline lighting energy use was 11.84 W/m^2.

Equipment Loads: Set at 5 W/m^2, representing typical equipment usage in office and teaching spaces.

Infiltration Rate: Defined as 0.0003 m^3/s per m^2 of exterior surface area. This measures the air leakage, which impacts the building's thermal performance.

Set Points: The heating setpoint was maintained at 20 °C and the cooling setpoint at 24 °C to ensure comfort levels. These setpoints were applied based on the building's weekly schedule, aligned with the National Construction Code (NCC).

HVAC systems were configured using a dual duct Variable Air Volume (VAV) system connected to a central chilled water (CHW) and heating hot water (HHW) system, providing heating and cooling through piping. The heating system relies on natural gas, while cooling is provided using electricity.

Step 2: Run Energy Simulation:

The energy simulation was performed using EnergyPlus 22.1.0 after converting the Honeybee model to OpenStudio 3.7.0. The simulation's key components were the following:

Model Details: The simulation model incorporated all relevant spaces, external shadings, and neighboring buildings to ensure realistic energy modeling.

Weather Data: The simulation used an EnergyPlus weather (EPW) file specific to Melbourne, essential for accurate climate-based performance analysis.

Analysis Period: The simulation targeted three critical times of day—morning, noon, and evening—during the selected months, focusing on periods of high solar radiation. These results provide insights into heating and cooling loads (kWh) for each season.

The results from this simulation were used to compare the energy performance of the kinetic façade building with the case study building, identifying reductions in heating and cooling energy demand during different times of the day in various seasons.

2.3.2. Energy Generation

The energy generation simulation evaluates the electricity production from the kinetic BIPV system. Several factors impacting photovoltaic (PV) performance were considered to assess how the kinetic façade generates energy across different conditions.

Key Factors Considered:

The simulation utilized the PVLib toolbox from Sandia National Laboratories and the National Renewable Energy Laboratory (NREL) inverter model to determine solar position, irradiance, and losses. The key factors included the followings:

Plane of Array (POA) Irradiance: This quantifies the solar energy received by the BIPV panels, crucial for estimating energy production.

Solar Position: The position of the sun relative to the building influences the efficiency of the BIPV system.

Losses: PV production losses were modeled to account for various inefficiencies such as inverter losses, shading, wiring, and dust accumulation. These losses were assumed to be 14%, and the system's PV efficiency was set at 15% for DC output calculations.

Simulation Inputs and Constraints:

The simulation uses an amorphous silicon glass BIPV product as the photovoltaic material. The model is constrained by parameters, such as shading from surrounding buildings and urban context, which are modeled using GIS (Geographic Information Systems) to assess urban shading impacts on solar production. These constraints are listed in Table 3, which outlines the key data inputs and system constraints used for PV modeling. The simulation provides energy generation outputs based on the PV system's configuration and efficiency. It also assesses different times of the day to understand how seasonal and diurnal variations affect the energy production of the kinetic façade. The efficiency of photovoltaic (PV) panels, particularly amorphous silicon thin-film modules, varies between modeling and real-world applications due to environmental factors like temperature and light intensity. Meanwhile, the panels are rated under Standard Test Conditions (STC) with parameters such as open-circuit voltage (Voc) and short-circuit current (Isc) potentially varying by ±10%, actual performance may differ. Real-world conditions, such as shading and temperature fluctuations, can lead to higher current or voltage outputs than those predicted in controlled environments. Amorphous silicon, a key material used in these panels, typically has lower efficiency compared to crystalline silicon but performs better in low-light conditions and across broader temperature ranges. Efficiency is also influenced by factors such as light-soaking degradation, with the data sheets accounting for this through an uncertainty rate of ±4.72%. Thus, the relationship between the modeled performance and the actual application underscores the importance of considering degradation effects and site-specific conditions when evaluating the panels' efficiency.

PV Energy Output (kWh):

For the scenarios involving BIPV, quantify the expected solar energy generation, e.g.,

PV Output in Case Study With BIPV: G kWh

PV Output in Kinetic Façade With BIPV: H kWh

The comparison of energy output reflects the additional energy generated by the BIPV, leading to overall enhancements in the building's energy performance.

The energy consumption and the energy generation are analyzed by calculating the energy balance as per Equation (1) [23].

$$energy\ balance\ yearly\ (\%) = \frac{energy\ generated\ yearly}{energy\ consumed\ yearly} \times 100\% \quad (1)$$

Table 3. Key data inputs and system constraints for the solar PV model.

Data Categories	Input Parameter	Data Structure	Unit	Reference Value
Time series	DNI irradiance	Time series	W/m^2	NA
	DHI irradiance	Time series	W/m^2	NA
	Dry bulb temperature	Time series	°C	NA
	Wind speed	Time series	m/s	NA
System specification	DC/AC ratio	Constant	-	1.1
	Inverter efficiency	Constant	%	95
	Module efficiency	Constant	%	15
	Temperature coefficient	Constant	1/K	−0.0047
	Reference temperature	Constant	°C	25
	Other losses (soiling, shading, mismatch, wiring, connect, etc.)	Constant	%	10
Geospatial raster data	Roof tilt angle	Raster data	°	NA
	Azimuth angle	Raster data	°	NA
	PV panel footprint	Raster data	m^2	NA
	Shading layers	Raster data	Boolean	NA

2.3.3. Daylighting Simulation

The daylighting simulation focuses on analyzing how the kinetic BIPV façade impacts natural light distribution within the building. The study was conducted on level 11, as shown in Figure 6, to assess how façade openings influence daylight penetration and reduce the need for artificial lighting.

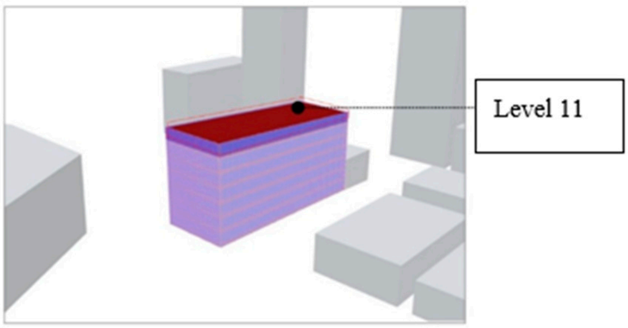


Figure 6. Selected floor for daylight analysis.

Simulation Setup: The point-in-time daylight simulations were carried out using Climate Studio on Rhino. The daylight illuminance levels were measured using sensors spaced 500 mm apart and placed at a height of 760 mm above the floor (workplane height). The simulation considered different VLT levels for the façades:

Kinetic BIPV Façade: Assigned a VLT of 20%.

Non-BIPV Façade: Assigned a VLT of 80%.

Parameters: The daylighting analysis considered various factors such as sky conditions, reflectance values, and exclusions, as outlined in Table 4. The simulation used a CIE Overcast sky, and reflectance values were set at 80% for walls, 30% for floors, and 85% for ceilings. Excluded areas such as toilets, service spaces, and internal circulation zones were not part of the analysis.

Table 4. Daylight Simulation Parameters.

Requirements	Parameters
Weather file	Melbourne.RO.948680
Sky	CIE Overcast sky
Overshadowing	Adjacent building
Exclusions	Toilets, cupboards, service area, and internal circulation areas were excluded from the analysis
Work plane Height	760 mm above floor level
Sensor Spacing	500 mm
Sensor Inset	200 × 300 mm
Wall Reflectance	80%
Floor Reflectance	30%
Ceiling Reflectance	85%

Simulation Process: The point-in-time simulations were conducted for four different months, one from each season (January, April, July, October), to represent daylight conditions during summer, autumn, winter, and spring, respectively. The daylight analysis was carried out during specific times of the day (morning and afternoon) to evaluate how the kinetic façade impacts daylighting inside the building.

