

TECHNO-ECONOMIC ASSESSMENT OF INTEGRATED DYNAMIC PHOTOVOLTAIC ON BUILDING FAÇADE IN HOT CLIMATE

BY

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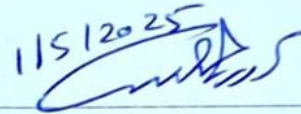
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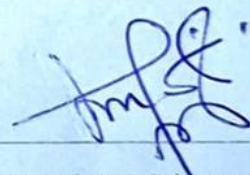


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[This research is dedicated to Almighty Allah.]

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ABSTRACT

Full Name : [Ajibade Yusuff Adelabu]
Thesis Title : [Techno-Economic Assessment of Integrated Dynamic Photovoltaic on Building Façade in Hot Climate]
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This research presents a comprehensive techno-economic assessment of integrated dynamic photovoltaic systems into the building façades in hot climate, using a high-rise office building in Al-Khobar, Saudi Arabia, as a case study. The research investigates the potential of technology in enhancing solar energy harvesting, improving visual comfort, and how economically feasible it is when integrated into the building envelopes.

A calibrated simulation model of the studied building was developed using DesignBuilder (EnergyPlus). Two dynamic PV configurations- closely installed PV (unspaced) and the moderately spaced PV- were adopted to analyze energy and visual performance, as well as the shading effect. The result revealed that the unspaced PV system generates approximately 1,187,515.35 kWh annually, while the spaced configuration produces 925,281.69 kWh/year. Notably, the integration of the dynamic PV systems led to significant building energy savings, particularly the reduction in the cooling energy demand, achieving approximately 30% savings in annual cooling loads, which is particularly relevant in hot climate where cooling mostly dominates the electricity consumption.

Economically, the systems have proved feasible. The Levelized Cost of Energy (LCOE) for the dynamic façade reduced over time- from 0.648 to 0.244 Sar/kWh (unspaced) and 0.671 to 0.220 Sar/kWh (spaced) over a 30-year span. The Payback Period (PBP) was estimated at 10.8 years and

8.56 years for the unspaced and spaced systems respectively, demonstrating long-term cost savings potential. These figures fall within the global benchmarks for PV systems and illustrate the viability of the proposed technology. While limitations such as PV output reduction during the peak summer period were noted, the study confirms that dynamic PV facades hold a strong potential for achieving energy-efficient, visually comfortable, and economically feasible building designs in hot climates.

ملخص الرسالة

الاسم الكامل: يوسف ديلابو اجيبادي

عنوان الرسالة: تقييم تقني واقتصادي لدمج الأنظمة الكهروضوئية الديناميكية في واجهات المباني في المناخات الحارة

التخصص: الهندسة المعمارية

تاريخ الدرجة العلمية: مايو 2025

تُقدم هذه الدراسة تقييماً تقنياً واقتصادياً شاملاً لإدماج الأنظمة الديناميكية للطاقة الكهروضوئية (PV) في واجهات المباني في المناخات الحارة، باستخدام مبنى مكتبي شاهق في مدينة الخبر، المملكة العربية السعودية، كدراسة حالة. تبحث الدراسة في قدرة هذه التقنية على تعزيز حصاد الطاقة الشمسية، وتحسين الراحة البصرية، ومدى جدواها الاقتصادية عند دمجها في أغلفة المباني.

تم تطوير نموذج محاكاة مضبوط للمبنى قيد الدراسة باستخدام برنامج (DesignBuilder) المعتمد على (EnergyPlus). وقد تم اعتماد تكوينين من الأنظمة الكهروضوئية الديناميكية لتحليل الأداء الطاقوي والبصري بالإضافة إلى تأثير التظليل: النظام الأول هو الألواح المركبة بدون فواصل (Unspaced)، والثاني هو الألواح ذات التباعد المعتدل (Spaced).

أظهرت النتائج أن النظام غير المفصول يولد حوالي 1,187,515.35 كيلوواط ساعة سنوياً، بينما يولد النظام المفصول حوالي 925,281.69 كيلوواط ساعة سنوياً. من الجدير بالذكر أن دمج هذه الأنظمة الكهروضوئية الديناميكية أدى إلى توفير كبير في استهلاك الطاقة داخل المبنى، لا سيما من خلال تقليل الطلب على طاقة التبريد، حيث تم تحقيق توفير يُقارب 30% في الأحمال السنوية للتبريد. وهذا مهم بشكل خاص في المناخات الحارة التي يهيمن فيها التبريد على استهلاك الكهرباء.

من الناحية الاقتصادية، أثبتت الأنظمة جدواها. فقد انخفض متوسط تكلفة الطاقة المنتجة (LCOE) من 0.648 إلى 0.244 ريال/ك.و.س للنظام غير المفصول، ومن 0.671 إلى 0.220 ريال/ك.و.س للنظام المفصول على مدار 30 عاماً. وقد قُدرت فترة الاسترداد (PBP) بـ 10.8 سنوات للنظام غير المفصول و8.56 سنوات للنظام المفصول، مما يُظهر إمكانية تحقيق توفير مالي كبير على المدى الطويل.

تتدرج هذه الأرقام ضمن المعايير العالمية لأنظمة الطاقة الشمسية، وتُظهر جدوى التكنولوجيا المقترحة. وعلى الرغم من بعض القيود مثل انخفاض إنتاج الكهرباء من الألواح الشمسية خلال ذروة الصيف، تؤكد الدراسة أن واجهات المباني الديناميكية المزودة بأنظمة PV تُعد خياراً واعداً لتحقيق تصميمات مباني موفرة للطاقة، مريحة بصرياً، وجدوى اقتصادية عالية في المناخات الحارة.

CHAPTER 1

INTRODUCTION

1.1 Background

Increase in energy demand has been one of the threatening global challenges for decades, this concern has even become a nightmare to most nations. The combination of rapid population growth, urbanization, economic development, sophistication in technologies, industrialization and climatic factors has led to an unprecedented rise in energy consumption and demand, reshaping energy landscape, hence necessitating comprehensive research endeavors (Jones, 1991). The escalation of energy demand in Saudi Arabia and other hot climate regions represents a critical aspect of global energy dynamics, with severe implications for economic development, environmental sustainability, and climate change mitigation efforts (Alarenan et al., 2020; Bayomi & Fernandez, 2018). Understanding the underlying factors driving this increase is essential for crafting effective policies and strategies to manage energy consumption sustainably in these regions.

Saudi Arabia, as one of the leading global energy producers, has historically relied heavily on fossil fuels, particularly oil, to meet its domestic energy needs (Aldhubaib, 2022). However, rapid economic growth, spurred by the country's vast oil reserves, has led to a significant rise in energy demand across various sectors. The expansion of industries such as petrochemicals, manufacturing, and construction, coupled with population growth and urbanization, has contributed to the surge in energy consumption.

Moreover, Saudi Arabia's hot desert climate intensifies energy demand, particularly for cooling purposes. The temperatures often soar above 40°C during the summer months, the demand for air conditioning and cooling systems has skyrocketed, placing additional strain on the country's energy infrastructure (AlHashmi et al., 2021). The escalating global demand for energy, coupled with the imperative to moderate climate change, has prompted an intensified exploration of renewable energy sources. Among these, solar energy holds immense promise, particularly in regions characterized by abundant sunlight. Solar photovoltaic power plants can shave peak electricity demand in desert climates, such as Saudi Arabia, between 2:00-5:30 PM during summers (Alanezi & Naraghi, 2018). However, harnessing solar power efficiently remains a challenge, especially in hot climates where the demand for cooling is high and traditional photovoltaic (PV) systems may face limitations in performance and architectural integration.

In recent years, building-integrated photovoltaics (BIPV) have emerged as a promising avenue for maximizing solar energy harvesting while simultaneously enhancing architectural aesthetics and functionality. The building and construction sector accounted for 36% and 37% of the global energy demand and energy-related CO₂ emissions in 2020, respectively (X. Zhang et al., 2018). This issue is particularly pronounced in high-rise buildings with substantially glazed facades, which are recognized as the least energy-efficient building components (Zhou et al., 2023; Skandalos et al., 2022). Similarly, because electricity contributes significantly to energy needs, the U.S. Energy Information Administration (EIA, 2024) concurred that addressing power consumption in the building sectors is crucial for achieving energy-efficient structures. For example, the U.S. commercial building sector accounts for 34% of the electricity demand. Furthermore, it is projected that the need for electricity in buildings would increase until cutting-edge energy-efficient technology, including renewable energy systems, can be incorporated into the design phase of a

building (Torcellini et al., 2006). As a result, installing PV systems in buildings ought to be given greater priority. Building-attached photovoltaic (BAPV) and building integrated photovoltaic (BIPV) are the two common methods that PV systems are used in buildings BAPV systems are a type of PV system that has its module placed on the building top such as building roof or the rooftop places or the combination of the two. It can only be installed for power generation without acting as a building secondary material. On the other hand, BIPV systems have multiple functional advantages because they serve as building subsidiary elements and also as a power generator on-site. Contrast to BAPV, BIPV is also more appropriate for buildings, as they are considered to have achieved aesthetically high social acceptance in building designs (Shukla et al., 2017). Glazed facades, prevalent in contemporary building design for their visual appeal and daylighting benefits, offer a prime opportunity for integrating PV technologies into the built environment. By transforming building envelopes into active energy-harvesting surfaces, BIPV systems can contribute significantly to reducing reliance on conventional energy sources and mitigating the environmental impact of buildings.

However, existing BIPV solutions often exhibit shortcomings when deployed in hot climates. Traditional PV installations, typically mounted on roofs or ground-mounted arrays, may suffer from reduced efficiency due to high temperatures and limited airflow (Radwan et al., 2023). Moreover, the architectural integration of PV modules into glazed facades can pose challenges in terms of aesthetics, structural integrity, and thermal performance (Luo et al., 2017). As such, there is a pressing need for innovative approaches to optimize solar energy harvesting in hot climates while addressing these technical and architectural constraints. The concept of dynamic photovoltaic integrated envelopes represents an innovative paradigm in BIPV design, offering the potential to overcome the limitations of traditional PV systems and maximize energy generation in hot climates (Youssef et al., 2015). By integrating dynamic elements that enable the adjustment of orientation

and tilt angle, these systems can optimize solar exposure throughout the day, capturing maximum sunlight while minimizing thermal loads on the building. Moreover, the vertical integration of PV modules within glazed facades enhances architectural compatibility and allows for seamless integration into building designs.

Several research studies have explored various aspects of BIPV technology, including performance analysis, architectural integration, and energy modeling. However, there remains a gap in the literature regarding the enhancement of dynamic PV integrated envelopes specifically designed for glazed facades in hot climates. This gap represents a significant opportunity for research to advance the state-of-the-art in solar energy harvesting technology and architectural integration, creating avenue for more sustainable and energy-efficient building design practices.

1.2 Problem Statement

High-rise buildings with large, glazed facades are among the least energy efficient, contributing significantly to the 36% global energy demand from the construction sector (S. Zhang et al., 2022). Even though the integration of PV systems in building has been widely explored, the conventional PV systems still face some certain limitations – roof-mounted PVs suffer from space constraints, while static PV shading devices waste solar energy and lack adaptability to changing weather conditions. Existing dynamic PVBEs, though promising, are not optimized for high-rise buildings in hot climates, often requiring external wall repositioning, which affects aesthetics and wind resistance. Additionally, their complex mechanical structures and hinge failures reduce long-term reliability. To address these challenges, this research proposes integrating dynamic PV slates as an innovative durable, efficient, and architecturally viable solution for high-rise facades in hot climates, enhancing energy sustainability while addressing mechanical and economic constraints.

1.3 Aim and Objectives

The research aims to overcome the limitations of traditional PV installations and maximize energy generation efficiency while ensuring architectural compatibility. The specific objectives are designed to:

- i. Analyze the energy performance of the dynamic PV integrated into the building façade.
- ii. Assess the impact of the façade integrated PV on the visual performance of the space.
- iii. Assess the economic feasibility of the implemented dynamic façade PV technology.

1.4 Significance of Study

The research shall contribute significantly to academia by advancing knowledge of building-integrated photovoltaics (BIPV) and sustainable architecture, particularly in hot climates. It shall explore the integration of dynamic photovoltaic systems specifically for glazed facades, offering insights into design parameters, material selection, and control strategies. In the industry, this research shall enhance professional practices in architecture, construction, and renewable energy sectors by providing architects and designers with innovative solutions to meet sustainability targets and regulatory standards. It should also drive innovation among manufacturers, facilitating the commercialization of technologies optimized for hot climates and promoting the adoption of sustainable building practices to address global climate challenges.

1.5 Scope and Limitation

The study shall focus on maximizing solar energy harvesting via a dynamic photovoltaic integrated envelope for high-rise glazed office buildings in Saudi Arabia, with a specific focus on the eastern province of the Kingdom represented by Dhahran weather, as a representative city known for its

hot climate. It shall investigate the system's performance, considering factors such as building orientation, PV type, energy generation, consumption patterns, and local environmental conditions. Economic feasibility analysis shall assess initial investment, operational savings, and potential incentives. However, the research's scope shall be limited to hot climates and shall be constrained by the available resources, and time. Despite these limitations, it shall endeavor to provide valuable insights into solar energy optimization through integrated dynamic photovoltaics. |

CHAPTER 2

LITERATURE REVIEW

2.1 Global Energy Consumption and Trend

The global energy landscape is at a critical juncture, characterized by the interplay between rising energy demand, the ongoing reliance on fossil fuels, and the urgent need to transition to more sustainable energy sources. Global energy consumption has always been a central concern for governments, industries, and environmental advocates alike, driven by the increasing demand for energy to fuel economic growth, technological advancement, and population expansion (Lan et al., 2016). As nations strive to balance economic development with environmental sustainability, understanding the trends, patterns, and drivers of global energy consumption becomes imperative. The historical progression of energy use, coupled with emerging trends in energy efficiency, renewable energy adoption, and geopolitical shifts, shapes the current and future landscape of global energy demand (Bollino et al., 2017).

The evolution of global energy consumption reveals a dynamic and complex relationship between human development and energy use. (Ahmad & Zhang, 2020) provide a comprehensive review of comparative global historical energy consumption, emphasizing the shift from traditional biomass to fossil fuels during the Industrial Revolution, which marked a significant turning point in energy consumption patterns. They further explained the rapid industrialization in the 19th and 20th centuries that led to a dramatic increase in energy demand, particularly for coal, oil, and natural gas, as these energy sources powered manufacturing, transportation, and residential sectors across the globe.

This historical trajectory has not been uniformed, as different regions have experienced varying rates of industrialization and energy consumption growth. (Hu et al., 2018) introduce the concept of an "evolution tree" to analyze the global energy consumption structure, highlighting the divergent paths taken by developed and developing nations. They further explained that developed countries that are primarily in the OECD have historically consumed most of the global energy due to their early industrialization and higher per capita energy needs. In contrast, developing countries have only recently begun to experience rapid energy consumption growth, driven by economic expansion and urbanization.

In recent decades, global energy consumption has continued to rise, although with significant regional variations and shifts in energy sources. In a study by (Al-Yasiri & Journal, 2021), they explain that while fossil fuels still dominate the global energy mix, there is a growing trend towards diversification, with renewable energy sources such as solar, wind, and hydropower gaining prominence. However, this transition is not uniform across regions, with some countries and regions lagging due to infrastructural, economic, or policy-related challenges.

(Demchyk Savage & Savage, 2023) study the variables that shape per capita energy consumption across OECD countries, identifying factors such as urbanization, fuel prices, and fossil fuel imports as significant determinants. Their analysis reveals that despite advances in energy efficiency and the adoption of renewable energy, fossil fuels remain deeply entrenched in the energy systems of many developed countries. The persistence of fossil fuel consumption in these regions signifies the complexity of transitioning to a sustainable energy future, particularly in economies heavily reliant on oil and gas.

2.2 Global Energy Consumption Projections

As the world continues to struggle with the dual challenges of energy security and climate change, future energy consumption patterns are expected to undergo significant transformations. According to (Huang, 2014), the drivers of rising global energy demand are complex, involving spatial, economic, and technological factors. The study further explains that the global energy demand will continue to grow, particularly in non-OECD countries, where rapid economic growth and urbanization are driving up energy needs.

However, this growth is expected to be tempered by increasing energy efficiency and the accelerated adoption of renewable energy technologies. (Gajdzik et al., 2024) explore the impact of the global energy crisis on energy efficiency, noting that the recent surge in energy prices and geopolitical tensions have prompted many countries to enhance their energy efficiency measures. These developments are likely to play a critical role in shaping future global energy consumption patterns, as nations seek to reduce their dependence on fossil fuels and mitigate the impact of energy price volatility.

Additionally, (T. Wang et al., 2023) carried out a comprehensive review of energy consumption in the household sector, explaining the importance of energy efficiency improvements in reducing overall energy demand. Their bibliometric analysis suggests that while energy consumption in households remains a significant contributor to global energy use, there is substantial potential for reducing this through the adoption of energy-efficient appliances, smart grids, and behavioral changes.

Moreover, (T. Wang et al., 2023) study the total-factor energy efficiency of ten major global energy-consuming countries, providing understanding on how these countries are managing their energy

use relative to their economic output. Their findings indicate that while some countries have made significant strides in improving energy efficiency, others continue to struggle with high energy intensity, particularly in the industrial and transportation sectors.