The results were compared to assess whether the building meets the standard illuminance requirement of 160 lux for 80% of the occupied hours. However, since a point-in-time analysis was performed, the focus was on achieving 160 lux at specific times of the day rather than across all occupied hours.

3. Results

The outcomes show the energy performance evaluation of the case study building and the improvements in the energy performance of the retrofitted building using the kinetic PV façade. The focus of the assessment includes heating and cooling loads per day (morning, noon, evening) during different seasons. For the analysis, the month of January from the summer season, April from the autumn season, July from the winter season and October from the spring season were considered. The remaining months for each season were considered to have the same temperature. The analysis was started by evaluating the outdoor weather conditions, which can have a severe impact on the performance of buildings. It is determined by the performance of the building envelope; therefore, improving the performance of the building envelope is crucial to achieving thermal comfort inside the building.

Figure 7 shows the annual outdoor temperature concerning each season, with the minimum temperature being 0 °C during July and reaches about 39 °C during February. This temperature will have an impact on the energy consumption of the building during the different seasons in which there will be more heating demand from June to August and cooling demand from December to February. The temperature starts increasing in August and decreases in February. Therefore, the study mainly aims to investigate the reduction of heating and cooling demand by the installation of kinetic PV panels on the façade of the case study building.

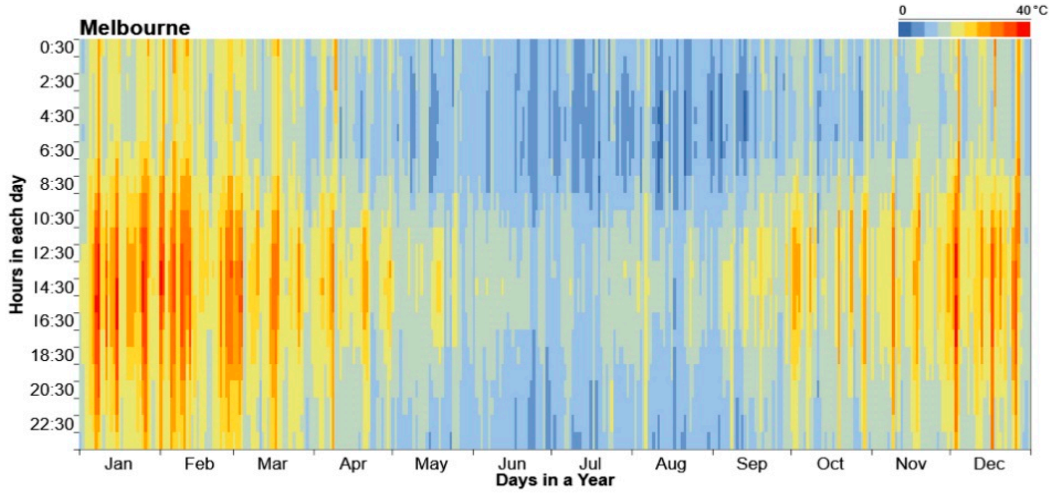


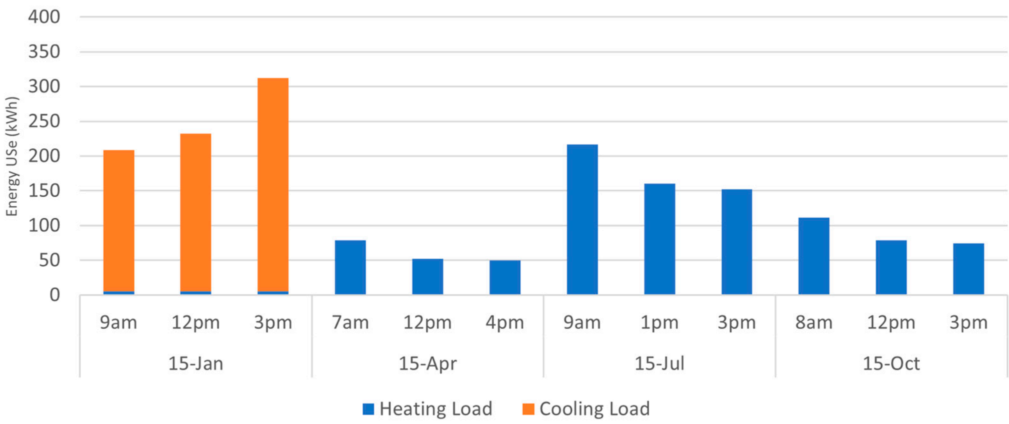
Figure 7. Outdoor temperature.

3.1. Energy Consumption

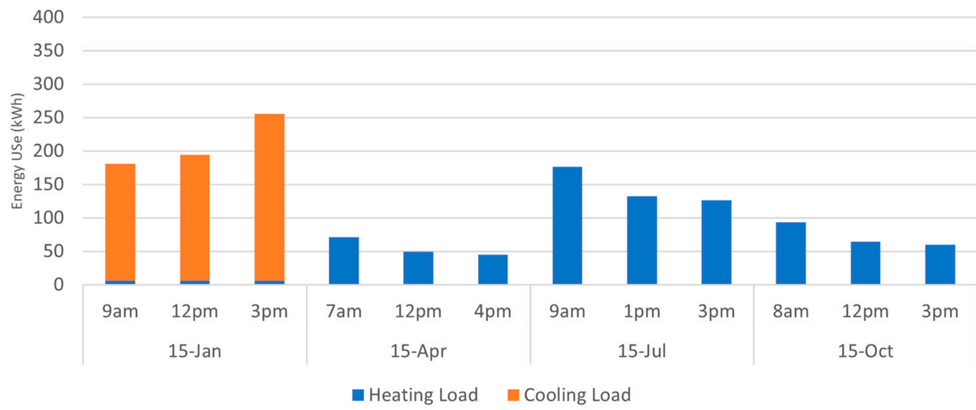
The energy consumption of the building is determined by four conditions. Figure 8 indicates different scenarios considered for the study, which include the case study building without BIPV, the case study building with BIPV, the kinetic building without BIPV, and the kinetic building with BIPV. Scenario A illustrates the heating and cooling loads of the case study building without BIPV and has a significant increase in the heating and cooling loads. It is found that the cooling loads are higher in the evening during the summer season and the heating loads are higher in the evening for the remaining seasons.

As per Scenario B, when static BIPVs are installed in the case study building, it is found that the total heating and cooling loads have been reduced by 16.5% compared to Scenario A. According to Scenario C, the kinetic building provided without BIPV has a significant increase in the heating and cooling loads by 23% compared to Scenario B and 3% compared to Scenario A. According to Scenario D, the kinetic building with BIPV has reduced the heating and cooling loads by 23% compared to Scenario C and 19% compared to Scenario A and Scenario C but increased the overall energy consumption by 0.2% compared to Scenario B in all four seasons. In terms of cooling loads, the Case study building without BIPV has much higher values compared to the other three scenarios. The cooling load difference is not that significant in the kinetic façade with BIPV compared to the heating loads. However, during the first quarter of the year, there is a noteworthy cooling load reduction in the BIPV kinetic façade.

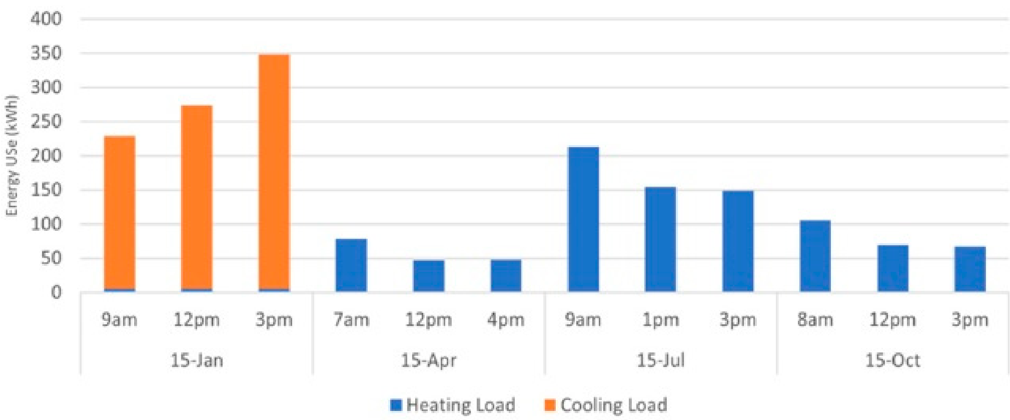
Figure 9 indicates the total heating and cooling loads of the building in different scenarios. Every season case study and kinetic building with BIPV displays the lowest energy use, while the case study and kinetic building without BIPV has the highest total energy demand. Accordingly, the kinetic building with BIPV has presented a noticeable reduction in energy consumption compared to the other scenarios in which the case study building with BIPV has a slight difference in energy use since the entire façade has been provided with BIPV in a closed state.



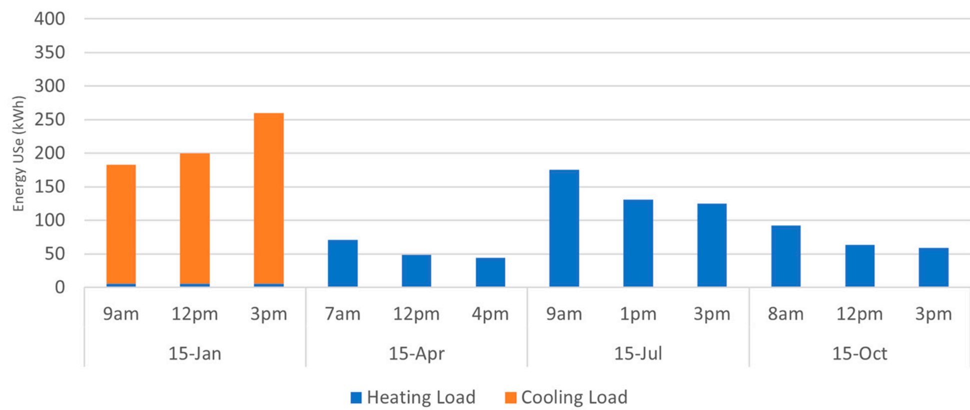
(**a**)



(**b**)



(**c**)



(**d**)

Figure 8. Energy Consumption in Case study and kinetic building. (**a**) Case study building without BIPV; (**b**) case study building with BIPV; (**c**) kinetic building without BIPV; (**d**) kinetic building with BIPV.

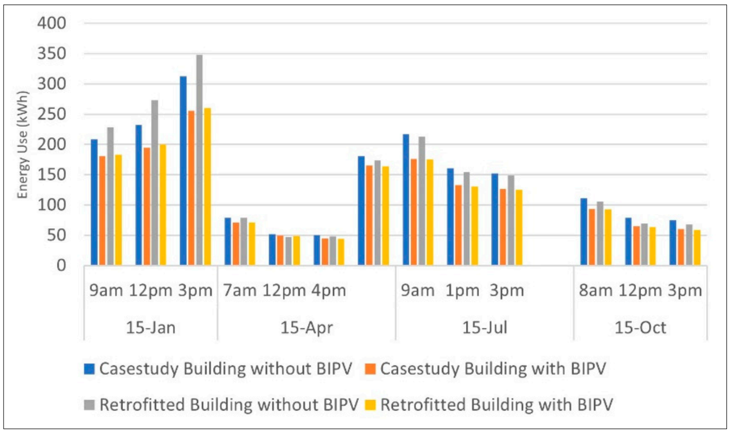


Figure 9. Total load in different scenarios.

3.2. Energy Generation

The energy generation from the PV panels was calculated for the morning (9 a.m.), noon, and evening (3 p.m.) times of a day, in which the noon time for the summer season has been neglected since the façade has less potential during that time. The energy generation has been compared with the kinetic building with BIPV since the major focus of the study was to implement a Kinetic BIPV façade on the existing building as the retrofitting option. The analysis includes the evaluation of several panels exposed by the solar exposure on each façade during different times of the day. For the analysis, the east, north and west façade have been given more consideration because they have more solar exposure and the potential to generate energy. During the summer season, the east and west façades have more potential to generate energy, and the north, east, and west façades show more potential during the remaining seasons. Figure 10 illustrates the energy generation during different times of the day in each season. From the results, it is found that maximum energy is generated during the summer season from the east and west façade due to the high irradiance conditions, while minimum energy generation occurs during the autumn season (April). From the results, energy generation during the morning is higher compared to the evening throughout all the seasons. Furthermore, energy generation is higher during the winter season (July) at noon from the north façade compared to the other seasons. It is found that 27% of energy demand (consumption) is covered by the energy generated from the kinetic BIPV panels in summer, while 21%, 27%, and 26% are covered in autumn, winter and spring, respectively. As per Equation (1), the kinetic building with BIPV depicted an energy balance of 26%.

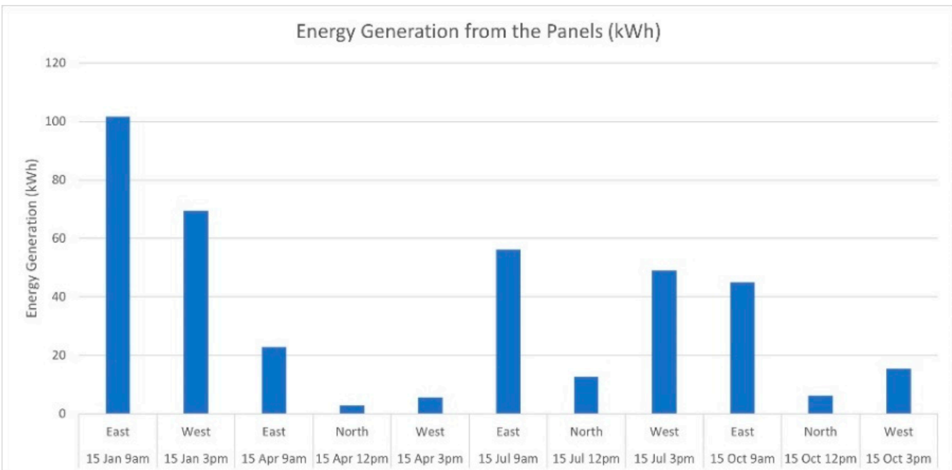


Figure 10. Energy generation during the analysis period for each season.

3.3. Daylighting

The results of simulations for daylighting performance were analyzed for both case study and kinetic buildings with and without BIPV panels. The analysis was carried out by considering specific times of the day which are during the morning (9 a.m.), noon and evening (3 p.m.). Figure 11 shows the comparison of the average lux levels during the different times of the day for all four seasons. The results show that the kinetic building without BIPV has the highest average lux levels during the summer season, while the case study building with BIPV has the lowest average lux levels throughout different seasons compared to the other cases. Furthermore, noon has the highest average lux level for all four cases compared to morning (9 a.m.) and evening (3 p.m.).