2.3 Energy Consumption in Saudi Arabia

Saudi Arabia, known for its vast reserves of oil and its role as a global energy powerhouse, is also facing growing challenges in rationalizing its domestic energy consumption. The country's rapid economic growth, urbanization, and population increase have led to a significant rise in energy demand, necessitating an in-depth analysis of consumption patterns across various regions and sectors (Rahman et al., 2021).

Approximately, the kingdom generates 453 terawatt-hour of electricity in 2023, with the energy mix comprising 38% oil, 62% natural gas, and less than 1% renewable source. With the substantial 153% annual generation growth in renewable-based electricity, the generation still remains a small fraction with an increment from 1TWh to 3TWh generation as compared to the energy consumption. Total electricity consumption in the kingdom grew by 6% from 372TWh in 2021 to 393TWh in 2022, with a further 5% increase in 2023. This surge in demand has historically led to increased reliance on oil-fired power generation. In June 2024, the monthly burn of fossil fuel reached 1.419 million barrels per day, the highest recorded since 2022 (U.S. Energy Information Administration, 2024). As the Kingdom embarks on its ambitious Vision 2030 plan to diversify its economy and reduce its reliance on fossil fuels, understanding the intricacies of energy consumption within its borders becomes more important.

Saudi Arabia's energy consumption has been on a steep upward trajectory, driven by aforementioned factors. In research by (Aldhubaib, 2022), he mentioned that the Kingdom's energy

consumption is among the highest in the world on a per capita basis, largely due to its heavy reliance on energy-intensive industries such as petrochemicals and aluminum smelting. The energy mix in Saudi Arabia is predominantly fossil-fuel-based, with oil and natural gas accounting for most of the country's energy supply. This reliance on fossil fuels presents both challenges and opportunities as the nation seeks to transition to a more sustainable energy future. In addition to industrial demand, the residential and commercial sectors also contribute significantly to the country's overall energy consumption. (Alrashed & Asif, 2014) note that the residential sector alone consumes a substantial portion of the total electricity produced in Saudi Arabia, driven by the widespread use of air conditioning, lighting, and household appliances. The authors also point out that energy consumption in the residential sector has been growing rapidly, particularly in the Eastern Province, reflecting broader national trends.

The rapid growth in energy consumption poses several challenges for Saudi Arabia, including the strain on its energy infrastructure, the depletion of fossil fuel reserves, and the environmental impact of increased carbon emissions. However, (Aldhubaib, 2022) identifies several opportunities for addressing these challenges, including the development of renewable energy sources such as solar and wind, as well as improvements in energy efficiency across all sectors. The Kingdom's Vision 2030 plan emphasizes the importance of diversifying the energy mix and reducing energy intensity, which could help mitigate the adverse effects of rising energy consumption.

In the effort made by the Kingdom and in line with the 2030 vision, Saudi Arabia aim to explore other energy portfolio by significantly increasing renewable energy capacity. The kingdom has decided and set target to elevate from the current 5GW to 130GW renewable capacity by 2030. Recent development to achieve these objectives include the mega solar project secured by TotalEnergies and EDF renewables in 2024 during the French president's visit to Riyadh.

TotalEnergies aim to develop a 0.3GW solar park in Rabigh Industrial City, which is proposed to be operational by 2026. The partnership of EDF Renewables with China State Power Investment Corporation also aim to develop two solar parks totaling 1.4GW. These projects are part of 25-years power purchase agreements with the Saudi Power Procurement Company (Ministry of Energy, Saudi Arabia, 2024).

2.3.1 Regional Energy Consumption Patterns in Saudi Arabia

Energy consumption patterns in Saudi Arabia vary significantly across different regions, influenced by factors such as population density, climate, and economic activity. (Darandary et al., 2023) provide a detailed analysis of regional fuel consumption and carbon dioxide emissions, noting that regions with higher levels of industrial activity, such as the Eastern Province, tend to have higher energy consumption rates. This region, which is home to most of the Kingdom's oil and gas industry, also has a higher concentration of energy-intensive industries, further driving up energy demand.

In contrast, regions with less industrial activity, such as the central and northern parts of the country, tend to have lower energy consumption levels. However, these areas are still significant contributors to overall energy demand due to the high energy consumption in the residential sector, particularly in urban centers like Riyadh. In correlation, (Mikayilov & Al Yamani, 2023.) highlight the implications of Riyadh's rapidly growing population on electricity demand, noting that the city's energy needs are expected to increase substantially in the coming years as its population continues to surge.

Recent electricity price reforms in Saudi Arabia have also had a significant impact on regional energy consumption patterns. (Darandary et al., 2023) discuss how the gradual removal of energy subsidies and the introduction of higher electricity tariffs have led to a reduction in energy

consumption in some regions. These reforms are part of the government's broader efforts to encourage more efficient energy use and reduce the financial burden of energy subsidies on the national budget. However, the impact of these reforms has not been uniformed across all regions. In areas where income levels are lower, the higher electricity prices have led to a more significant reduction in energy consumption, while wealthier regions have been less affected. This regional disparity stresses the need for targeted policies that consider the varying economic conditions and energy needs of different regions within the Kingdom.

2.3.2 Energy Demand by Building Types in Saudi Arabia

Saudi Arabia's energy consumption patterns are characterized by regional variations and significant contributions from the residential, commercial, and industrial sectors. As the Kingdom continues to grow and develop, managing this energy demand will be crucial to achieving its Vision 2030 goals. The challenges posed by rising energy consumption, particularly in regions with high industrial activity and urbanization, require targeted policies and investments in energy efficiency and renewable energy. By addressing these challenges, Saudi Arabia can reduce its reliance on fossil fuels, lower its carbon emissions, and ensure a more sustainable energy future for its citizens.

2.3.2.1 Residential Sector

The residential sector is a major contributor to energy demand in Saudi Arabia, accounting for a significant portion of the country's electricity consumption. (Felimban et al., 2019) assess the current energy consumption in residential buildings in Jeddah, one of the largest cities in the Kingdom, highlighting the inefficiencies in building design and energy use. The study reveals that many residential buildings in Saudi Arabia are poorly insulated and rely heavily on-air conditioning to maintain comfortable indoor temperatures, leading to high energy consumption.

(R. A. Almasri et al., 2023) further study the energy consumption in the residential sector, focusing on the Qassim region. The authors evaluated the total exergy and energy consumption in residential buildings, identifying several areas where energy efficiency improvements could be made. These include the adoption of energy-efficient appliances, better insulation, and the use of renewable energy sources such as solar panels. The study stresses the potential for significant energy savings in the residential sector, which could help reduce overall energy demand and lower carbon emissions.

2.3.2.2 Commercial and Industrial Sectors

The commercial and industrial sectors also play a key role in Saudi Arabia's energy consumption landscape. (Gasim, 2020) provides a commentary on industrial energy consumption in the Kingdom, noting that the industrial sector is the largest consumer of energy, particularly in regions with a high concentration of energy-intensive industries. The author's analysis highlights the need for more stringent energy efficiency measures in the industrial sector to reduce energy consumption and improve overall sustainability.

In the commercial sector, energy demand is driven by the need for lighting, cooling, and other building services. (Fahmy et al., 2023) predict that electricity consumption in Saudi Arabia's commercial sector will continue to rise in the coming years, driven by economic growth and the expansion of the services sector. The study suggests that the adoption of energy-efficient technologies and practices, such as smart building systems and energy management, could help alleviate this rise in energy demand.

2.4 Sustainable Energy Solutions to Energy Demand

With continuous rapid economic growth and urbanization, the demand for energy has coursed to unprecedented levels. This increase in energy consumption presents significant challenges, particularly in a country where the energy mix is heavily reliant on fossil fuels. In response to these challenges, Saudi Arabia has recognized the need for sustainable energy solutions that can meet the growing energy demand while reducing the environmental impact.

Saudi Arabia has made significant strides in investing in renewable energy as a sustainable solution to its growing energy demand. (Almulhim et al., 2022) examine the Kingdom's investments in renewable energy, particularly solar and wind, which are abundant resources in the region. The study describes the government's ambitious targets under the Vision 2030 plan, which includes generating 50% of the country's energy from renewable sources by 2030. This shift towards renewable energy is seen as an important step in diversifying the energy mix and reducing the Kingdom's dependence on oil and natural gas.

One of the major renewable energy projects in Saudi Arabia is the development of large-scale solar power plants. According to (Aldhubaib, 2022), the Kingdom's geographic location offers some of the highest solar irradiance levels in the world, making it an ideal location for solar energy generation. The deployment of photovoltaic (PV) systems in both residential and commercial buildings is also gaining traction as part of efforts to sustain energy demand sustainably. These initiatives are expected to significantly reduce the carbon footprint of the energy sector and contribute to the global fight against climate change.

2.5 Renewable Energy Integration with Traditional Energy Sources

The integration of renewable energy with traditional fossil fuel-based energy sources is a crucial aspect of Saudi Arabia's strategy to meet its energy demand sustainably. (Gasim, 2020) discusses the potential for hybrid energy systems that combine renewable energy with natural gas, which is abundant in Saudi Arabia. These hybrid systems can provide a more reliable and stable energy supply by compensating for the intermittent nature of renewable energy sources, such as solar and wind. The integration of these systems can also help to reduce the overall carbon emissions of the energy sector, as the share of renewable energy in the mix increases.

Furthermore, (R. A. Almasri et al., 2023) additionally discussed the concept of exergy analysis in the residential sector, highlighting the potential for integrating renewable energy sources with traditional energy systems to improve overall energy efficiency. The study suggests that by optimizing the use of both renewable and non-renewable energy sources, Saudi Arabia can achieve a more sustainable energy future while meeting the growing demand for electricity.

2.5.1 Energy Efficiency Measures

Improving energy efficiency is another key strategy for addressing energy demand in Saudi Arabia. As discussed by (Alrashed & Asif, 2014), the residential sector as well as office buildings are major consumer of electricity, primarily due to the high usage of air conditioning and other energy-intensive appliances. To mitigate this, the government has implemented various energy efficiency measures, such as building codes that require better insulation and the adoption of energy-efficient appliances. These measures are designed to reduce energy consumption without compromising the comfort and quality of life of residents.

(Felimban et al., 2019) emphasize the importance of retrofitting existing buildings to improve energy efficiency. Many residential and commercial buildings in Saudi Arabia are poorly insulated and lack energy-efficient design features, leading to excessive energy consumption. Retrofitting these buildings with modern insulation materials, energy-efficient windows, and HVAC systems can result in substantial energy savings. Additionally, the implementation of smart grid technologies can further enhance energy efficiency by optimizing the distribution and consumption of electricity.

To achieve the efficiency objectives, bodies such as Saudi Energy Center (SEEC) and the National Energy Service Company (Tarshid) are pivotal in advancing energy efficiency initiatives within the kingdom, which strongly align with the nation's 2030 vision. The primary objective of SEEC is to enhance energy production and consumption efficiency across the kingdom. The body developed a licensing system for energy efficiency service providers, to ensure the quality and reliability of the service offered. It developed a comprehensive guideline to standardize the assessment of energy efficiency projects (Saudi Energy Efficiency Center (SEEC), 2025). Similarly, the National Energy Service Company (Tarshid) owned by the Public Investment Fund, is mandated to develop, fund and manage energy efficiency projects, particularly in public buildings and facilities. It collaborates with various medical institutions to enhance energy efficiency. For instance, the retrofitting project at King Abdullah Medical City in Makkah targeted 16 facilities, aiming for an estimated annual energy savings of 23%. It also collaborates with important entities like the Saudi Standards, Metrology and Quality Organization (SASO), and the Ministry of Municipal, Rural Affairs and Housing (MOMRAH) to implement energy-saving measures (Public Investment Fund (PIF), 2022).

2.5.2 Policy and Regulatory Frameworks

The successful implementation of sustainable energy solutions in Saudi Arabia requires a supportive policy and regulatory framework. (Fahmy et al., 2023) discuss the importance of government policies in promoting the adoption of renewable energy and energy efficiency measures. The Vision 2030 plan includes several policy initiatives aimed at encouraging investment in renewable energy, such as subsidies, tax incentives, and feed-in tariffs for solar and wind energy. These policies are designed to create a favorable environment for the growth of the renewable energy sector and to ensure that sustainable energy solutions are widely adopted across the country.

(Darandary et al., 2023) described the impact of electricity price reforms on energy consumption patterns in Saudi Arabia. The gradual removal of energy subsidies and the introduction of higher electricity tariffs have incentivized consumers to adopt more energy-efficient practices and technologies. These reforms are part of the government's broader strategy to reduce the financial burden of energy subsidies and to promote the efficient use of energy resources. By aligning energy prices with the true cost of production, the government aims to encourage more sustainable energy consumption behaviors.

2.6 Renewable Energy and Solar Potential

The Kingdom has identified renewable energy as a key component of its Vision 2030 plan, which aims to create a sustainable and resilient economy. Saudi Arabia is endowed with vast solar energy potential due to its geographic location, which receives some of the highest levels of solar irradiance in the world. According to (Tlili, 2015), the country has the potential to generate over 7,000 terawatt-hours (TWh) of solar energy annually, far exceeding its current energy consumption. The Kingdom's solar energy strategy primarily focuses on the development of large-scale photovoltaic (PV) and concentrated solar power (CSP) plants. These projects are expected to play a key role in

meeting the growing domestic energy demand and in supporting the Kingdom's transition to a low-carbon economy.

(Imam et al., 2024) study the land suitability and techno-socio-economic feasibility of solar PV installations in Saudi Arabia. The study indicates that vast areas of the country, particularly in the central and western regions, are highly suitable for solar energy generation. The government's commitment to solar energy is further evidenced by its ambitious targets, which include generating 40 GW of solar power by 2030. This expansion is expected to not only meet domestic energy needs but also position Saudi Arabia as a leading exporter of solar energy in the region.

Wind energy is another promising renewable energy source in Saudi Arabia, particularly in regions with favorable wind conditions such as the Red Sea coast and the northeastern areas of the country. (Hassan et al., 2024) assess the potential of wind energy in Saudi Arabia, noting that the country has several high-wind zones that are ideal for large-scale wind farms. The study stresses the importance of integrating wind energy into the national grid to complement solar power and provide a more balanced and reliable energy mix. Despite its potential, the development of wind energy in Saudi Arabia faces several challenges, including the need for significant infrastructure investment and the variability of wind patterns, hence, this makes solar energy the most promising.

In addition to solar and wind energy, the kingdom is exploring other emerging renewable energy technologies, such as green hydrogen and geothermal energy. According to (Al-Gahtani, 2024), green hydrogen is seen as a potential game-changer for the Kingdom's energy sector, given its ability to store and transport energy efficiently. Although the development of green hydrogen projects is still in its early stages, the government has expressed strong interest in this technology as part of its broader strategy to achieve net-zero carbon emissions by 2060.

2.6.1 Solar Energy Potential in Saudi Arabia

Saudi Arabia's geographical location offers a significant potential for harnessing solar energy. Situated in the Sun Belt, the country experiences high solar irradiance, making it one of the most promising regions for solar energy utilization globally. The Kingdom receives an average solar irradiance of approximately 2200 kWh/m² annually, which is among the highest in the world (Al-Ghamdi & A. Alshaibani, 2018). This high level of solar exposure provides a robust foundation for large-scale solar energy projects. The vast deserts of Saudi Arabia provide an ideal setting for solar energy installations. These areas offer large expanses of uninhabited land with minimal environmental constraints, which are crucial for establishing solar farms. As shown in Figure 1, the country's solar radiation map highlights the high potential across most regions, with particularly strong irradiance in the central and western parts of the Kingdom (AlYahya & Irfan, 2016; Alyahya & Irfan, 2016). The development of solar energy in these regions could significantly reduce the reliance on fossil fuels, aligning with Saudi Arabia's Vision 2030 goals for sustainability and economic diversification.

PHOTOVOLTAIC POWER POTENTIAL SAUDI ARABIA

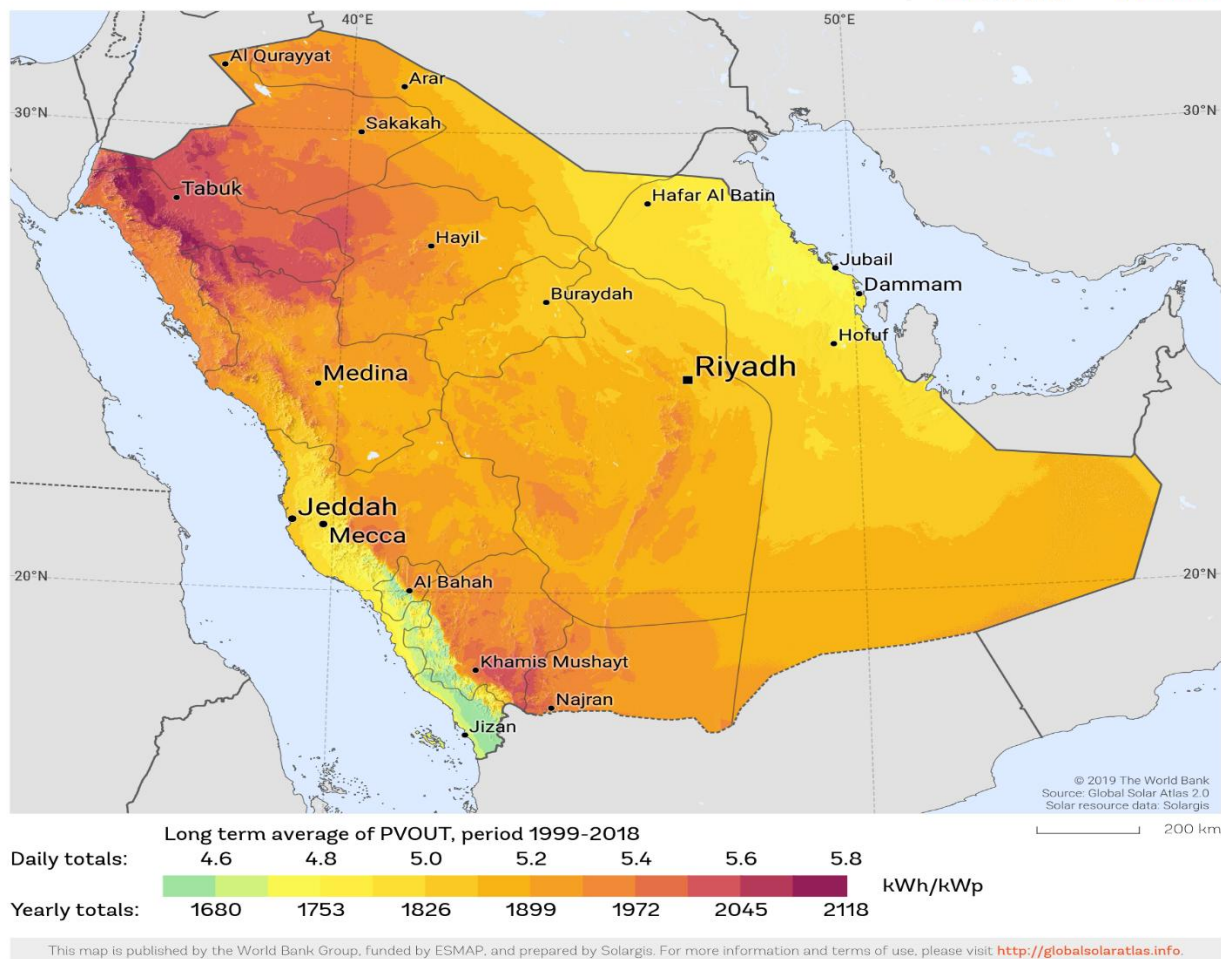


Figure 1 Saudi Arabia geographical locations showcasing photovoltaic power potentials (Global Solar Atlas, 2019)

Advancements in photovoltaic (PV) technology have further enhanced the feasibility of solar energy in Saudi Arabia. Research indicates that the efficiency of PV systems can reach up to 22% in optimal conditions within the Kingdom (Imam et al., 2024). Additionally, the development of Concentrated Solar Power (CSP) systems, which are particularly effective in regions with high direct normal irradiance (DNI), presents another viable option for large-scale solar energy production (Almasoud & Gandayh, 2015). The integration of CSP and PV technologies could offer

a hybrid solution that maximizes energy generation and efficiency. The economic benefits of solar energy development in Saudi Arabia are substantial. Solar energy provides an opportunity to diversify the economy, reduce dependence on oil exports, and create new jobs in the renewable energy sector. The implementation of solar energy projects is also expected to lower carbon emissions significantly, contributing to global efforts to combat climate change (L. Zhang et al., 2022). Studies have shown that widespread adoption of solar energy could reduce the Kingdom's greenhouse gas emissions by up to 50 million tons annually (Rashid et al., 2023).

Moreover, the cost of solar energy has been declining globally, making it a more attractive investment. In Saudi Arabia, the cost of solar energy production is expected to decrease further as the technology matures and economies of scale are realized (Salam & Khan, 2018). This trend aligns with global projections where solar energy is anticipated to become one of the most cost-effective sources of electricity.

2.7 Photovoltaic (PV) Technology and Integration

Photovoltaic (PV) technology has undergone significant evolution since its inception, driven by the need for sustainable and renewable energy sources. The initial development of PV cells in the 1950s laid the foundation for modern solar energy technology, which has since experienced rapid advancements. Key milestones include the introduction of silicon-based cells, the development of thin-film technology, and the emergence of multi-junction cells, which have significantly improved the efficiency and cost-effectiveness of solar panels (Li, 2023)

Recent technological advancements have focused on enhancing the efficiency of PV systems, reducing production costs, and increasing their adaptability to various environmental conditions. For instance, the development of perovskite solar cells has shown promise in achieving higher

efficiencies compared to traditional silicon-based cells, with the potential for lower manufacturing costs (Panagoda et al., 2023). Additionally, innovations in materials and manufacturing processes, such as the use of nanotechnology and advanced coatings, have further improved the performance and durability of PV systems (Dada & Popoola, 2023)

2.7.1 Types of Photovoltaic Systems (control): Fixed vs. Dynamic

PV systems can be broadly categorized into two types based on their control mechanisms: fixed and dynamic. Fixed PV systems are stationary and typically mounted at a fixed angle, optimized for maximum solar exposure during peak sunlight hours. These systems are simpler and less expensive to install and maintain but may not capture sunlight as efficiently throughout the day, especially in regions with significant seasonal variation in the sun's path (Li, 2023)

Dynamic PV systems, on the other hand, are equipped with tracking mechanisms that allow the solar panels to follow the sun's movement across the sky. These systems can be single-axis or dual-axis trackers, depending on the degree of movement they offer. Dynamic PV systems can capture more sunlight and generate more electricity compared to fixed systems, making them more efficient. Although, they are also more complex and costly to install and maintain due to the additional mechanical components required (Panagoda et al., 2023).

2.7.2 Building Integrated Photovoltaics (BIPV)

Building Integrated Photovoltaics (BIPV) represents a significant innovation in the field of solar energy, where PV materials are integrated into the building envelope, such as roofs, facades, and windows. The concept of BIPV has been around for several decades, but its adoption has accelerated in recent years due to advancements in PV technology and increasing demand for sustainable building practices (Lazaroiu et al., 2023).

Globally, BIPV has gained traction in both residential and commercial sectors, driven by policies promoting energy efficiency and the development of smart cities. In Europe and North America, BIPV systems have been integrated into a wide range of buildings, from residential homes to large commercial complexes, as part of efforts to reduce carbon emissions and enhance energy self-sufficiency (Elomari et al., 2022). In Saudi Arabia, the adoption of BIPV is also on the rise, with several pilot projects and government initiatives aimed at promoting the integration of solar energy into the built environment (Ali, 2023).

The integration of PV systems into buildings offers several benefits beyond the generation of clean energy. BIPV systems contribute to the aesthetic appeal of buildings by seamlessly integrating solar panels into the architectural design, eliminating the need for separate mounting structures. This integration not only reduces material costs but also enhances the overall energy efficiency of the building by providing additional insulation and shading (K et al., 2018).

Moreover, BIPV systems can significantly reduce energy costs for building owners by generating electricity on-site, reducing reliance on grid-supplied power. This is particularly beneficial in regions with high energy costs or limited access to reliable electricity. Additionally, BIPV systems contribute to the sustainability of buildings by reducing their carbon footprint and supporting the transition to renewable energy sources (Alfaoyzan & Almasri, 2023).

2.7.3 Comparative Analysis of Fixed and Dynamic PV Systems

A comparative analysis of fixed and dynamic PV systems reveals distinct advantages and disadvantages for each type, depending on the application and environmental conditions. Fixed PV systems are generally more cost-effective and easier to install, making them suitable for residential and small-scale commercial applications where budget constraints are a primary concern (Alharthi

& Alamoud, 2023). However, their efficiency can be limited by their inability to capture sunlight optimally throughout the day.

Dynamic PV systems, with their ability to track the sun's movement, offer higher efficiency and energy yield, particularly in regions with significant variations in sunlight exposure throughout the year. Research has shown that dynamic systems can generate up to 25-30% more electricity compared to fixed systems under optimal conditions (Li, 2023). However, the higher installation and maintenance costs associated with dynamic systems may limit their adoption in certain markets, particularly in regions where the cost of solar energy is already a significant barrier (Panagoda et al., 2023). The choice between fixed and dynamic PV systems depends on a variety of factors, including budget, energy needs, control mechanism, and environmental conditions with each type offering distinct advantages. While fixed systems remain a popular choice for many applications due to their simplicity and lower costs, dynamic systems offer higher efficiency, which is the main priority to extensive energy generation and sustainability goal. As PV technology continues to advance, its role in sustainable energy production is likely to expand, particularly in regions like Saudi Arabia, where solar energy is abundant.

2.8 Dynamic Photovoltaic Systems in Building Envelopes

Dynamic PV systems integrated into building envelopes represent a significant advancement in sustainable building design. By combining energy generation with adaptive building features, these systems optimize energy efficiency while contributing to occupant comfort and building aesthetics. It represents a cutting-edge approach in integrating solar energy generation with building design. Unlike traditional fixed PV systems, dynamic PV systems are designed to adapt to changing environmental conditions, such as sunlight intensity and angle of incidence, optimizing energy generation throughout the day and across seasons. The concept involves embedding PV

components within the building envelope, such as façades, roofs, or even windows, with the ability to move or adjust in response to solar exposure, temperature, and other climatic factors (Perino & Serra, 2015).

Several mechanisms and technologies enable the dynamic behavior of these systems. For instance, some dynamic PV systems use motorized tracking devices that adjust the orientation of PV panels to follow the sun's path. Others employ adaptive materials that change their properties in response to external stimuli, such as thermochromic or photochromic materials that alter their transparency or reflectivity based on temperature or light intensity. These systems can also incorporate smart controls, utilizing sensors and algorithms to manage the movement and operation of the PV components in real-time, thereby maximizing energy efficiency while maintaining indoor comfort (Luther, 2000). Another prominent example is the use of "smart façades" in building envelopes, where PV panels can rotate, tilt, or slide to capture maximum sunlight or to provide shading, depending on the building's energy needs and the external environment. These façades can be part of an integrated system that balances solar gain with thermal insulation and daylighting, contributing to both energy generation and energy savings (Goia et al., 2010).

Case studies from around the world demonstrate the effectiveness of dynamic PV systems in various climatic conditions, showcasing their potential to transform the energy performance of modern buildings. Dynamic PV systems have been increasingly implemented in various buildings worldwide, serving as pilot projects or part of sustainable building initiatives. One notable case study is the adaptive solar façade installed on a building in Switzerland, which integrates dynamic PV panels into the building's exterior. This system uses a combination of rotating PV panels and advanced control algorithms to optimize solar energy capture while minimizing glare and maintaining indoor comfort. The project demonstrated a significant increase in energy efficiency

compared to static systems, as well as improved occupant comfort through automated shading (B. Svetozarevic et al., 2019).

Another example is a high-rise building in China that incorporates a dynamic and vertical PV-integrated building envelope. This system is designed specifically for glazed façades, which are common in modern urban architecture. The PV panels in this system can adjust their angle to optimize solar energy capture and reduce the cooling load by providing shading. The case study described the system's potential to contribute significantly to the building's overall energy performance, particularly in high-density urban areas where space for traditional solar installations is limited (Zou et al., 2024).

In Europe, dynamic PV systems have been integrated into building envelopes in various pilot projects, such as the Adaptive Solar Façade (ASF) in Austria. This system combines PV panels with a dynamic shading device, allowing for both energy generation and effective daylight management. The project demonstrated that dynamic systems could significantly enhance the energy performance of buildings, particularly in regions with varying climatic conditions (Rotas et al., 2023).

2.8.1 Energy Performance of Dynamic PV Envelopes

The integration of dynamic PV systems into building envelopes has profound implications for building energy efficiency. By adjusting to real-time environmental conditions, dynamic PV systems can optimize solar energy capture and minimize energy losses, leading to substantial improvements in energy performance. Research has shown that dynamic PV systems can reduce a building's overall energy consumption by up to 30% compared to static systems, primarily by

optimizing solar gain and reducing the need for artificial lighting and heating or cooling (B. Svetozarevic et al., 2019).

One of the key advantages of dynamic PV envelopes is their ability to balance solar energy generation with other aspects of building performance, such as thermal comfort and natural lighting. For instance, in buildings with large-glazed façades, dynamic PV systems can provide shading during peak sunlight hours, reducing the cooling load and thereby enhancing overall energy efficiency. At the same time, these systems can adjust to allow more daylight into the building during less intense sunlight periods, reducing the need for artificial lighting (Bot et al., 2022). Case studies have also shown that dynamic PV systems can contribute to significant energy savings in different climatic zones. For example, in temperate climates, dynamic PV façades have been found to reduce heating demand in winter by optimizing solar gain while minimizing cooling demand in summer through effective shading. In hot climates, these systems can significantly reduce cooling loads, which often constitute most of a building's energy consumption (Rotas et al., 2023).

Furthermore, dynamic PV systems enhance the overall sustainability of buildings by integrating renewable energy generation with energy-saving features. This dual functionality not only reduces the building's carbon footprint but also contributes to achieving near-zero energy building (nZEB) standards, which are increasingly required by building codes and regulations worldwide (G. Wang et al., 2024).

2.9 Energy Performance of Building Integrated PV in Saudi Buildings

The integration of photovoltaic (PV) systems in Saudi Arabian office buildings has gained significant attention due to the region's abundant solar resources and the growing emphasis on

sustainable energy solutions. Office buildings in Saudi Arabia present a prime opportunity for PV integration, primarily due to the high demand for electricity for air conditioning, lighting, and other electrical appliances. Several studies have explored the potential for energy savings and the improvement of energy efficiency through the adoption of PV systems in Saudi office buildings. For instance, (Abdelhafez et al., 2021) and (Abd-ur-Rehman et al., 2018) discuss the potential for PV systems to contribute to net-zero energy buildings, particularly in Hail City and other regions characterized by high solar insolation. Their findings indicate that integrating PV systems with energy-efficient design strategies can significantly reduce the reliance on conventional energy sources.

Moreover, (Alharthi & Alamoud, 2023) highlight the feasibility of utilizing solar PV in corporate buildings in Riyadh. Their study stresses the economic benefits and potential energy savings of PV systems, particularly when integrated with existing energy management systems. This research highlights the importance of location-specific factors, such as solar irradiance and building orientation, in optimizing PV system performance.

Similarly, (Alfaoyzan & Almasri, 2023) investigate the utilization of solar PV systems in educational facilities, aiming for a zero-bill campus. Their research reveals that with proper system design and implementation, educational institutions in Saudi Arabia can achieve significant energy savings, making a compelling case for the broader adoption of PV technologies in other commercial and office buildings across the kingdom.

2.10 Regulatory and Standard Frameworks Guiding PV Integration

Saudi Arabia's Vision 2030 has set ambitious targets for renewable energy, aiming to diversify the country's energy mix and reduce dependence on oil. The National Renewable Energy Program

(NREP), initiated by the Saudi Ministry of Energy aimed at increasing the share of renewable energy with a specific focus on solar energy. The NREP outlines the regulatory frameworks and incentives designed to promote the adoption of renewable energy technologies, including PV systems. Instances of the regulatory frameworks developed include the framework for small-scale solar PV systems initiated in 2020. It governs the connection of small-scale solar PV systems to the national grid, introducing mechanisms like net billing (Ministry of Energy, Saudi Arabia, 2024). Additionally, a broader framework developed is the Renewable Energy Generation for Self-Consumption initiated in 2022. It covers a broader range of renewable technologies facilitating both grid-connected and off-grid systems (Ministry of Energy, Saudi Arabia, 2024).

In resourceful research by (Ali, 2023), he provides a comprehensive overview of the progress made in deploying solar PV energy in Saudi Arabia. He explained the key policies that have facilitated the growth of PV installations, such as feed-in tariffs, tax incentives, and the establishment of special economic zones for renewable energy projects. These policies have created a conducive environment for the propagation of PV systems in both residential and commercial sectors.

Moreover, the study by (Alhashmi et al., 2021) discuss the energy performance assessment frameworks that have been developed to guide PV integration in Saudi Arabia. These frameworks are critical for ensuring that PV systems meet the required standards and contribute effectively to the kingdom's energy efficiency goals. The authors emphasize the need for continuous improvement in these frameworks to accommodate advancements in PV technology and the evolving energy landscape.

2.10.1 Building Codes and Standards for PV Integration in Saudi Arabia

Building codes and standards play a crucial role in the successful integration of PV systems into Saudi Arabian buildings. The Saudi Energy Conservation Code (SECC) is a key regulatory

instrument that sets the minimum energy performance standards for buildings, including provisions for the integration of renewable energy systems such as PV (Saudi Building Code National Committee., 2018).

(R. Almasri, 2021) study the impact of integrating the SECC with solar PV systems in residential buildings. Their study demonstrates that adherence to the SECC can significantly enhance the energy performance of buildings, particularly when combined with PV technologies. The authors recommend further revisions to the SECC to incorporate more stringent requirements for PV integration, particularly in commercial buildings. Additionally, (Saidi et al., 2024) study the modeling, integration, and simulation of a 20 MW photovoltaic power plant within Saudi Arabia's distribution network, considering the Low Voltage Ride Through (LVRT) capability. This research expresses the importance of adhering to technical standards and codes to ensure the stability and reliability of the power grid, particularly as the penetration of PV systems increases.