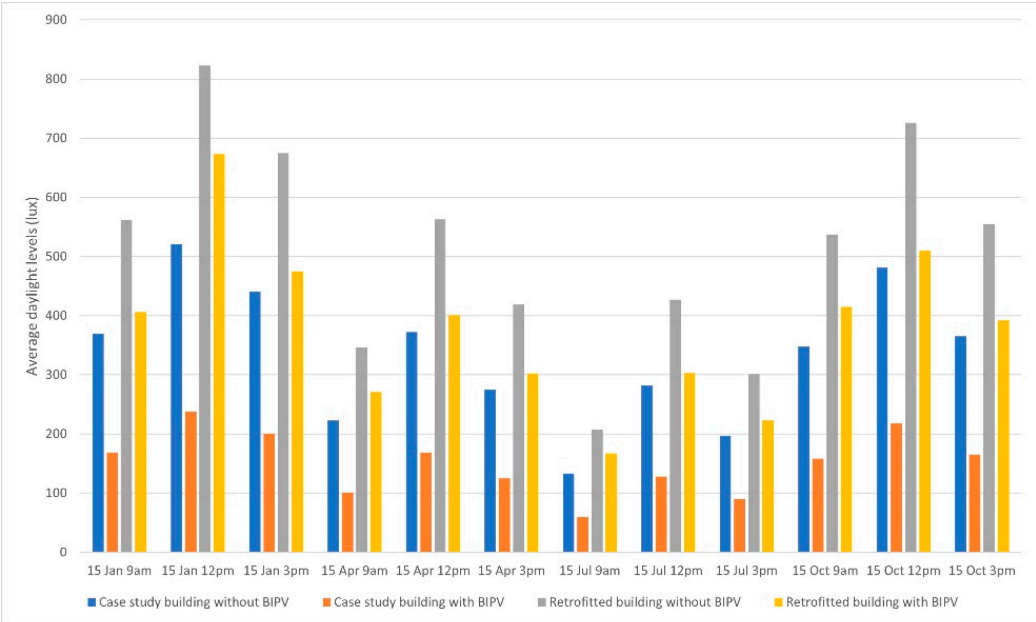


Figure 11. Average Daylight levels (lux).

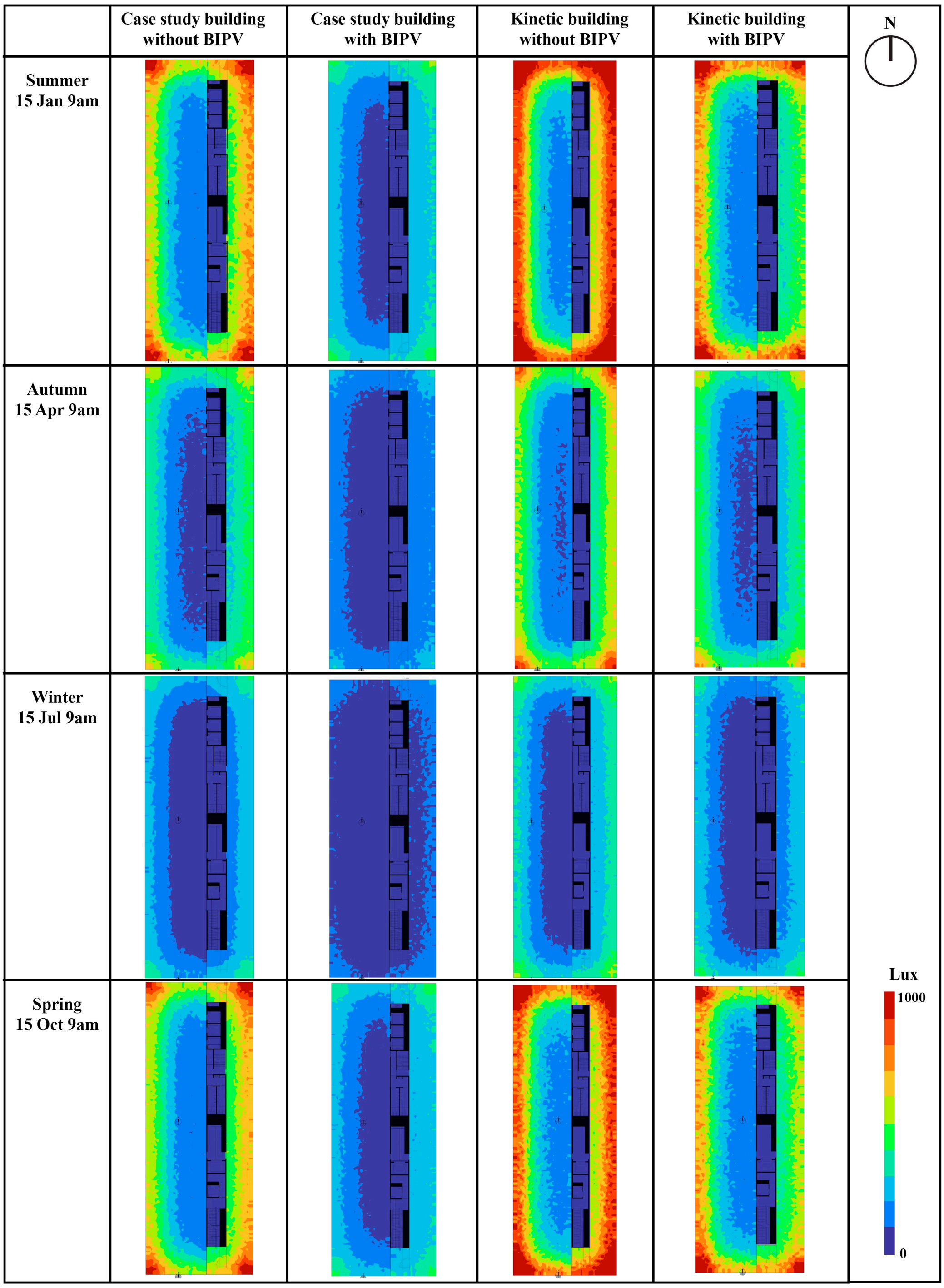
Figure 12 presents the daylighting levels for both case study and kinetic buildings with and without BIPV panels, captured at different times of the day—9 a.m.,12 p.m., and 3 p.m.—for four seasons: summer, autumn, winter, and spring. The color scale on the right represents the daylighting levels in lux, with values ranging from 0 lux (dark blue) to 1000 lux (red).

Case Study Building Without BIPV: The areas near the edges of the building tend to experience high daylighting levels, often close to 1000 lux (depicted in red), especially during the morning and noon periods. The central areas of the building are dimmer, especially in winter and autumn, indicating uneven daylight distribution.

Case Study Building With BIPV: The introduction of BIPV panels drastically reduces the daylighting levels, particularly in the winter season, where the central parts of the building see very low lux levels (dark blue, around 0–100 lux). This suggests that fully closed BIPV panels significantly block daylight, potentially leading to reduced lighting in internal spaces.

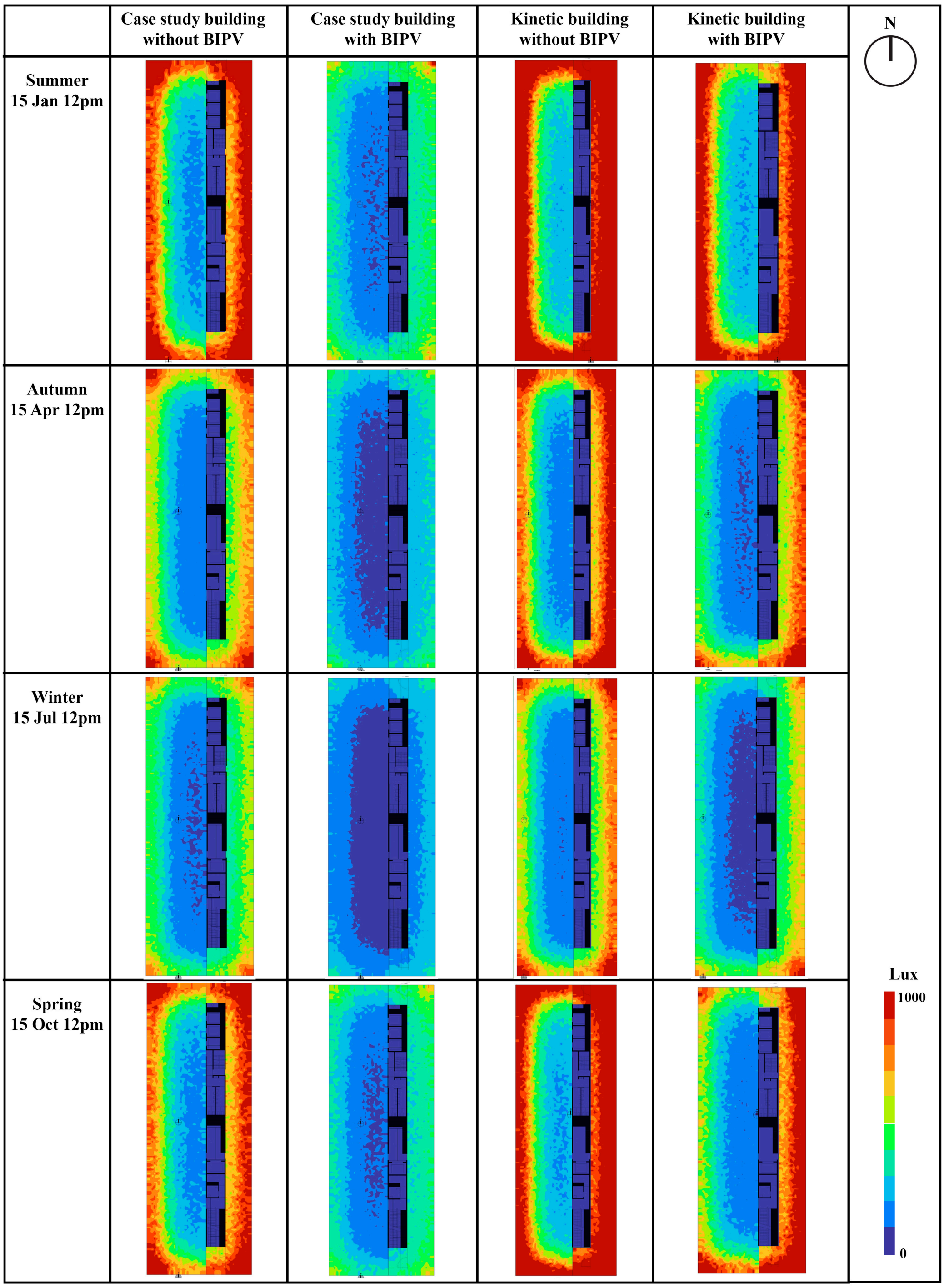
Kinetic Building Without BIPV: Like the case study building without BIPV, this building shows a similar pattern of higher daylight levels near the edges of the space but with slightly more daylight reaching the central areas. The absence of BIPV leads to higher overall daylight levels.

Kinetic Building With BIPV: Similar to the case study with BIPV, the daylighting levels in the kinetic building with BIPV are more moderate, with lux values ranging between 160 and 500 lux (represented in light blue and green). This shows that the kinetic nature of the BIPV panels helps balance the light levels, particularly in spring and autumn.



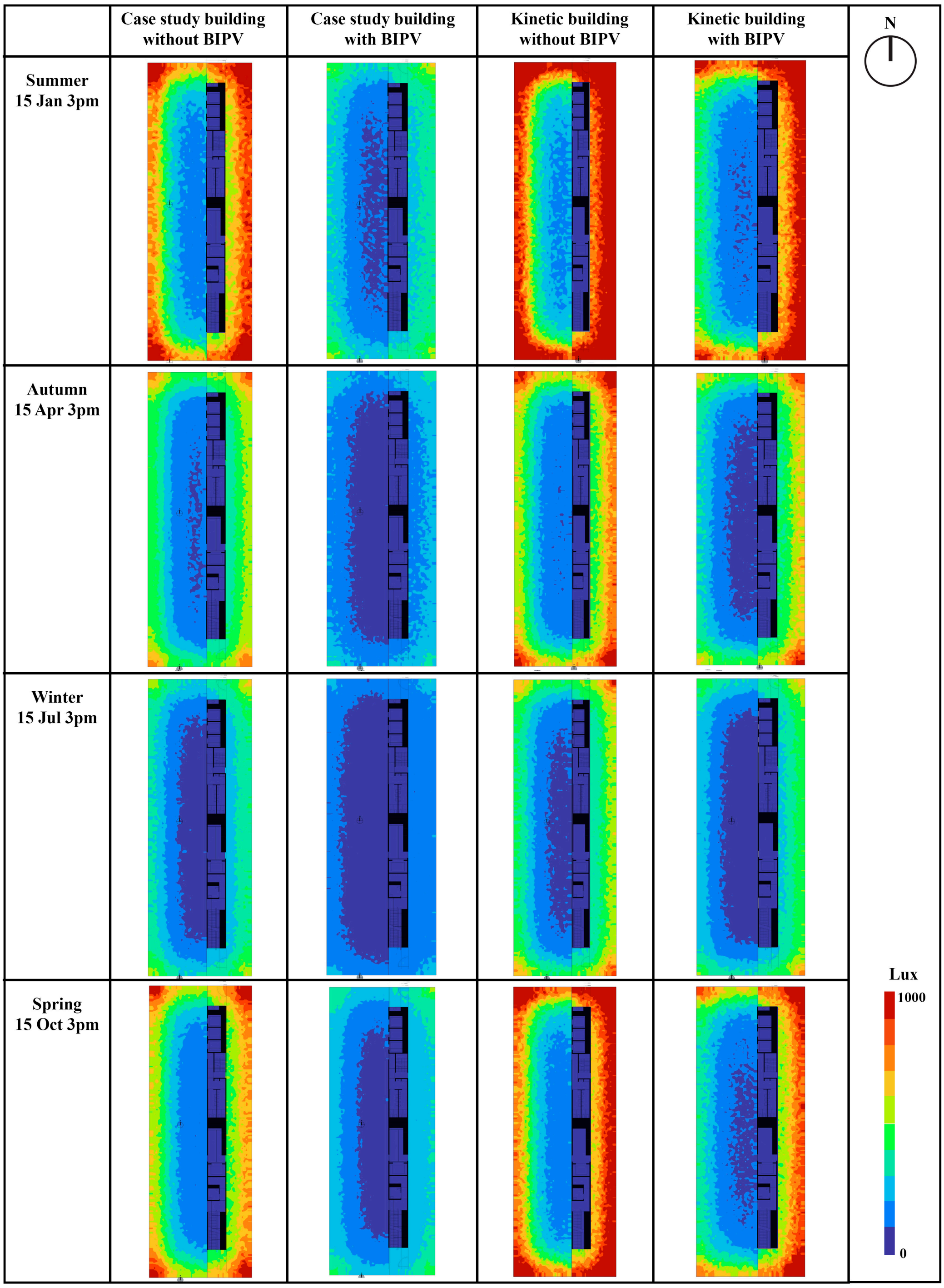
(a)

Figure 12. *Cont.*



(**b**)

Figure 12. *Cont.*



(c)

Figure 12. (**a**) Morning daylighting; (**b**) noon daylighting; (**c**) afternoon daylighting.