2.11 Visual Comfort and Shading in PV Integrated Facades

The dual function building integrated systems, which include energy generation and the regulation of indoor environmental quality, make them a critical component in modern building design. One of the key challenges in PV-integrated facades is balancing energy efficiency with visual comfort, particularly in hot climates where solar exposure can lead to excessive daylight, glare, and increased cooling loads (Mesloub et al., 2020). Hence discussing the impact of PV integration on visual comfort, focusing on aspects such as Useful Daylight Illuminance (UDI), Spatial Daylight Autonomy (SDA), and Annual Sunlight Exposure (ASE) is very key and paramount, as these metrics help evaluate how well a space is naturally lit while avoiding issues such as glare and overheating.

Several studies have discussed extensively the impact of PV integration on visual comfort. According to (Biloria et al., 2023), the implementation of real-time adaptive BIPV shading systems enhances visual comfort by optimizing UDI, particularly in hot climates. The study found that these systems could effectively manage daylight levels, ensuring that indoor spaces remain within the ideal UDI range, which reduces reliance on artificial lighting and enhances occupant comfort. In addition, (Mandalaki et al., 2014) discussed the importance of maintaining adequate SDA in PV-integrated buildings. Their research showed that well-designed PV shading devices could ensure that a significant portion of the indoor space receives sufficient daylight throughout the day, thereby reducing the need for artificial lighting. In a review by (Chen et al., 2024), they established the effectiveness of PV-integrated shading systems in reducing glare and enhancing visual comfort in hot climates. These systems are particularly effective in regions like Saudi Arabia, where intense sunlight can lead to significant visual discomfort.

Annual Sunlight Exposure is one of the vital visual comfort metrics that cannot be overlooked, because its excessiveness can be challenging. In a study by (Skandalos & Tywoniak, 2019), they discussed the challenges of managing ASE in buildings with PV facades. They established that excessive ASE could lead to glare and increased cooling loads, which are particularly problematic in hot climates. The research showed that PV-integrated shading systems could manage these issues by controlling the amount of direct sunlight entering the building, thereby enhancing visual comfort while also contributing to energy efficiency. In another study, (Khraisat et al., 2024) explained the potential of kinetic facades to dynamically adjust shading based on solar conditions. Their study mentioned the benefits of such systems in hot climates, where controlling solar gain is essential for maintaining visual comfort. Furthermore, (Zou et al., 2024) introduced a new vertical photovoltaic integrated building envelope designed for high-rise glazed buildings. The study demonstrated that

such systems could significantly reduce glare and improve visual comfort, particularly in environments with high solar exposure.

Based on the several reviews from past studies and facts, research has shown the essence and promising advantages that building integrated photovoltaics hold especially in regions prone to high sunlight such as Saudi Arabia, however, even with the numerous research on advance BIV technologies, there remains a gap in the literature regarding the integration of dynamic PV on envelopes specifically tailored for glazed facades in hot climates. Although many studies might have evaluated the impact of dynamic integrated PV systems, nevertheless, there remains a disadvantage in the workability and performance due to the lack of consideration of the width and the overall weight of the conventional PV adopted, as cited by many studies, which will however have a significant setback and reduction in its lifespan.

This gap represents a significant opportunity for this research to advance in the solar energy harvesting technology and architectural integration, paving the way for more sustainable, durable and energy-efficient building design practices, particularly in hot climates that pose unique challenges and opportunities for maximizing solar energy utilization. The adoption of this dynamic photovoltaic integrated envelope for glazed facades has the potential to significantly contribute to energy efficiency, environmental sustainability, and the advancement of green building practices.

CHAPTER 3

METHODOLOGY

The research methodology for enhancing solar energy harvesting through dynamic photovoltaic (PV) integrated envelopes in hot climates begin with a comprehensive literature review, building modelling, calibration and validation of the case study model, modification of the model, simulations and finally, discussion of result and analysis as depicted in Figure 2.

The literature review encompasses studies on global energy consumption and projections, energy consumption in Saudi Arabia, PV technologies and integration, dynamic PV systems, codes and standards for PV integration, as well as visual comfort & shading in PV integrated facades among others. By identifying existing research gaps and methodologies, the review lays the foundation for the subsequent stages of the study. Following the literature review, a case study high-rise office building located in a typical hot climate region of Saudi Arabia is selected as the research subject. Factors such as building orientation, size, occupancy patterns, and energy usage profiles were considered in this selection process, along with the collection of relevant building data including floor plans, construction materials, and HVAC systems.

With the building being selected, the next step involves the development of a detailed three-dimensional model using EnergyPlus, a widely used building energy simulation software. The model incorporates accurate representations of the building envelope, glazed facades, and internal layout, after which it was calibrated. Validation of simulation results against real-world data or empirical measurements from similar case studies was carried out to ensure the accuracy and reliability of the calibration. Subsequently, dynamic PV systems were integrated into the building

model, utilizing appropriate simulation tools and plugins. Parameters such as PV panel orientation, tilt angles, and other properties of the PV, were defined during this phase.

Energy and daylighting simulations shall be conducted to assess the energy performance and visual comfort of the building under different scenarios. Following simulation runs, the performance of the integrated PV systems shall be evaluated, considering factors such as energy generation potential, building energy consumption and the peak demand.

The research findings, methodology, and results shall be documented in a comprehensive report to provide clear explanations of the simulation methodology, assumptions, and limitations. The essence of the research findings for sustainable building design in hot climates shall be discussed, along with potential avenues for future research.

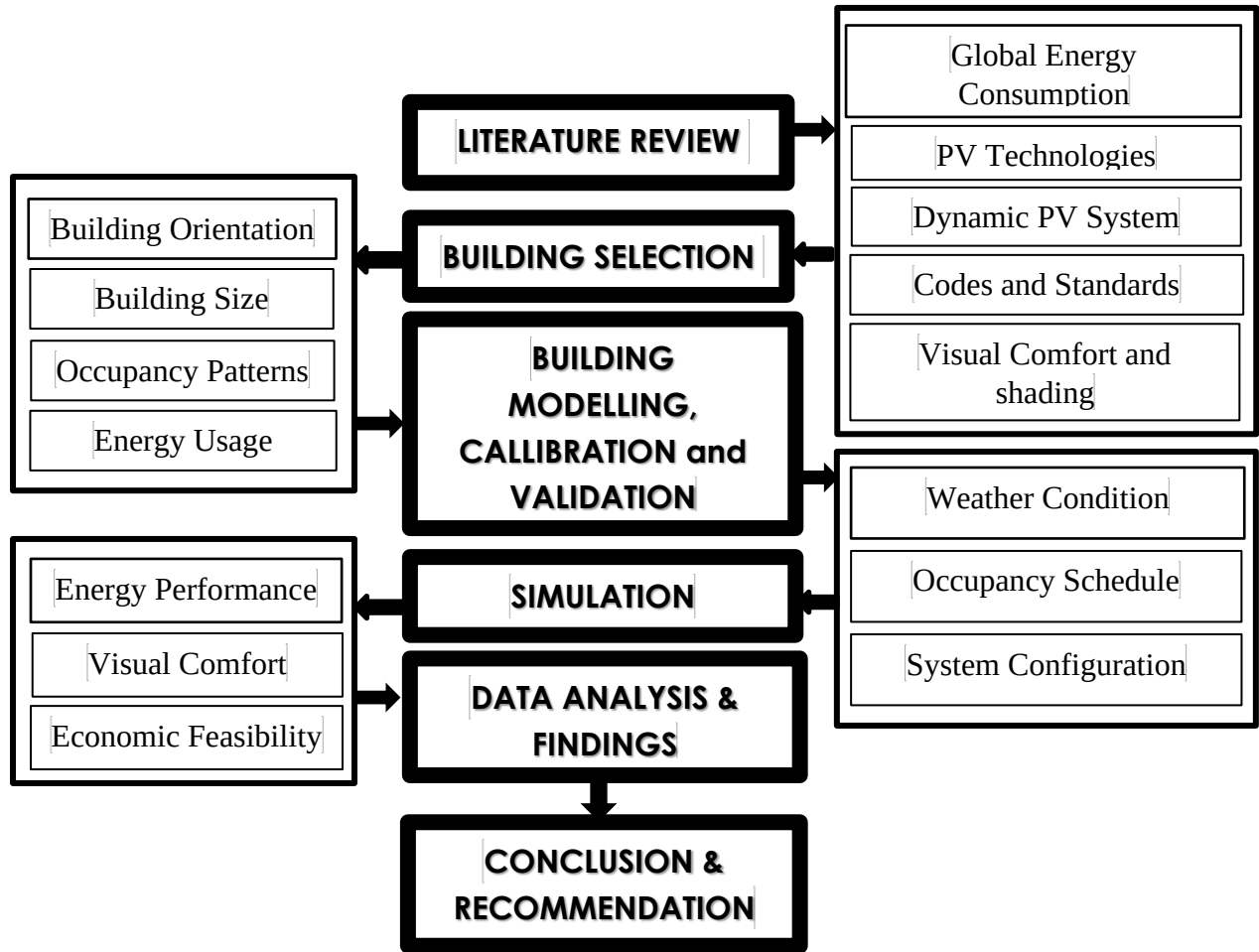


Figure 2 Research Methodology

3.1 Building Selection

The selected case study building is an office building located in the hot-humid climate of Al-Khobar (Twin city with Dhahran), Saudi Arabia. It has been previously adopted in the study of The Impact Assessment of HVAC System Operation and Selection in Energy Efficiency in Hot Climate by (Najid & Al-Homoud, 2023). The building can be described as sort worth rectangular, although with a couple of recesses as shown in Figure 3. The building with dimensions 30m length x 30m

width x 41m height, has its entrance façade at the east direction. The building consists of nine floors, among which the first to seventh floors have similar characteristics; while the remaining floors (ground, mezzanine and eighth floor) have different unique attributes compared to the remaining floors as shown in Figure 4. The total floor area of the building, as obtained from building plans, is 8400 m² (Najid & Al-Homoud, 2023). Each floor occupies an area of 862 m², except the mezzanine floor, which occupies an area of 642 m².

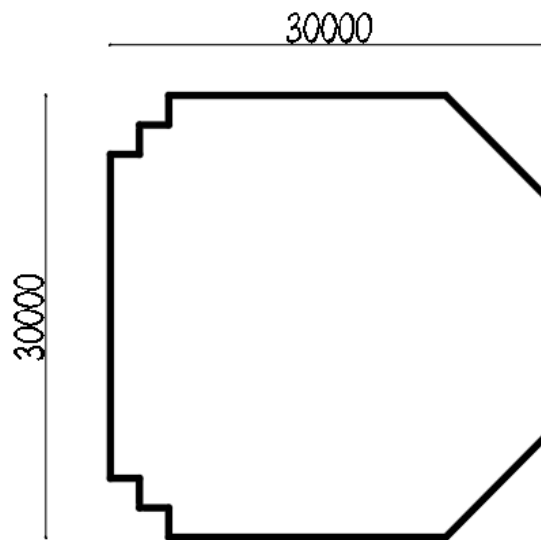


Figure 3 Case study building basic layout

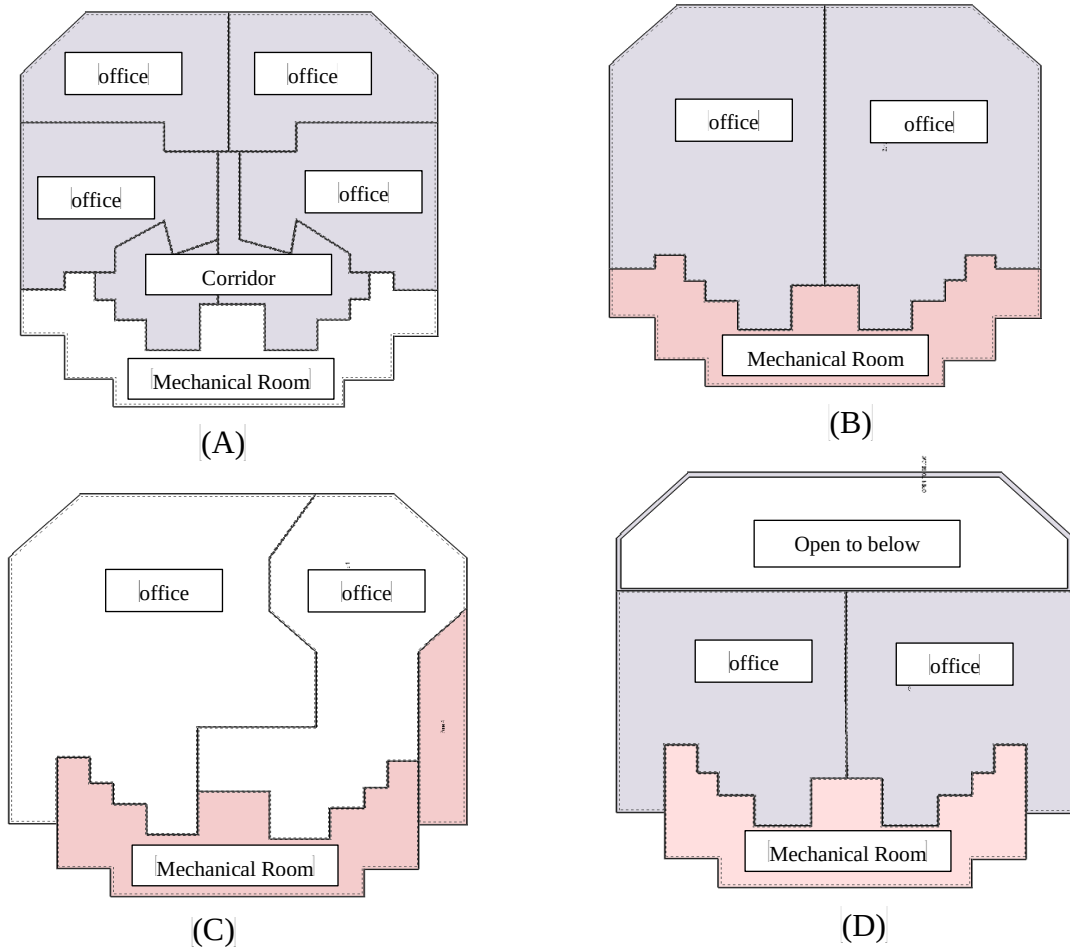


Figure 4 Floor plans of the building (a) Typical first to seventh floors, (b) Ground floor, (c) Eighth floor, (d) Mezzanine floor.

Rationales for selecting the case study building

- The type of HVAC system used in the selected building is a packaged single zone (PSZ), which is one of the most used types of HVAC system in office buildings in Al-Khobar region. The survey conducted by Al-Ashwal (2008) showed that about 63% of the surveyed designers in Al-Khobar region use PSZ systems in their designs.

- The case study building can be categorized as square shaped, although with little recesses. This type of building shape is one of the most common shapes used by designers of office building in Al-Khobar
- Most of the office buildings in Al-Khobar are designed between 4-10 floors, and since the selected building is nine floors, it lies within the range of common height of office buildings in Al-Khobar.
- The type of glazing used in the selected building is double-glazed (clear and tinted) which is a common type of glazing used in office buildings in Al-Khobar.
- The selected building has open-planned offices, which is the commonly used type of distribution of workspaces in the office buildings in general.

3.2 Different Building Compartments

As illustrated in Figure 4, the case study building is divided into different compartments namely-offices, corridors, and mechanical rooms. Each floor has its mechanical room and offices, except for the mezzanine floor that has an open corridor that connects to the floor below. The functions of each compartment are as follows:

- **Offices:** These compartments are designated for work-related activities and provide space for employees to perform their tasks. Offices are typically equipped with desks, computers, and other necessary equipment to support daily operations.
- **Corridors:** Serving as pathways between different areas of the building, corridors ensure smooth circulation and access to various rooms. They also play a key role in emergency evacuation routes, helping with the efficient movement of occupants during a crisis.
- **Mechanical Rooms:** These compartments house the building's essential systems, such as HVAC (heating, ventilation, and air conditioning), electrical panels, and plumbing equipment.

Mechanical rooms are important for maintaining the building's indoor environment comfort and managing energy use.

3.3 Building Energy Audit Process

Energy audit is a common tool to assess and study the energy profile of buildings. As reported by (Najid & Al-Homoud, 2023), a systematic and detailed energy audit of the building was performed. Each stage of the procedures of the audit process is discussed in detail in the following sections:

3.3.1 Building Characteristics Analysis

The first stage of the energy audit process includes determining the physical and operational characteristics of the building. These characteristics information was obtained through reviewing of the building design drawings and interviews with the building maintenance personnel respectively. The architectural, mechanical and electrical drawings of the building were reviewed to obtain detailed information regarding the building envelope, HVAC systems and equipment, and lighting fixtures (Najid & Al-Homoud, 2023).

3.3.1.1 Envelope details

A building envelope is a critical component of any structure, serving as the interface between the interior and exterior environments. It plays an important role and serve as serves as a barrier to external environmental factors while maintaining internal conditions such as thermal, acoustic, and visual comfort ("Building Envelope," 2021). The building envelope significantly influences a building's energy consumption and environmental impact. Its components walls, windows, doors, and roofs, are essential for protecting and sheltering the interior spaces, significantly influencing energy consumption (Anderson, 2019); (Altun, 2022) . Effective design can lead to substantial energy savings and improved environmental performance. A high-performance envelope design

can save around 42% for total energy use, 64% for heating, and 34% for electric lighting by optimizing glazing type, window-to-wall ratio, sun shading, and roof strategies (Raji et al., 2016).