Seasonal Performance:

Summer (15 January, 9 a.m., 12 p.m., 3 p.m.):

Case Study Without BIPV: High daylight levels near the building's perimeter, with lux levels reaching 1000, but a significant drop in light as we move toward the center of the building.

Case Study With BIPV: Daylighting is greatly reduced across the entire space, suggesting that BIPV panels, when fully closed, block a large portion of direct sunlight.

Kinetic Building Without BIPV: Similar pattern to the case study without BIPV, with high lux values near the edges.

Kinetic Building With BIPV: Balanced daylight distribution, especially at noon, with less intense glare from direct sunlight due to the kinetic BIPV panels.

Autumn (15 April, 9 a.m., 12 p.m., 3 p.m.): Daylighting levels are more balanced across the kinetic building with BIPV panels. The case study with BIPV panels shows a marked reduction in lux values, while the kinetic building without BIPV continues to show high daylight levels along the perimeter.

Winter (15 July, 9 a.m., 12 p.m., 3 p.m.):

Case Study With BIPV: This has the least daylighting overall, with most areas in dark blue (indicating very low lux levels). BIPV panels seem to reduce winter daylight even further.

Kinetic Building With BIPV: There is better daylighting than the case study with BIPV, although still reduced compared to summer and spring.

Spring (15 October, 9 a.m., 12 p.m., 3 p.m.):

Both kinetic buildings (with and without BIPV) show better daylighting than the case study buildings, particularly with BIPV in operation. Lux values are spread more evenly due to the vertical movement of panels that block glare and provide diffused light.

Kinetic Buildings With BIPV: These have the best balance of daylight distribution throughout the year and across different times of day. The panels' ability to move and block direct sunlight reduces glare while maintaining acceptable daylight levels.

Case Study Buildings With BIPV: These show the most significant reduction in daylighting, especially in winter and autumn, due to the static and fully closed panels blocking out most of the light.

The optimal range of 160 lux is most consistently achieved in kinetic buildings, particularly in the spring and autumn seasons. In general, the kinetic building with BIPV achieves better daylighting than the case study building through vertical movements and blocking the direct daylight into the building which reduces the glare effect. From the results, it is found that the application of BIPV panels with 20% VLT has a significant reduction in daylight especially for the case study with BIPV since all the panels are fully closed. The non-BIPV panels with 80% VLT have found the highest levels of daylight. Therefore, the application of Kinetic BIPV panels has the potential to increase the daylight in the building by blocking direct daylight and providing diffused daylight for the remaining spaces.

4. Discussion

The building envelope has a significant impact on the energy performance of the building. Therefore, it is important to improve the efficiency of the building envelope to tackle the issues. Currently, the global construction industry faces several challenges in the commercial uptake of Kinetic PV panels. Some of the challenges are high initial cost, microclimate change, lifetime, governmental support, and disproportionate payback times [24]. It has been thought that the extra expense of Kinetic PV panels is above conventional roof or façade installation. However, the additional cost of BIPV for façades in office buildings can be low or even negative when the profits from energy production are taken into consideration. In this investigation, the kinetic BIPV façade has been implemented on the case study building as a retrofit measure to improve energy performance, daylighting, and generate renewable energy. This was carried out by blocking the excessive solar exposure by utilizing a kinetic system which can reduce the heat gain entering the building. During winter, it can be reversed due to less solar exposure, which allows solar exposure into the building and reduces the heating load. This acts as passive heating and cooling for the building, which can reduce its energy demand.

In the current study, the kinetic façade has been set up to block solar exposure during the winter season since the panels are set up to face the sun's direction. However, the results show that the heating load has been reduced, even though the solar exposure is blocked by the kinetic façade. This was due to the building façade geometry in which the solar exposure enters the building through the gaps, which reduces the efficiency of the overall façade (Figure 13). The kinetic façade blocks a significant amount of solar exposure, but the building still gets solar exposure from the other parts of the façade, and this reduces the overall efficiency. This effect has been demonstrated during the morning time of the winter season as shown in Figure 14.

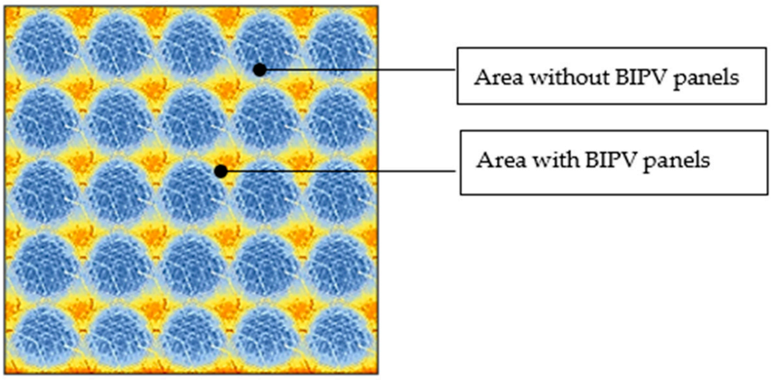


Figure 13. Façade impact with BIPV Panels.

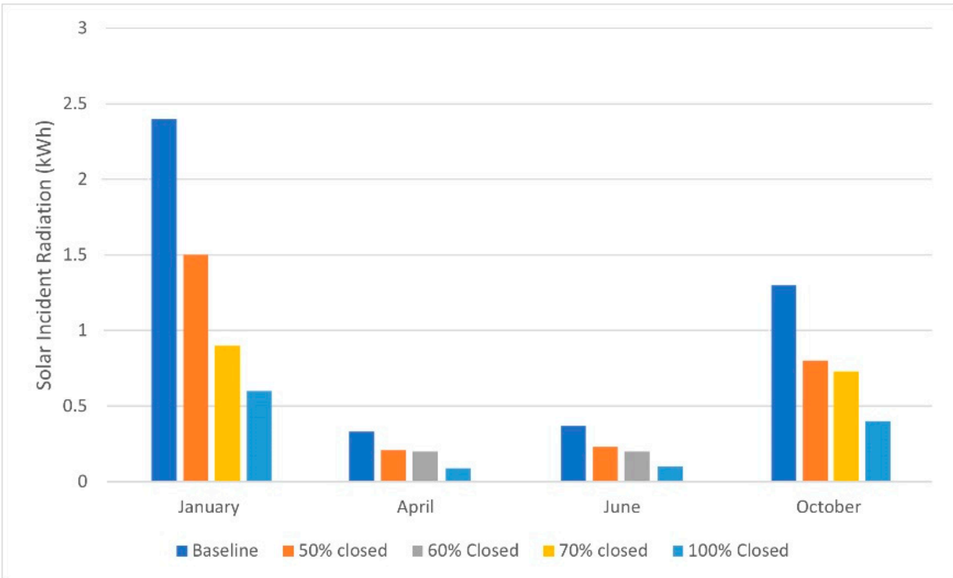


Figure 14. Solar incident radiation impact with different closing angles.

The efficiency of the kinetic façade depends on the closing percentage of the BIPV panels. The current façade has a different closing percentage of the panel during each season, based on the sun's position. The autumn and winter season have closing percentages of 50%, 60%, and 100%, and the spring and summer seasons have closing percentages of 50%, 70%, and 100%. The efficiency of the kinetic BIPV panels is based on the closing percentage, with higher closing percentages showing a greater for reducing the energy consumption in the building. During the daytime in the summer season, the indoor surface temperature of the BIPV window was 1 °C lower than that of normal windows due to its lower SHGC. In contrast, during the nighttime in the winter season, the indoor surface temperature of the BIPV window was approximately 2 °C higher than that of normal windows due to its better thermal insulation effect [25]. On the other hand, the energy can be generated using photovoltaic panels when the solar irradiation is higher. Therefore, this strategy has the potential to improve the energy performance of the building. Furthermore, it has been identified that kinetic BIPV façades could play an essential role as daylit solar screens as well as sun protection devices when both daylight and solar gain are taken into design consideration. Therefore, this investigation provides various contributions to the industry. One of the major contributions of this investigation was the implementation of both kinetic and BIPV panels together to provide energy reduction and energy generation.

Parametric design accommodates the dynamic coordination of cross-disciplinary intelligence delivered across a variety of analytical tools and techniques [26]. The performance and benefits of the kinetic PV façade were demonstrated through the institutional building, which can raise public awareness about the benefits of these systems. According to the energy consumption results for different building design scenarios, kinetic BIPV façades indicated a significant reduction in total energy use. There were a few limitations and technical difficulties faced during this study and, therefore, the investigation was carried out based on a few assumptions. The energy generated from the PV panels and solar exposure on each façade was calculated for three time periods: 8 a.m. to 12 p.m. for the morning; 12 p.m. to 4 p.m. for noon; and 4 p.m. to 6 p.m. for the evening. The percentage of the opening of the kinetic PV panels has been used as the method to determine the energy performance of the building. The energy consumption and energy generation using the kinetic PV panels were calculated for a single day in each season and assumed to be the same for every day in each season. Thus, all the results were calculated per day and then multiplied for all the months to evaluate the overall energy consumption and generation annually. Microclimate change caused by photovoltaic modules was a significant concern for nearby residents [27]. The panel's temperature increases because of the heating caused by the infrared component of solar irradiation. This is referred to as the heat island effect, and it is comparable to the problems associated with any other dark surface that receives solar radiation [28]. This can be reduced by providing additional ventilation to the PV, which improves electrical performance. Furthermore, it is reported that in summer, solar panels reduce the energy needed for air-conditioning (by 12%), and the Urban Heat Island (UHI) by up to 0.2 K by day and up to 0.3 K at night [29]. The embodied carbon emissions due to kinetic BIPV façades are higher than that of static façades due to the added control system. However, when considering the multi-functionality aspect of the kinetic façades, i.e., savings of energy demand and reduction of carbon dioxide emissions through electricity generation, these benefits can offset the drawbacks [19]. Finally, although the kinetic façade with BIPV panels improves the building's performance, it is important to make sure that the selected BIPV product is designed for easy maintenance and operates without any potential safety issues.

5. Conclusions

This paper evaluates the energy and daylighting performance of an Australian commercial building, addressing the nation's unique climate challenges and high energy demands. It explores the use of kinetic BIPV façades, which dynamically adjust to optimize energy efficiency and occupant comfort by reducing heat gain and enhancing natural light. The significance of this research lies in its innovative focus on kinetic BIPV façades, addressing energy efficiency, daylighting, and comfort levels in tandem—a combination not explored in past studies. This is particularly relevant for Australia, a region with high solar potential. The study's findings demonstrate that the implementation of a kinetic building-integrated photovoltaic (BIPV) façade as a retrofit on an existing building in Melbourne, Australia, leads to measurable improvement in energy performance, achieving an 18% reduction in total energy consumption. The façade, designed to respond dynamically to seasonal solar exposure, plays a dual role: in reduces heat gain during summer and allows passive heating during winter. It effectively covers up to 26% of the building's energy demand by generating renewable energy while controlling daylighting, enhancing occupant comfort, and reducing reliance on artificial lighting. To substantiate these findings, detailed energy performance simulations were conducted across various scenarios, with kinetic BIPV panels set at different closing angles depending on seasonal solar positions. For example, the closing percentages for autumn and winter ranged from 50% to 100%, while those for spring and summer ranged from 50% to 70%. The panels showed higher energy-saving potential at greater closing percentages. Data also indicated that, during the summer, the indoor surface temperature behind the BIPV windows was 1 °C lower than that of normal windows, thanks to the reduced solar heat gain coefficient (SHGC). In winter, the BIPV window surface temperatures were approximately 2 °C higher than those of normal windows, due to better thermal insulation, leading to a reduction in heating loads. These outcomes reinforce the potential of kinetic BIPV systems to enhance building energy efficiency while maintaining occupant comfort. The design's ability to block excessive solar radiation during the summer and permit sunlight during winter illustrates its role in passive climate control, effectively reducing the building's reliance on active HVAC systems. However, it is crucial to acknowledge that solar exposure still enters the building through other parts of the façade, particularly in the mornings during winter, reducing the overall façade efficiency. This highlights a key area for future research to further optimize the kinetic design to enhance energy savings. Furthermore, the kinetic BIPV façade functions as both a daylighting device and a shading system, making it a multifunctional façade element. This adaptability, combined with energy generation, positions kinetic BIPV façades as a significant innovation in sustainable building technologies. The parametric design approach used in this investigation allowed for dynamic coordination of cross-disciplinary insights, leading to optimized building performance. The ability of the kinetic BIPV system to reduce energy demand and generate electricity simultaneously demonstrates the practical benefits of integrating kinetic elements into BIPV façades.

Several challenges remain in the commercial uptake of kinetic BIPV façades. High initial costs, maintenance requirements, disproportionate payback periods, and concerns about long-term durability are critical issues. Although kinetic façades may initially seem costlier than conventional static façades, the additional expense can be offset by the energy generated over the lifespan of the system. In commercial buildings, this payback period may be lower or even negative when energy production profits are factored in. The study also touched on the microclimatic impacts of BIPV systems, such as the heat island effect. Photovoltaic panels can increase surface temperatures due to infrared absorption, although this effect can be mitigated with adequate ventilation. On the positive side, BIPV systems have been found to reduce air-conditioning energy demand by 12% during summer, helping to alleviate urban heat island (UHI) effects by up to 0.3 °C at night. These considerations further demonstrate the broad environmental benefits of BIPV systems beyond individual building performance. Finally, while kinetic BIPV façades significantly enhance energy performance and sustainability, future research must address several areas. First, there is a need for detailed economic analyses that consider long-term maintenance costs and potential energy savings across different climates and building typologies. Second, further investigations are required to explore the impact of kinetic BIPV façades in various urban contexts, especially concerning glare in outdoor environments and near transportation infrastructure. Third, as the embodied carbon emissions of kinetic façades are higher due to the added control systems, life cycle assessments (LCA) should be conducted to balance the benefits of energy savings and carbon reduction from electricity generation against the initial environmental costs. Furthermore, future research could extend to more complex simulations, including all façades and internal spaces, to better understand the overall lighting dynamics within the building. This study provides valuable insights into the benefits of kinetic BIPV façades, reinforcing their potential to improve energy performance, contribute to renewable energy generation, and enhance daylighting in commercial buildings. The integration of dynamic design approaches such as kinetic façades into the broader field of sustainable building technologies represents a critical step forward in reducing energy demand and carbon emissions in the built environment.