The envelope details of the case study building were obtained from the building's architectural drawings (Najid & Al-Homoud, 2023). The components of the walls include granite cladding on the outside, followed by concrete hollow block, gypsum board and paint on the interior side. It was to be noted that the walls do not contain any insulation. The overall U-value of the wall, calculated using Visual-DOE software, is $2.68 \text{ W/m}^2 \cdot ^\circ\text{C}$. The cross-section of the wall, reproduced based on drawings, is shown in Figure 5.

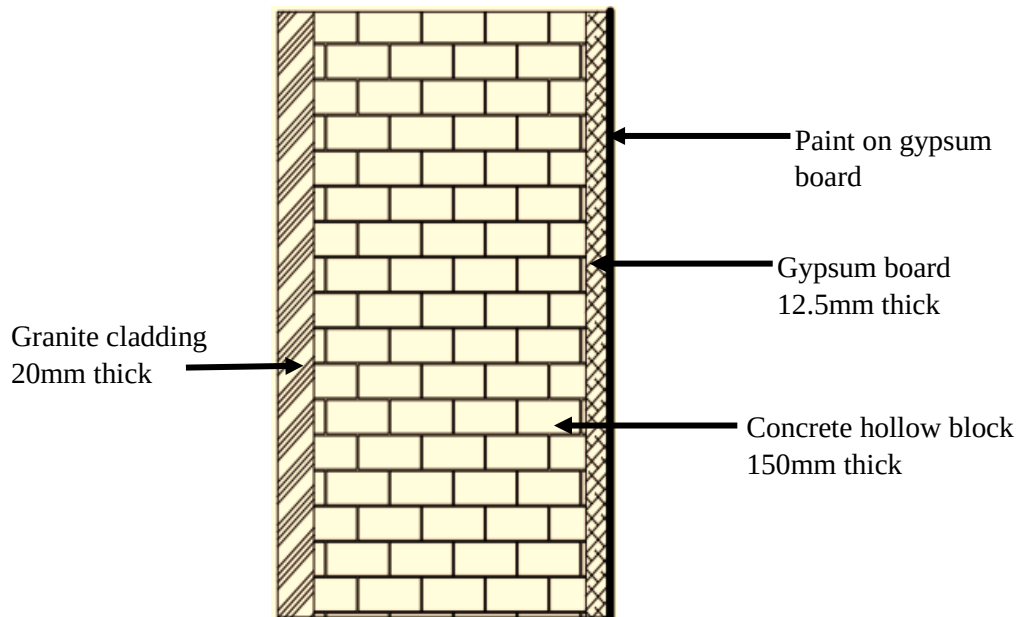


Figure 5 Wall Cross-Section

The roof of the building consists of a 200mm thick reinforced concrete slab with asphalt tiles on the outside and cement plaster on the inside. The overall calculated U-Value of the roof using Visual-DOE, is $4.01 \text{ W/m}^2 \cdot ^\circ\text{C}$ (Najid & Al-Homoud, 2023). The building floor is a slab-on-grade floor. Figure 6. illustrates the cross-sections of roof and floor, as depicted in the architectural drawing.

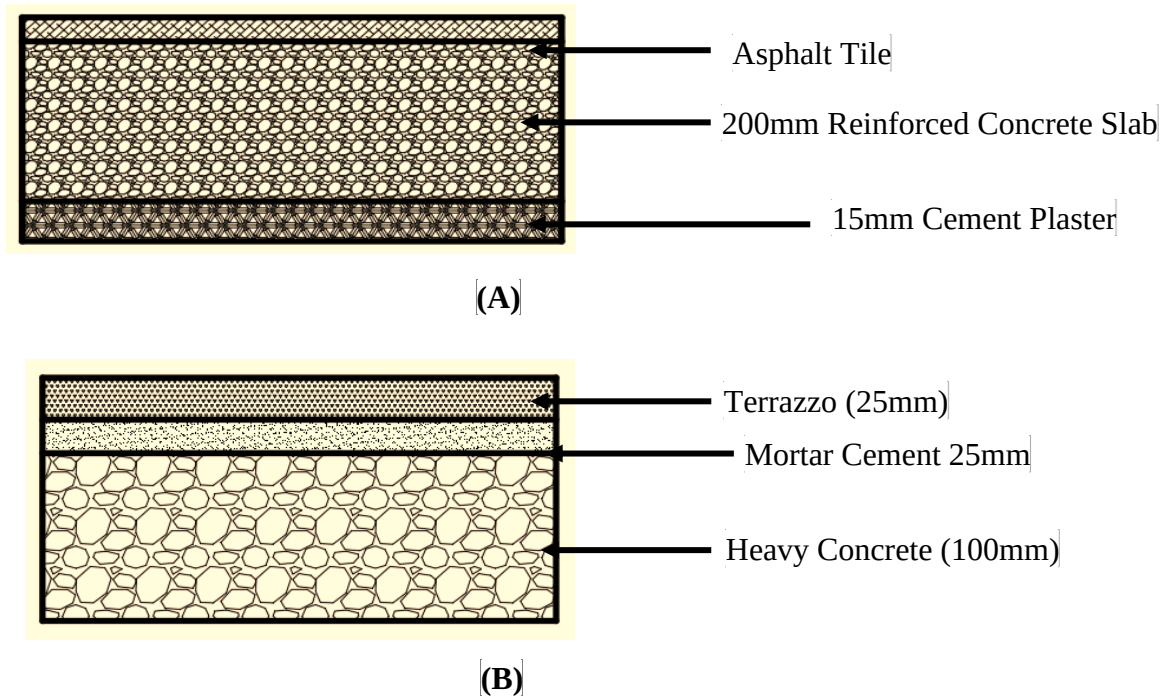


Figure 6 Roof (a) and (b) Floor cross-section

Two different types of glazing are used in windows throughout the building as stated in Table 1. In the ground and mezzanine floors, double clear glass is used while reflective-tinted double glazing is used in the first to the eighth floors. The window-to-wall ratios (WWR) are 4% and 51% for the west and east facades, respectively. On the north and south facades, the WWR ratios are 37.46% each (Najid & Al-Homoud, 2023).

Table 1. Building Envelope Details (Najid & Al-Homoud, 2023)

Characteristics	Description
Plan shape	Square
Total height of the building	41 m
Gross floor area	8400 m ²
Gross wall area	4690 m ²
Glazing area	2040 m ²
Overall WWR	43.5%
Type of glazing	Double Glazed-Clear 6/6/6 mm, Reflective Double Glazed-Tinted 6/6/6 mm
External walls	Granite cladding 20mm thick, Concrete hollow block 150mm thick, 12.5mm thick Gypsum Board, Paint on gypsum board
Roof	15mm Cement Plaster, 200mm Thick Reinforced Concrete Slab, Asphalt Tiles
Floor	100 mm Heavyweight Concrete, 25 mm Mortar Cement, 25 mm Terrazzo

3.3.1.2 HVAC system details

Heating, ventilation, and air-conditioning (HVAC) systems are essential for maintaining thermal comfort and indoor air quality in buildings. These systems regulate temperature, humidity, and airflow, ensuring a comfortable and healthy environment for occupants (Sinopoli, 2010). The main purposes of a heating, ventilation, and air-conditioning (HVAC) system are to provide thermal comfort and to help maintain good indoor air quality. They are significant energy consumers, accounting for a large portion of energy use in buildings (Kant et al., 2018).

An important aspect of determining the details of HVAC system is to establish the building thermal zoning. Thermal zoning is a critical aspect of HVAC system design, involving the subdivision of building spaces into zones with varying thermal conditions. Effective thermal zoning can significantly impact energy efficiency, thermal comfort, and overall HVAC system performance (Shin & Haberl, 2019). However, the thermal zoning details of the case study building were not illustrated in the building drawing (Najid & Al-Homoud, 2023). Hence, each thermal zone or the

area served by the HVAC systems were assumed as per the compartment of each of the building floor as portrayed in Figure 7.

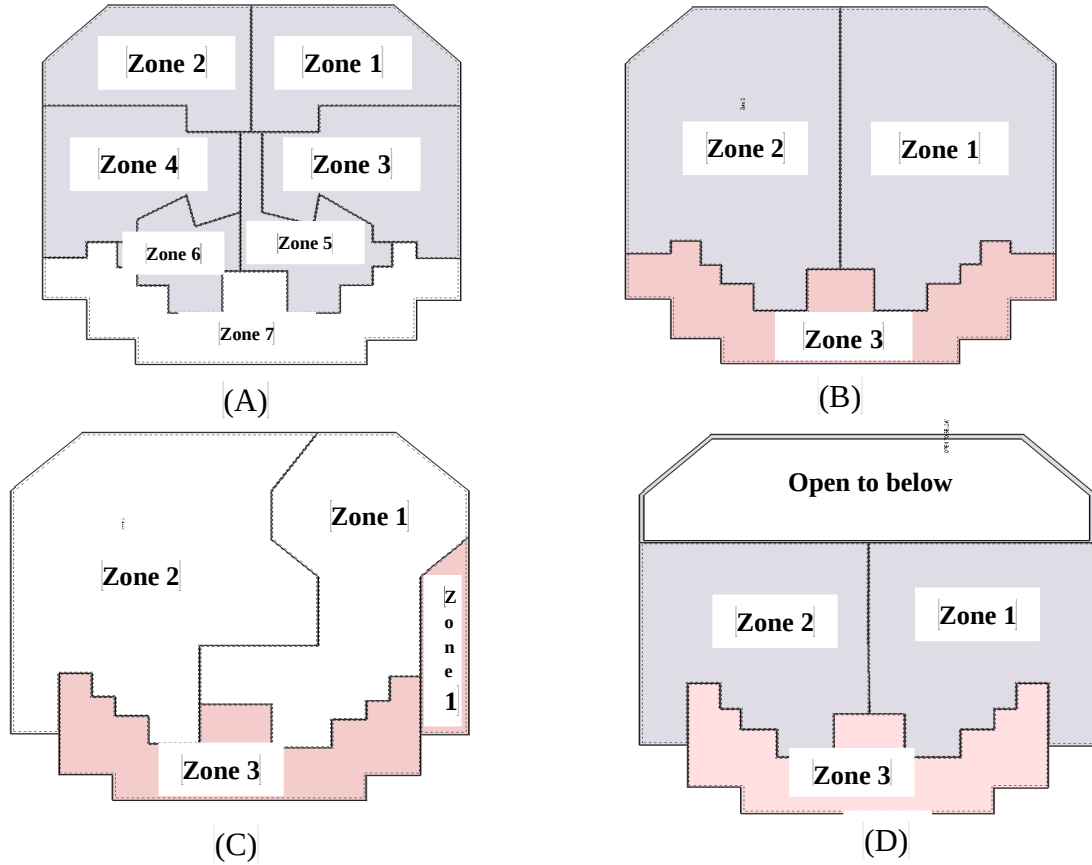


Figure 7 Building Thermal zoning of (a) Typical first to seventh floors, (b) Ground floor, and (c) eighth floor, (d) Mezzanine floor

It was deduced from the reviewed mechanical drawings that the building makes use of two types of HVAC systems, packaged single zone (PSZ) units and fan coil units (FCUs). The previous serves all the office zones while the latter serves the corridors. The capacities of the available HVAC systems along with supply and ventilation air flow rates are presented in Table 2. The study building is assumed to be airtight, therefore, based on (ASHRAE, 2009), the infiltration rate is assumed to be 0.38 ACH, for outdoor design conditions of 43°C, 7.5 mph wind speed and indoor temperature of 24°C.

Table 2 Building HVAC System Details (Najid & Al-Homoud, 2023)

Floor	Zone	Type of system	Capacities		Supply air flow		Ventilation	
			Tons	KW	cfm	l/s	cfm	l/s
Ground floor	Zone-1	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-2	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-3	Unconditioned zone						
Mezzanine floor	Zone-1	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-2	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-3	Unconditioned zone						
Typical first to seventh floor	Zone-1	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-2	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-3	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-4	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-5	FCU	3.5	12.33	1,400	660.69	0	0
	Zone-6	FCU	3.5	12.33	1,400	660.69	0	0
	Zone-7	Unconditioned zone						
Eighth floor	Zone-1	PSZ	30	105.50	10,500	4955.17	530	250
	Zone-2	PSZ	30	105.50	10,500	4955.17	178	84
	Zone-3	Unconditioned zone						
	Zone-4	Unconditioned zone						

3.3.1.3 Lighting details

The lighting details were derived from the building electrical drawings. The different types of fluorescent lighting fixtures used in the building along with wattage for each type of fixture are shown in Table 3. The lighting power density (LPD) for each zone in the building was calculated by multiplying the number of fixtures of each type by wattage of lamps in each type of fixture (Najid & Al-Homoud, 2023). The LPD calculated for different zones in the building is summarized in Table 4.

Table 3 Types of lighting fixtures used in the building (Najid & Al-Homoud, 2023)

Description	Wattage	Voltage
Fluorescent light with above mirror, rapid start	20	127
Wrap around fluorescent fixture with prismatic diffuser, rapid start	40	127
Wraparound fluorescent fixture with prismatic diffuser, rapid start	2x40	127
Industrial Type wraparound fluorescent fixture with prismatic diffuser	2x40	127
Fluorescent fixture with fully anodized louver	4x18	127
Spotlight with ring	50	127

Table 4 Building lighting power density (Najid & Al-Homoud, 2023)

Floor	Zone	LPD(W/m ²)
Ground floor	Zone-1	11.2
	Zone-2	10.9
	Zone-3	21.5
Mezzanine floor	Zone-1	14.6
	Zone-2	14.6
	Zone-3	21.5
Typical first to seventh floor	Zone-1	13.6
	Zone-2	13.6
	Zone-3	15.3
	Zone-4	15.3
	Zone-5	20.2
	Zone-6	24.6
	Zone-7	21.5
Eighth floor	Zone-1	18.8
	Zone-2	12.1
	Zone-3	21.5
	Zone-4	0.0

3.3.1.4 Building Maintenance Personnel Interviews

The undistinguishable building operation details which could not be deduced from the building design drawings were derived through interviewing the building maintenance personnels (Najid & Al-Homoud, 2023). Ideally, the building operation information and detail is usually provided by the building facility manager, however, no facility manager was appointed or assigned to the case

study building, therefore, the building operation details were obtained from the building maintenance personnels. The information obtained during this stage of the audit process is discussed below.

i. Building operation and occupancy schedules

As documented from the interview by (Najid & Al-Homoud, 2023), the building operations and occupancy schedules remain consistent throughout both summer and winter seasons, with occupancy beginning at 7:00 a.m. and ending at 5:30 p.m., including a 30-minute lunch break from 12:00 to 12:30 p.m. During the holy month of Ramadan, however, the schedule is adjusted: while occupancy still starts at 7:00 a.m., approximately 65% of occupants depart two hours earlier at 3:30 p.m., with the remaining 35% adhering to the usual 5:30 p.m. close. Table 5. provides a detailed summary of occupancy profiles and schedules for various building systems.

ii. HVAC system operation schedule

Interviews with building maintenance staff revealed that the HVAC systems operate around the clock during the summer months (April to November) to ensure required indoor conditions. In winter (December to March), however, HVAC system fans are programmed to shut off automatically from 9:00 p.m. to 6:00 a.m. if the zone temperature falls below 28°C. Additionally, the building's setpoint temperatures are maintained at 21°C in summer and 24°C in winter. Table 5 illustrates the operational profiles for both setpoint temperatures and fan schedules (Najid & Al-Homoud, 2023).

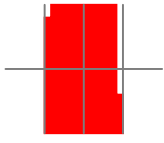
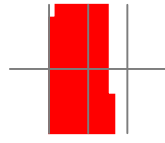
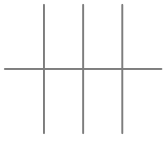
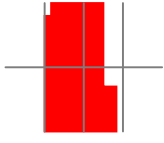
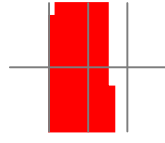
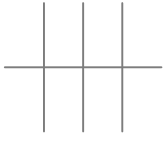
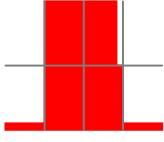
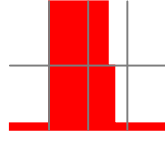
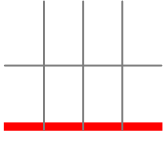
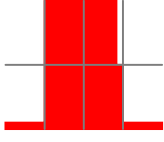
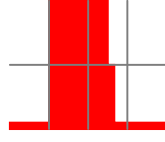
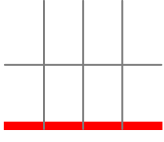
iii. Lighting operation schedule

It was known from the interview that most of the lighting in the building was left on during the occupancy period. To be precise, 100% lighting is made use of from 7:00 am to 5.30 pm, to maintain the required illumination levels for all spaces. 95% of the lighting is reported to be switched off during unoccupied hours, as this is a strategy to reduce the energy consumption of the building, especially when it's not occupied. In addition, 5% of the lighting is left on for security purposes. Table 5 illustrates the occupancy lighting schedule (Najid & Al-Homoud, 2023).

iv. Equipment operation schedules

The equipment in the building mainly includes desktop computers, small and large printers and photocopying machines (Najid & Al-Homoud, 2023). The operation schedules for equipment in the building are shown in Table 5. To calculate equipment power density (EPD) for different zones in the building, average heat gain values for different types of equipment were estimated based on (American Society of Heating, (2009). The EPD calculated for different zones in the building is shown in Table 7.