Author Contributions: Conceptualization, R.J.Y.; Methodology, S.D.S.J. and C.L.; Validation, S.D.S.J. and C.L.; Formal analysis, S.D.S.J.; Resources, R.J.Y.; Writing—original draft, S.T.I.; Writing—review & editing, S.D.S.J., S.T.I., S.Y., M.M., P.S.C., A.F.B. and N.W.; Visualization, S.T.I.; Supervision, R.J.Y. and M.M.; Project administration, R.J.Y. 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: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: Author Siliang Yang was employed by the company Mott MacDonald. Authors Max Marschall, Pablo Sepulveda Corradini, Adolfo Fernandez Benito and Nick Williams were employed by the company Aurecon Group Pty Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. United Nations Environment Programme. *Global Status Report for Buildings and Construction*; United Nations Environment Programme: Nairobi, Kenya, 2020. Available online: http://globalabc.org/ (accessed on 30 July 2024).
2. Henemann, A. BIPV: Built-in solar energy. *Renew. Energy Focus* **2008**, *9*, 14–19. [CrossRef]
3. Hwang, T.; Kang, S.; Kim, J.T. Optimization of the building integrated photovoltaic system in office buildings—Focus on the orientation, inclined angle and installed area. *Energy Build.* **2012**, *46*, 92–104. [CrossRef]
4. Nagy, Z.; Svetozarevic, B.; Jayathissa, P.; Begle, M.; Hofer, J.; Lydon, G.; Willmann, A.; Schlueter, A. The adaptive solar facade: From concept to prototypes. *Front. Archit. Res.* **2016**, *5*, 143–156. [CrossRef]
5. Aries, M.B.; Newsham, G.R. Effect of daylight saving time on lighting energy use: A literature review. *Energy Policy* **2008**, *36*, 1858–1866. [CrossRef]
6. Cort, K.A.; Dirks, J.A.; Hostick, D.J.; Elliott, D.B. Analyzing the Life Cycle Energy Savings of DOE-Supported Buildings Technologies. 2009. Available online: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-18658.pdf (accessed on 30 July 2024).
7. IEA. *Light's Labour's Lost*; IEA: Paris, France, 2006.
8. Bui, D.-K.; Nguyen, T.N.; Ghazlan, A.; Ngo, N.-T.; Ngo, T.D. Enhancing building energy efficiency by adaptive façade: A computational optimization approach. *Appl. Energy* **2020**, *265*, 114797. [CrossRef]
9. Aelenei, D.; Aelenei, L.; Vieira, C.P. Adaptive Façade: Concept, applications, research questions. *Energy Procedia* **2016**, *91*, 269–275. [CrossRef]
10. Pesenti, M.; Masera, G.; Fiorito, F.; Sauchelli, M. Kinetic solar skin: A responsive folding technique. *Energy Procedia* **2015**, *70*, 661–672. [CrossRef]
11. Somboonwit, N.; Boontore, A.; Rugwongwan, Y. Obstacles to the automation of building performance simulation: Adaptive building integrated photovoltaic (BIPV) design. In Proceedings of the 5th AMER International Conference on Quality of Life, Bangkok, Thailand, 28–30 April 2023. Available online: https://doi.org/10.21834/e-bpj.v2i5 (accessed on 30 July 2024).
12. Peng, C.; Huang, Y.; Wu, Z. Building-integrated photovoltaics (BIPV) in architectural design in China. *Energy Build.* **2011**, *43*, 3592–3598. [CrossRef]
13. Salah, F.; Kayili, M.T. Responsive kinetic façade strategy and determination of the effect on solar heat gain using parametric bim-based energy simulation. *J. Green Build.* **2022**, *17*, 71–88. [CrossRef]
14. Koukelli, C.; Prieto, A.; Asut, S. Kinetic Solar Envelope: Performance Assessment of a Shape Memory Alloy-Based Autoreactive Façade System for Urban Heat Island Mitigation in Athens, Greece. *Appl. Sci.* **2021**, *12*, 82. [CrossRef]
15. Karaseva, L.; Cherchaga, O. Conceptual Designs of Kinetic Facade Systems. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1079*, 042053. [CrossRef]
16. Bacha, C.B.; Bourbia, F. Effect of kinetic facades on energy efficiency in office buildings-hot dry climates. In Proceedings of the 11th Conference on Advanced Building Skins, Bern, Switzerland, 11 October 2016; pp. 458–468.
17. Tabadkani, A.; Shoubi, M.V.; Soflaei, F.; Banihashemi, S. Integrated parametric design of adaptive facades for user's visual comfort. *Autom. Constr.* **2019**, *106*, 102857. [CrossRef]
18. Tabadkani, A.; Banihashemi, S.; Hosseini, M.R. Daylighting and visual comfort of oriental sun responsive skins: A parametric analysis. In Proceedings of the Building Simulation 2023: 18th Conference of IBPSA, Shanghai, China, 4–6 September 2023; pp. 663–676.
19. Jayathissa, P.; Jansen, M.; Heeren, N.; Nagy, Z.; Schlueter, A. Life cycle assessment of dynamic building integrated photovoltaics. *Sol. Energy Mater. Sol. Cells* **2016**, *156*, 75–82. [CrossRef]
20. Jayathissa, P.; Schmidli, J.; Hofer, J.; Schlueter, A. Energy performance of PV modules as adaptive building shading systems. In Proceedings of the European Photovoltaic Solar Energy Conference (EU PVSEC), Munich, Germany, 20–24 June 2016; pp. 2513–2517.
21. Kensek, K.; Hansanuwat, R. Environment control systems for sustainable design: A methodology for testing, simulating and comparing kinetic facade systems. *J. Creat. Sustain. Archit. Built Environ.* **2011**, *1*, 27–46.
22. Board, A.B.C. National Construction Code. 2019. Available online: https://ncc.abcb.gov.au/ (accessed on 30 July 2024).

23. 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. [CrossRef]
24. Loonen, R.C.; Trčka, M.; Cóstola, D.; Hensen, J.L. Climate adaptive building shells: State-of-the-art and future challenges. *Renew. Sustain. Energy Rev.* **2013**, *25*, 483–493. [CrossRef]
25. Chow, T.-t.; Li, C.; Lin, Z. Innovative solar windows for cooling-demand climate. *Sol. Energy Mater. Sol. Cells* **2010**, *94*, 212–220. [CrossRef]
26. Vanucci, M. Open systems: Approaching novel parametric domains. In *From Control to Design: Parametric/Algorithmic Architecture*; Actar Publishers: Barcelona, Spain, 2008.
27. Chiabrando, R.; Fabrizio, E.; Garnero, G. The territorial and landscape impacts of photovoltaic systems: Definition of impacts and assessment of the glare risk. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2441–2451. [CrossRef]
28. Barron-Gafford, G.A.; Minor, R.L.; Allen, N.A.; Cronin, A.D.; Brooks, A.E.; Pavao-Zuckerman, M.A. The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Sci. Rep.* **2016**, *6*, 35070. [CrossRef] [PubMed]
29. Masson, V.; Bonhomme, M.; Salagnac, J.-L.; Briottet, X.; Lemonsu, A. Solar panels reduce both global warming and urban heat island. *Front. Environ. Sci.* **2014**, *2*, 14. [CrossRef]