Table 5 Building operation and occupancy schedules (Najid & Al-Homoud, 2023)

		Saturday to Tuesday	Wednesday	Thursday-Friday
Occupancy schedule	Regular months (Jan-1 to Aug-31 and Oct-1 to Dec-31)	 Normal Operation	 Normal Operation	 0% Occupancy
	Ramadan Months (Sep-1 to Sep-30)	 Normal Operation	 Normal Operation	 0% Occupancy
Lighting schedule (all year round)		 Unocc. – 5% Occ. – 100%	 Unocc. – 5% Occ. – 100%	 5%
Equipment schedule (all year round)		 Unocc. – 5% Occ. – 100%	 Unocc. – 5% Occ. – 100%	 5%

Infiltration (all year round)			
Space Temp (summer)	Cooling  21 °C all time	Cooling  21 °C all time	Cooling  21 °C all time
Space Temp (winter)	Cooling  24 °C (7am to 8pm) 28 °C (9pm to 6am)	Cooling  24 °C (7am to 8pm) 28 °C (9pm to 6am)	Cooling  24 °C (7am to 8pm) 28 °C (9pm to 6am)
Fan Profile (summer)	 100% On all time	 100% On all time	 100% On all time
Fan Profile (winter)	 Turned off from 9pm to 6am if temp is below 28°C	 Turned off from 9pm to 6am if temp is below 28°C	 Turned off from 9pm to 6am if temp is below 28°C

Table 6 Heat gain of typical office equipment (Najid & Al-Homoud, 2023)

Equipment	Type	Continuous (W)	1 page per min. (W)	Idle (W)
Laser Printers	Small Desktop	130	75	10
	Desktop	215	100	35
	Small Office	320	160	70
	Large Office	550	275	125
Copiers	Desktop	400	85	20
	Office	1100	400	300
Computers	Average Value	55	-	-
Monitor	Medium (16 to 18 inch)	70	-	-

Table 7 Equipment power density (Najid & Al-Homoud, 2023)

Floor	Zone	EPD, (W/m ²)
Ground floor	Zone-1	15.7
	Zone-2	14.9
	Zone-3	0
Mezzanine floor	Zone-1	10.9
	Zone-2	10.1
	Zone-3	0
Typical first to seventh floor	Zone-1	24.6
	Zone-2	24.6
	Zone-3	19.8
	Zone-4	19.8
	Zone-5	0
	Zone-6	0
	Zone-7	0
Eighth floor	Zone-1	9.7
	Zone-2	5.4
	Zone-3	0
	Zone-4	0

3.4 Summary of the Collected Building Information

During the first stage of the energy audit process, information regarding building characteristics was collected by reviewing the design drawings, and through interviews with building maintenance personnel. The information included physical and operational characteristics of the building, the HVAC system, lighting and equipment. All the information gathered during this stage of the audit process is summarized in **Table 8**.

Table 8 Summary of Building Characteristics and Operational Parameters from the Initial Energy Audit (Najid & Al-Homoud, 2023).

Characteristics		Description																
Location		Al-Khobar, Saudi Arabia																
Building type		Office																
Plan shape		Square																
Total height		40.730 m																
Gross wall area		4690 m ²																
Gross floor area		8400 m ²																
Window area		2040 m ²																
Over WWR		43.5%																
Type of glazing		Double Glazed-Clear 6/6/6 mm, Reflective Double Glazed-Tinted 6/6/6 mm																
Total no. of people		400																
Operating hours		Ramadan: 7:00am to 3.30pm on all working days for 65% of occupants, Remaining 35% of occupants- Sat. to Tue.-7:00am to 5.30pm, Wed.-7:00am to 3:30pm. Normal Days: Sat. to Tue.-7:00am to 5.30pm, Wed.-7:00am to 3:30pm																
External walls		Granite cladding cut to size 20mm thick, Concrete hollow block 150mm thick, 12.5mm thick Gypsum Board, Paint on gypsum board																
Roof		15mm Cement Plaster, 200mm Thick Reinforced Concrete Slab, Asphalt Tiles																
Floor		100 mm Heavyweight Concrete, 25 mm Mortar Cement, 25 mm Terrazzo																
		Ground Floor			Mezzanine Floor			Typical First to Seventh Floor							Eighth Floor			
		Zone1	Zone2	Zone 3	Zone1	Zone2	Zone3	Zone1	Zone2	Zone3	Zone4	Zone5	Zone 6	Zone 7	Zone1	Zone2	Zone3	Zone4
Occupancy density(m2/person)		23.5	23.5	-	35.3	35.3	-	24.5	24.5	20	20	-	-	-	51	80	-	-
Lighting Power Density (LPD) (W/m2)		11.2	10.9	21.5	14.6	14.6	21.5	13.6	13.6	15.3	15.3	20.2	24.6	21.5	18.8	12.1	21.5	0
Equipment Power Density (EPD) (W/m ²)		15.7	14.9	0	10.9	10.1	0	24.6	24.6	19.8	19.8	0	0	0	9.7	5.4	0	0
HVAC system type		PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	FCU	FCU	PSZ	PSZ	PSZ	PSZ
Supply Temperature (°C)		13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Thermostat Setpoint temperature (°C)	Summer	21	21	-	21	21	-	21	21	21	21	21	21	21	21	21	-	-
	Winter	24	24	-	24	24	-	24	24	24	24	24	24	-	24	24	-	-
Total ventilation air flow rate for each zone (l/s)		375	375	0	375	375	0	180	180	180	180	0	0	0	250	84	0	0
Legend: WWR=Window to Wall Ratio; PSZ = Packaged Single Zone; FCU = Fan Coil Unit																		

3.5 Analysis of Electric Energy Utility Bills

The third stage of the energy auditing process involved analyzing the building energy utility bills of the case study building to determine the energy use pattern. It was stated by (Najid & Al-Homoud, 2023) that the utility bills of the building for the year 2008 were obtained from the building management. It was noted that the details of the bills were converted to kWh units for further analysis. The breakdown of the annual electricity consumption for the year was breakdown into monthly use as depicted in Figure 8. The total annual electricity consumption of the building for the year was determined to be 2,989,508kWh, resulting in 355.9kWh/m²/yr.

It can be deduced that the month of July has the maximum electric energy usage, which is also the peak summer month in the eastern province of Saudi Arabia. The utility data obtained were useful in the later stages of the research, especially for the calibration of the base case model of the case study building.

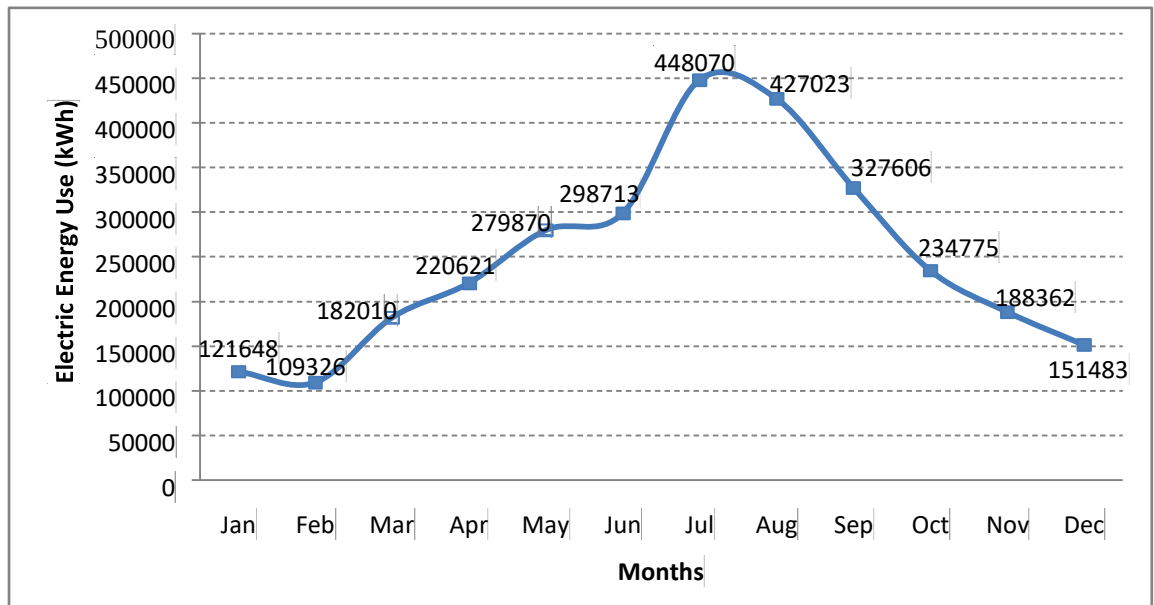


Figure 8 Building electric energy use pattern for the year 2008 obtained from utility bills

3.6 Building Modelling

Building modeling is the first essential process in energy simulation, especially with the use of simulation software such as DesignBuilder, used in creating a detailed virtual representation of a building to be analyzed, in term of its performance, energy use, or/and environmental Impact. Building modelling on DesignBuilder involves designing or virtually constructing an accurate 3D model that represents the case study building (real or hypothetical building) to be simulated. This procedure is the preliminary to calibration, as it forms the basis for subsequent adjustment and validation of the simulation outputs against the real-world data.

The case study building of 9-floors was modelled using DesignBuilder, an energy simulation software. The modelling started with creation of 3D geometry and boundary that represents the building layout, this includes the walls, floors, windows, among others. Precise geometric modelling is very crucial, as it determines the envelope's interaction with external environmental factors, such as the sunlight. The software allows accurate dimensional input, which enables the replication of the exact building layout and structure.

The next process of modelling is thermal zoning. This involves dividing the building into different thermal zones, to ensure the accurate HVAC requirement of the spaces. Zones represent spaces with uniform heating, cooling, or ventilation needs, enabling more accurate load calculations and system simulations. Proper zoning allows differential analysis of energy loads across different parts of the building. The material and construction specifications were considered after the thermal zoning. This process includes specifying detailed information of the materials used for various elements of the model, elements such as the walls, roofs and the glazing. The software (DesignBuilder) provides a database of materials with specific properties such as the thermal conductivity, density, and specific heat capacity. Different types of walls, window types, roofing

material and finishes are also provided in the database, in order to enhance the accurate selection of the correct material, which will in turn impact on the simulation process.

The building orientation and site location were also considered. The modelling process also includes selecting the accurate building orientation as per the case study building, as well as the precise geographical location. Orientation affects the solar gains, and the location determines the climatic conditions. Integrating accurate weather data and the building orientation will greatly influence the building simulation process and outcome.

The HVAC, lighting system, occupancy, and the usage patterns are extremely important in the modelling process and were also considered. To accurately simulate energy use, the heating, cooling and the ventilation system needs to be precisely specified. The software allows detailed customization of the HVAC systems, including equipment efficiency, as well as the operation schedule. In addition, the accurate occupancy schedule and the building usage pattern which also include the equipment loads and the lighting use patterns need to be specified. DesignBuilder enables users to define occupancy profile of each zone, specifying periods of peak activity and low occupancy. The details influence internal heat gains, which can significantly impact the heating, cooling and ventilation needs, and in turn affects the general simulation outcome.

3.7 Model Calibration

Calibration is one of the key phases of building energy simulation, it makes sure the virtual model closely resembles the performance of the real building. It is a systematic and iterative process aimed at aligning the simulation model in DesignBuilder with real-world building performance data. By adjusting input parameters based on actual usage and operational data, the calibrated model achieves a high degree of accuracy, making it a reliable tool for energy analysis, performance

benchmarking, and sustainability assessment in the built environment. Calibration in DesignBuilder is used to fine-tune the model's inputs until the outputs precisely match observed data, usually from historical records, utility bills, or on-site sensor data (Bergero & Chiari, 2021). By increasing simulations' dependability, calibration makes the model an effective instrument for analyzing building retrofits, evaluating energy-saving strategies, and boosting operational effectiveness.

A variety of model factors, including internal loads, HVAC operations, building envelope features, and schedules, must be adjusted for accurate calibration. The model can offer understandings that are highly realistic of the energy behavior of the building under various operating or environmental scenarios by modifying these components to reflect actual conditions. This precision is important, especially in research focused on energy conservation, system optimization, and environmental impact reduction.

3.7.1 Model Calibration Procedures

The calibration process began with a preliminary model, which included valuable foundational data on the building's operational characteristics. This data encompassed the occupancy density for each zone, lighting power density, equipment power density, HVAC system type, supply temperature, thermostat set points for summer and winter, and total ventilation airflow rates per zone. Such parameters were invaluable as they offered understanding of the building's operational patterns and energy requirements. The information gathered from building drawings, walkthrough inspections, and interviews with building managers further substantiated these values, presenting a detailed picture of the building's functional setup.

However, despite the usefulness of this preliminary information, significant gaps remained in the model, impacting the initial calibration's accuracy. The initial calibration, run using only the provided data, resulted in substantial discrepancies when compared to the actual annual energy

consumption data Figure 9, far exceeding the acceptable tolerance levels set by calibration standards (*Normalized Mean Bias Error and Root Mean Square Error*). According to these standards, the discrepancy between actual and simulated energy use should ideally fall within 15% to ensure the model’s reliability. Considering these requirements, additional adjustments and informed assumptions were essential to refine the model for an accurate calibration outcome.

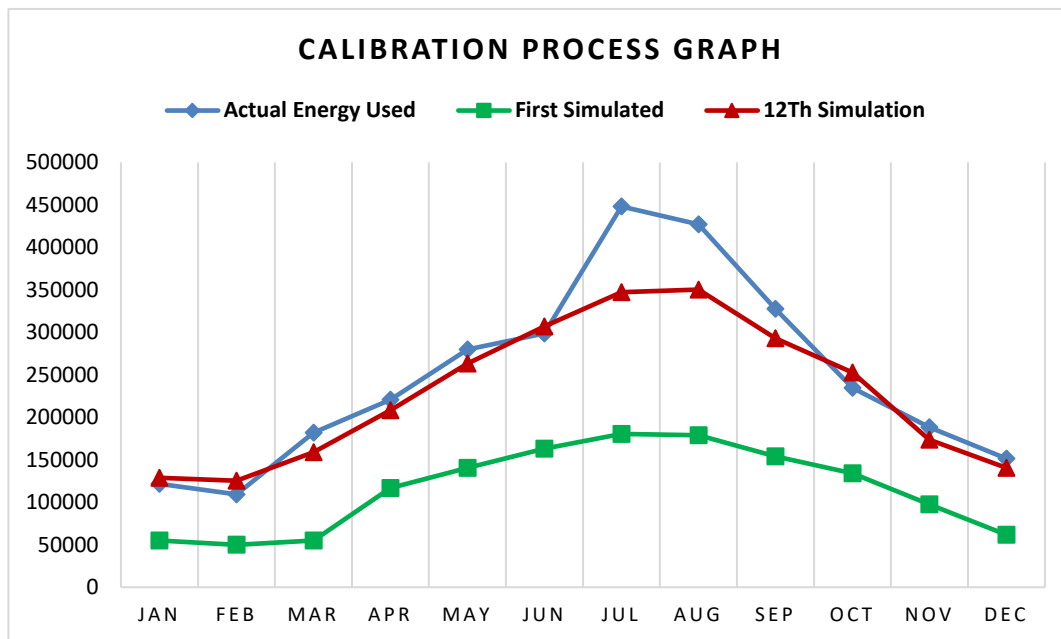


Figure 9 Graph shows disparities between the actual energy consumption and calibration results.

3.7.1.1 Calibration Practical Assumptions

To bridge the gaps in missing data and enhance the model’s accuracy, the practicable assumptions below were implemented:

- **Heating and Cooling Set Points:** Since specific heating and cooling set points were not provided, a standard temperature range was assumed, guided by typical building practices in similar climatic and operational contexts. Setting these values within a practicable temperature range

allowed the model to better represent the actual thermal comfort controls, ensuring that heating and cooling loads matched realistic conditions.

- **HVAC System Detailing and Zonal Assignment:** The building employed a combination of Packaged and Fan Coil Unit (FCU) HVAC systems, which were not fully detailed in the initial model. Each HVAC system type was modeled meticulously, with systems assigned according to the unique requirements of each zone. This detailed assignment was significant, as it allowed for zone-specific calibration, reflecting the diverse heating and cooling demands across different functional areas of the building.
- **Coefficient of Performance (COP) for Heating and Cooling Units:** Another key assumption involved setting the Coefficient of Performance (COP) for both heating and cooling units to a standardized acceptable range. This adjustment helped address energy efficiency discrepancies that arose in initial simulations, aligning the model's energy output more closely with actual energy efficiency levels observed in real-world performance data.
- **Occupancy, Equipment, Lighting, and HVAC Schedules:** The calibration model also required modification of daily operational schedules for occupancy, equipment use, lighting, and HVAC. These schedules were refined based on previous interviews with building managers and typical operational patterns. By closely aligning these schedules with actual building use, the discrepancies were reduced in internal gains and energy loads. Adjustments were made to reflect peak and off-peak hours, variations in occupancy density, and equipment usage throughout the day.
- **Consideration of Holidays and National Observances:** In line with actual building usage, a total of 19 holidays observed during the year, comprising Saudi National Day (1 day), Eid Al-Fitr (7 days), and Eid Al-Adha (11 days), were integrated into the model. These non-operational days were particularly important, as they significantly impact energy consumption patterns. During these periods, occupancy and equipment use drop evidently, which directly affects the HVAC loads and

overall energy usage. Accounting for these holiday breaks introduced a more realistic representation of the building's operational cycle, thereby improving calibration accuracy.

- **Iterative Adjustment and Model Refinement**

Following these initial adjustments, an iterative calibration approach was adopted to further minimize discrepancies between the simulated and actual energy usage as illustrated in Figure 10. After each adjustment, the model was re-simulated, and outputs were compared against the measured energy data. Discrepancies identified in each iteration informed subsequent refinements to parameters, allowing a gradual alignment of simulated and actual energy consumption within the acceptable error thresholds.

This iterative process focused particularly on refining energy-related factors that had the most impact on the building's operational efficiency, such as HVAC control settings, lighting density, and equipment schedules. Each round of calibration was guided by statistical indicators such as Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)) to quantify the alignment between simulation outputs and actual performance as depicted in Table 9. Iterations continued until these metrics indicated compliance with standard calibration tolerances, signifying that the model now accurately represented the building's operational characteristics.

Table 9 Monthly Actual vs. Simulated Energy Use with NMBE and RMSE Metrics

Month	Actual Building Consumption (kWh)	Calibrated Simulation (kWh)	NMBE	RMSE
Jan	121648	127200	-5%	2%
Feb	109326	115210	-5%	2%
Mar	182010	188400	-4%	3%
Apr	220621	218190	1%	1%
May	279870	279500	0%	0%
Jun	298713	310300	-4%	5%
Jul	448070	448700	0%	0%
Aug	427023	415790	3%	5%
Sep	327606	319720	2%	3%
Oct	234775	239100	-2%	2%
Nov	188362	182210	3%	2%
Dec	151483	159600	-5%	3%

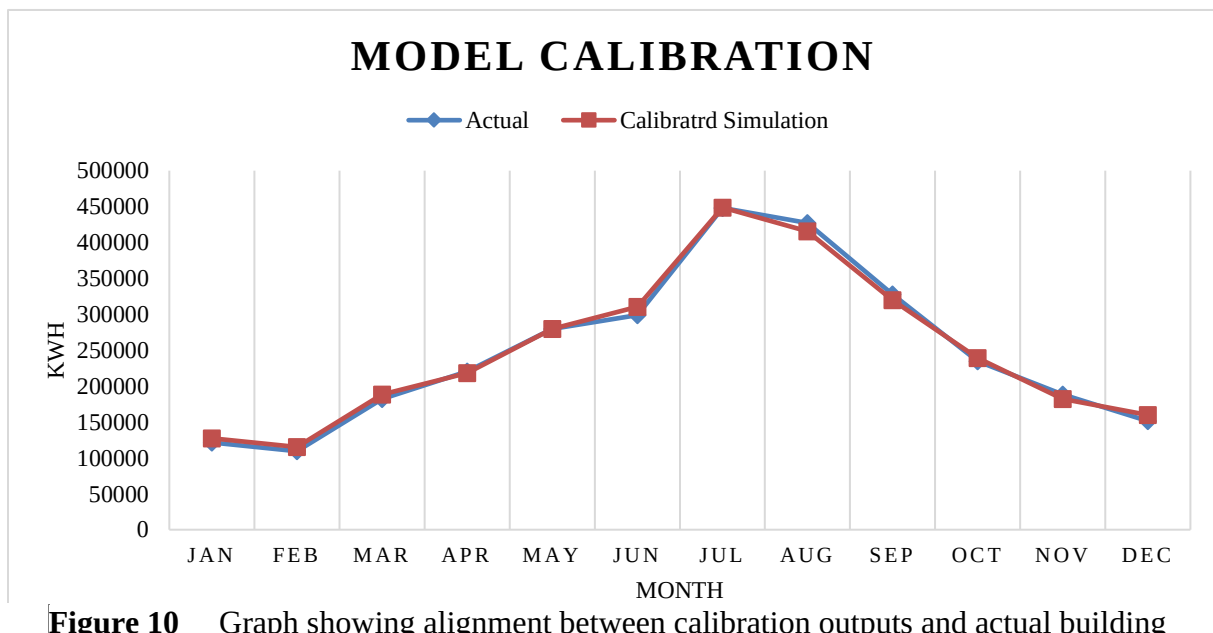


Figure 10 Graph showing alignment between calibration outputs and actual building energy consumption.

3.8 Building Model Validation

Following the previously indicated modifications, and to ensure that simulated results accurately reflect the performance of the actual building, the model was validated. Model Validation is critical, as it certifies the model's reliability for predicting energy consumption under diverse operational conditions. Calibration procedures are important for making simulation models representative of actual field conditions (Kampelis et al., 2020). Two fundamental metrics were utilized to evaluate the correctness of the model: the Normalized Mean Bias Error (NMBE) and the Root Mean Square Error (RMSE).

The metrics are widely accepted as a standard for evaluating the accuracy of calibrated energy models. They are adopted to ensure that the predictions are within acceptable error margins (Chong et al., 2017); (O'Neill & Eisenhower, 2013); (Chaudhary et al., 2016). The Normalized Mean Square Error (NMBE), with an acceptable range of $\pm 5\%$, evaluates the systematic deviation of the simulated data from actual measurements, showing the potential biases in the model. Meanwhile, Root Mean Square Error (RMSE), with the acceptable range of 15%, measures the average magnitude of error, addressing the spread of discrepancies across the entire dataset.

Ultimately, after a rigorous process of considerable adjustments, the calibrated model aligned with both NMBE and RMSE standards, consistently falling within the required acceptable thresholds. This progress confirmed that the model could reliably be referred to as a representation of the case study building's energy performance, enabling accurate further optimization and improvements.

3.9 Proposed Dynamic PV Concept and Operating Principles

The proposed dynamic PV system combines energy generation, solar shading, and visual comfort enhancement into a single adaptive façade solution. It comprises horizontally installed monocrystalline PV slates, mounted on a custom extruded window frame which serves as a structural support that allows for single-axis rotational movement. It is integrally assembled with the glazed portions of the building envelope, forming a tight external layer over the windows as illustrated in Figure 11b. The main body of the system, including the frame structure and the PV-integrated blind slats, is assumed to be constructed using high-strength aluminum alloy. This material ensures that the system is lightweight yet highly durable, offering excellent structural performance under severe weather conditions typical of hot climates.

Each blind slate spans approximately 6 meters in length with a depth of 0.091meters and is mounted on the custom extruded frame that projects 100mm horizontally and 50mm vertically around the window edge. This frame can discreetly accommodate the motor and support components, making the system architecturally compactible with modern façade designs.

The key features of the dBIPV system lie in its ability to rotate the PV-integrated slates between 0° and 90°, transitioning from a fully horizontal to a fully vertical orientation, allowing the blind area exposed to solar radiation and the slat angle to be adjusted independently and intelligently. This rotation could be enabled by a precise motorized stroke mechanism or controlled via an embedded motor controller. The control system could be designed for both automatic and manual operation. In the automated mode, sensors and control algorithms respond to solar conditions and adjust the slate angles in real time. Alternatively, the system can operate on pre-programmed schedules or be manually adjusted through wireless remote or computer control interfaces.

3.10 Simulation Procedures

Simulation is a powerful computational process that models the real-world performance of buildings by calculating energy use under specific conditions. In building energy performance studies, simulation serves as an important tool for evaluating and optimizing how buildings respond to various environmental and operational factors, such as the weather conditions, occupancy patterns, lighting, HVAC setting, among others (Crawley et al., 2008). Through creating a virtual representation of a building that is to be studied, simulation provides perceptions that are critical for achieving energy efficiency and sustainability objectives (Gan et al., 2020). The process outcomes can help in predicting annual building's energy consumption, and aid in identifying potential energy-saving measures.

Different operational scenarios are set up to observe how the building behaves under various conditions. After all the parameters have been set, the simulation is run to generate detailed report on energy use, and other targeted assessments. Designbuilder give different performance outputs, the results are then analyzed to determine how closely the building's simulated energy performance aligns with desired standards.

3.11 Case Study Building Simulation

The primary goals of this research include analyzing the energy performance of the integrated dynamic photovoltaic, as well as its influence on visual performance and shading within the building. By running the simulation, the PV technology performance, as well as daylighting distribution and overall impact of PV shading on indoor light level can be quantified.

In the simulation, the 9-story office building located in Al-Khobar, Saudi Arabia was modelled using the energy simulating software (DesignBuilder), as shown in Figure 11. It is assumed that

there are no additional high-rise buildings surrounding the case study building, hence, the shading and the reflection caused by surroundings were ignored. Prior to the simulation process, specific adjustments were made to the model in order to accommodate the PV mechanism and accurately represent its performance. An extruded window frame with dimensions of 100mm and 50mm thickness was created around the windows' edges. The purpose of the frame is to serve as a sturdy platform to support the dynamic PV states rotation mechanism and also act as a shading component. The total glazed window area of the envelope resulted in 2,040 m², although the windows are of diverse sizes and shapes. Resulting in a window-to-wall ratio of (43.5%). Specifically, the glazed area is equipped with either double clear glazing, or reflective double tinted glazing.

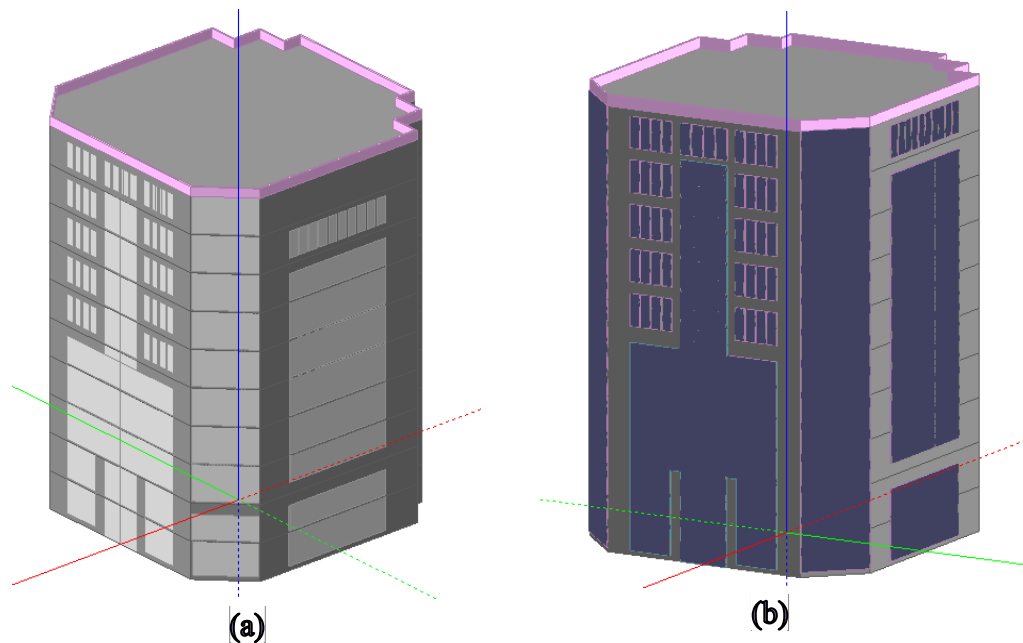


Figure 11 3D model 9-story office building in DesignBuilder (a) base-case without PV, (b) Model with integrated PV

The dynamic PV slates were integrated into the extruded window frame with each of the windows having different numbers of slates due to the difference in the sizes and shape of the windows as shown in Figure 11. Each integrated slate consists of diverse numbers of solar cells due to the aforementioned reasons. The slate separation to the slate depth was set to be 0.05m in order to

enhance smooth rotating process to different angles, and to reduce wide space for both heat and moisture transfer. The energy performance of the building was simulated using energy modelling engine (EnergyPlus, Version 9.4) through DesigBuilder software, which can simulate transient heat conduction, daylighting controls and onsite PV power generation. To assess the overall energy performance of dynamic PV technology, several sub-modules were employed.

Due to the limitation of DesignBuilder, which limits the simulation of the PV energy generation to 150 load centers, an alternative method was devised to achieve the assessment of the energy generation potential of dynamic PV technology. A frame module of (6.0m x 4.0m) resulting in 24m² was modelled, the dimension was chosen as it fit to all the building facades. The total of 41 PV slates carrying 33-unit solar cells were each integrated into the frame. By simulating these configured modifications, the model captures the effect of the PV slates, although not only as an energy-generating component, but also as a shading element that reduces solar heat gain into the building. The module was used for each orientation and floors, with the consideration of manual rotation of the PV slate to different angles, ranging from 0°, 10°, 20°... till 90°. Each simulation result, and the cumulative PV energy generation of each floor and angles were documented.

The accurate estimation of energy generation is a vital step in evaluating the performance of the dynamic photovoltaic (PV) system. A structured mathematical approach was adopted in calculating the generation potential at various angles, enabling a comprehensive understanding of its contribution to the building's energy performance.

The energy generation potential of the PV module was calculated using a series of mathematical expressions that systematically determine the output per unit area, individual window generation contributions, and the cumulative energy generation of the entire building as represented in equations 1, 2 and 3 respectively. The equations leverage key parameters of the PV system,

including the total generation, effective generation area, and the geometrical properties of the windows.

- **Generation per Unit Area of the PV Module**

The first step involves determining the energy generation per square meter of the effective area of the sample module. This is expressed as:

$$G/1m^2 = \frac{TG_m}{EG_m} \dots\dots\dots \text{equation 1}$$

Here, $G/1m^2$ denotes the generation per square meter, TG_m represents the total energy generation of the sample module, and EG_m represents the effective generation area of the module. This equation standardized the energy output, allowing for easy extrapolation across various window sizes.

- **Energy Generation for Individual Windows**

Once the energy generation per square meter is known, the output for each window-integrated PV panel is calculated using the formula:

$$G_w = G/1m^2 \times A_w \dots\dots\dots \text{equation 2}$$

Where G_w is the energy generation of a specific window, and A_w is the effective area of the window. The calculation considers the varying dimensions of windows across the building, ensuring an accurate representation of energy contributions from each PV-integrated surface.

- **Cumulative Energy Generation of the Building**

The final step aggregates the energy generation of all PV-integration windows to determine the total output for the entire building. This is expressed as.

$$CG = \sum_{i=0}^n Aw_i \dots\dots\dots \text{equation 3}$$

Where **CG** represents the cumulative generation, and **Aw_i** is the effective area of each window from 1 to n. This cumulative figure provides a general view of the PV system's overall energy contribution.

The application of these equations enhances the better understanding of the energy generation potential under dynamic conditions, by varying the angles of the PV panels during simulation, the energy generation per square meter was recalculated to account for changes in sunlight exposure and incident radiation. The process provided a detailed determination of energy output across different scenarios. Additionally, the integration of these calculations into the simulation process enabled the comparison of energy generation performance under various operational conditions.

3.12 Visual Performance Simulation Procedures

The visual performance analysis of the building was conducted through daylighting simulations using DesignBuilder. The daylighting module within the software incorporates internationally recognized metrics for evaluating the visual performance of a building, including Spatial Daylight Autonomy (SDA), Useful Daylight Illuminance (UDI), and Annual Sun Exposure (ASE). These metrics are widely adopted in green building certification systems such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and Green Star, ensuring compliance with global standards for daylighting

performance (IES, 2012; LEED v4. 1, 2020). To ensure the accuracy and reliability of the daylighting simulations, several key parameters were carefully configured.

The Simulation type was set to align with general daylighting performance standards, encompassing criteria from LEED, BREEAM, and Green Star. This approach ensures that the results are applicable across multiple certification frameworks and adhere to internationally recognized benchmarks.

The simulation template was set to “high quality” to maximize the precision of the results. While this setting increases computational time, it significantly enhances the accuracy of the daylighting analysis by employing advanced algorithms and finer grid (Reinhart et al, 2006). The working plane height was set to 0.75m above the floor level. This height represents the typical position of a seated occupant’s work surface and is widely used in daylighting studies to evaluate illuminance levels in occupied spaces (IES, 2012).

The metrics and illuminance threshold adopted includes the Spatial Daylight Autonomy (sDA) which was set to 300 lux, representing the minimum illuminance level required for typical office tasks. The Useful Daylight Illuminance (UDI), with the lower and upper thresholds set to 100 lux and 2000 lux respectively.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Optimal Configuration of the dBIPV on Typical Season Days

The earth's axial tilt and its orbit around the sun gives rise to four key astronomical events that define the change in season - the vernal equinox, summer solstice, autumnal equinox, and winter solstice as illustrated in Figure 12. These four selected representative days are known as sunny days with high solar radiation.

They were selected to analyze the influence of seasonal changes on energy performance, as well as optimal configurations of the dynamic building integrated PV in detail.

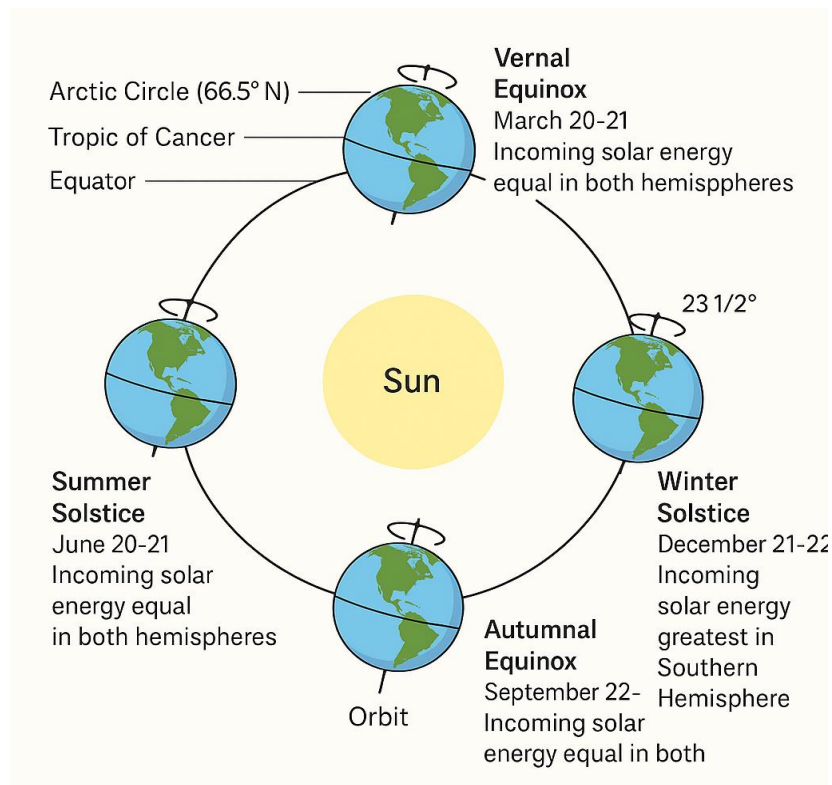


Figure 12 Earth's Orbit and Seasonal Solar Energy Distribution

4.1.1 Vernal (Spring) Equinox and Autumnal Equinox

The vernal equinox occurs around March 20th or 21st in the Northern Hemisphere. On this representative day, the sun crosses the celestial equator moving northward, resulting in nearly equal durations of day and night across the globe. The term “equinox” is derived from the Latin words *aequus* (equal) and *nox* (night). This event marks the beginning of spring in the Northern Hemisphere (NASA Science, 2022).

The autumnal equinox occurs around September 22nd or 23rd in the Northern Hemisphere. Similar to the vernal equinox, the sun crosses the celestial equator, but this time moving southward. This results in nearly equal lengths of day and night. The autumnal equinox marks the beginning of autumn in the Northern Hemisphere.

4.1.2 Summer and Winter Solstice.

The summer solstice that signifies the commencement of summer occurs around June 20th or 21st in the Northern Hemisphere as illustrated in Figure 12. The sun reaches its highest point in the sky at noon, resulting in the period of the longest daylight of the year. This phenomenon occurs because the earth’s axial tilt positions the Northern Hemisphere at its maximum inclination towards the sun.

The winter solstice, which marks the onset of winter in the Northern Hemisphere occurs around December 21st or 22nd. On this day, the sun reaches its lowest elevation in the sky at noon, leading to the shortest period of daylight and the longest night of the year. This is as a result of the earth’s axial tilting positions at its maximum inclination away from the sun.

4.2 Energy Generation Dynamics and Offset Potential

The energy performance of the dynamic PV integrated into the building façade was assessed based on both the generation potential of the PV slates, and the shading effects induced by their generation, as comprehensively illustrated in appendices A to F. Two distinct PV integration scenarios were considered. In the first scenario, PV slates were installed in close proximity with 0.005m spacing on the glazed façade. This minimal gap was designed to facilitate smooth tilting mechanisms while maximizing solar energy generation due to higher density of PV slates. Although this configuration enhances total energy yield, it also increases the likelihood of self-shading, potentially affecting the overall visual performance of the system.

The second scenario involved PV slates spaced at 0.091m, maintaining the same slate width, hence reducing shading susceptibility. By allowing more direct solar exposure across various angles, this configuration aimed to improve solar harvesting efficiency while reducing shading-induced losses. However, based on fundamental PV generation principles, the total energy output in this scenario is expected to be lower than in the first scenario, due to the reduced number of PV slates installed. The trade-off between generation efficiency and shading mitigation in these two configurations is critical in optimizing the overall performance of dynamic PV-integrated facades.

Figures 13 and 14 illustrate the optimal hourly tilt angles at which maximum solar energy generation is achieved, while Figures 4.4–4.7 present the corresponding photovoltaic (PV) generation profile for the office building across selected representative seasonal days. These findings highlight the dynamic nature of solar energy harvesting in relation to seasonal variations and optimal panel orientation.

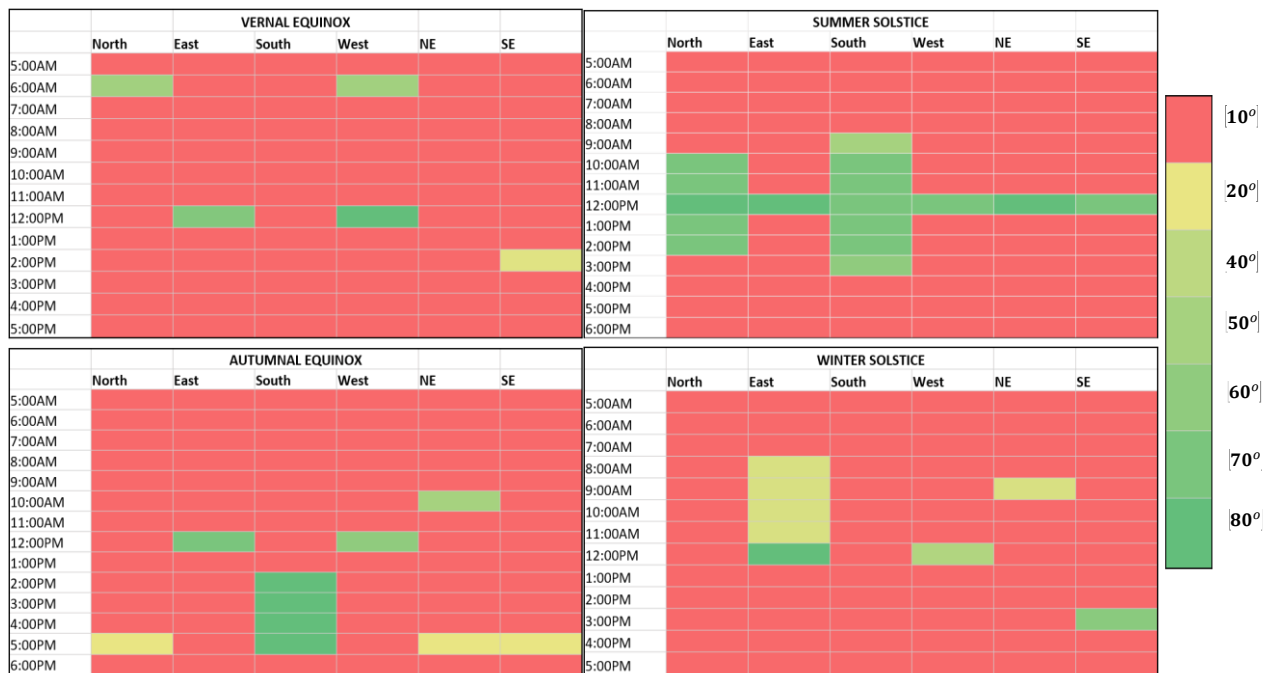


Figure 13 Heat Map Illustrating Closely Integrated PV Slate dynamism (Unspaced PV)

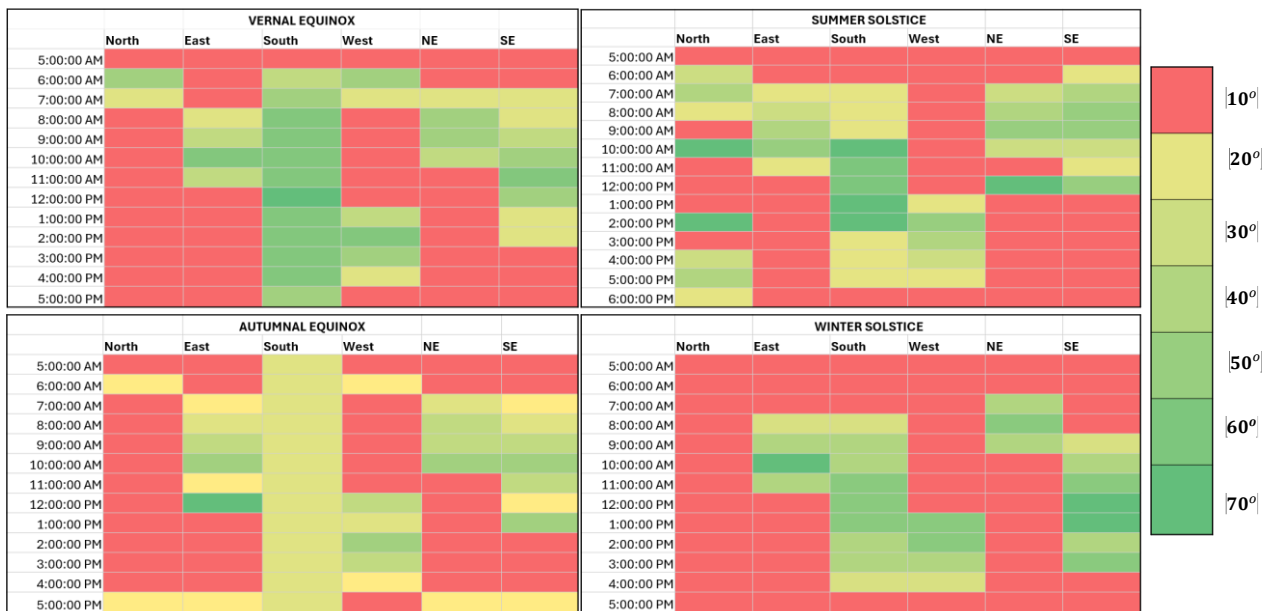


Figure 14 Heat Map Illustrating Spaced Integrated PV slate dynamism (Spaced PV)

4.2.1 Analysis of Solar Energy Generation During the Vernal Equinox

In both the vernal (spring) and autumnal equinoxes, energy consumption before 6am in both the first and second scenario occurs despite the absence of solar generation. These could be attributed to the baseline operation of essential systems, including a minimal percentage of lighting and cooling loads that remain active outside office hours to maintain thermal stability and operational efficiency. A similar trend is observed during the summer and winter solstices, though with notable variations in solar generation onset. As shown in Figure 15, solar generation begins around 5am during the summer solstice due to extended daylight hours, whereas during the winter solstice, generation is delayed until approximately 7am due to shorter daylight periods and a lower solar altitude.

The substantial PV generation recorded during the vernal equinox both scenarios is primarily a result of the synergistic contribution of multiple optimal tilt angles across all six orientations, which is even more pronounced in the second scenario as depicted in Figure 14. In the first scenario, despite a 10° tilt angle being predominant for most hours, localized optimal angles vary throughout the day. At 6am, the highest generation was recorded on the north and west orientations at 40° in both scenarios, with the south orientation having the maximum generation at 30° in the second scenario, demonstrating the influence of early morning solar incident angles. Although the recorded PV generation on the north and west orientations at 6am during the vernal equinox is extremely minimal (0.00.9002 kWh and 0.001835 kWh respectively), it remains notably greater than zero, unlike other tilt angles that exhibited no generation under the same condition. This observation demonstrates that a 40° tilt provides a favorable angular relationship with the early morning solar path, allowing for the capture of a small amount of diffuse or oblique solar radiation when all other angles result in total shading. By midday (12pm), higher energy yields were observed at tilt angles

of 50° and 60° on the east and west facades when the PV slates were closely installed, coinciding with the sun's higher altitude and increased irradiance intensity. The dynamic adaptation of tilt angles in the first scenario is further emphasized by the significant generation at 20° in the southeast orientation around 2pm, pointing out the benefits of an adaptive PV system in optimizing solar capture. Notably, the pronounced dynamism in the second scenario when the PV slates were spaced cannot be overemphasized, especially the south, west and southeast orientation as shown in Figure 14, bridging the gap between generation and PV self-shading.

From the cumulative perspective of both scenarios, the total energy generated on this representative vernal equinox day exhibits the potential to offset 62% of the building's energy demand when the PV slates were spaced, and 66% when the PV slates were closely installed. This finding substantiates the effectiveness of an adaptive PV system in harnessing seasonal solar variations to enhance almost self-sufficiency and reduce total grid dependency. Additionally, the ability to dynamically adjust tilt angles throughout the day contributes to maximizing generation efficiency, particularly in orientations that would otherwise yield suboptimal performance with fixed PV systems. These results align with existing research on solar tracking systems and dynamic façade integration, which emphasize the significance of adaptive PV orientations in maximizing energy yield under varying solar conditions (Svetozarevic et al, 2019). The findings further reinforce the necessity of incorporating dynamic solar strategies in building-integrated photovoltaic (BIPV) for enhanced energy resilience and sustainability in hot climate regions (Jayathissa, 2017).

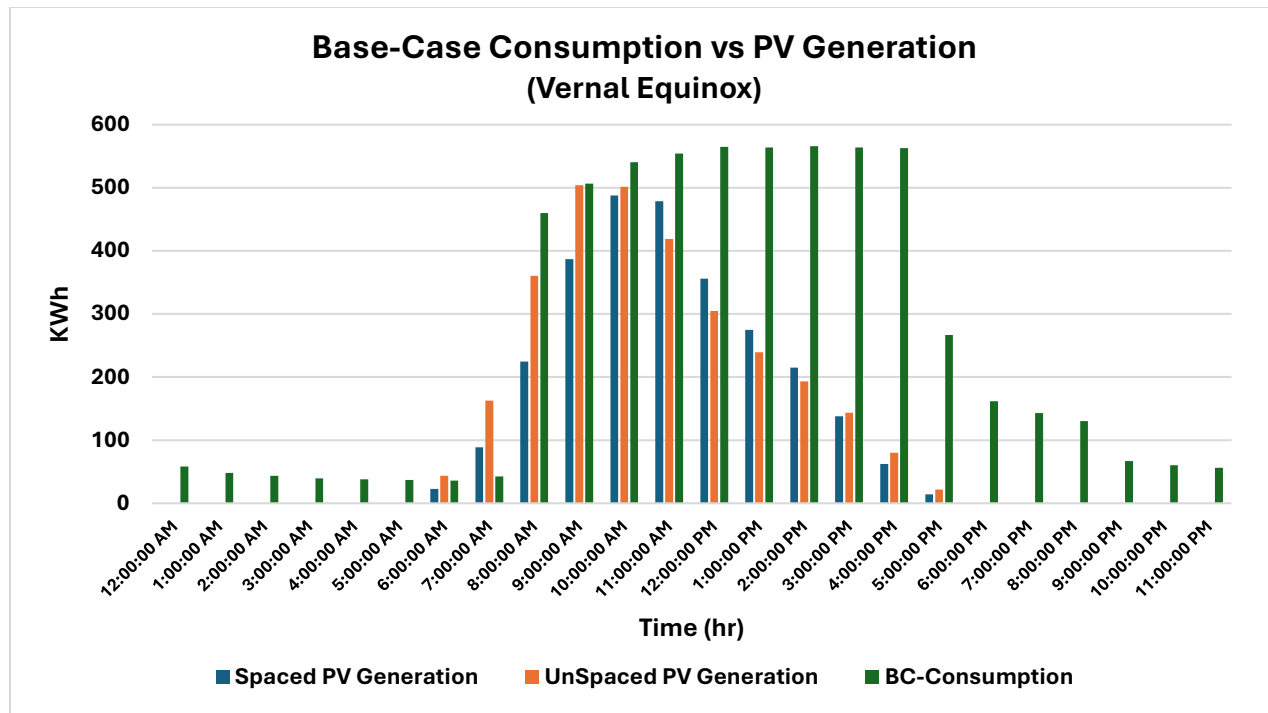


Figure 15 Hourly Comparison of Base-Case Energy Consumption vs Dynamic PV-Generation (Spaced & Unspaced) – Vernal Equinox

4.2.2 Analysis of Solar Energy Generation During the Autumnal Equinox

Similar to the vernal equinox, the autumnal equinox demonstrates a significant solar energy generation (represented by the blue bars in Figure 16) that can offset some percentages of the cumulative hourly energy consumption of the building. This substantial energy yield is primarily driven by the combined energy output from optimal slate angles across multiple orientations. The findings show the critical role of orientation-specific and dynamic adaptability of PV slate angle adjustments in maximizing energy yield during this representative day.

In the first scenario, the 10° angle dominates energy generation across all orientations from 6:00am to 9:00am, reflecting the low solar elevation, and capturing sufficient solar irradiance to initiate generation during early morning hours. As the sun's elevation increases, the optimal generation angle shifts dynamically. For instance, the north-east orientation achieves optimal generation at a

50° angle around 10:00am, coinciding with the sun's movement towards the southern sky. By 12:00pm, the east and the west orientations record their maximum generation at 70° and 60° angles for these orientations during midday, corresponding to the sun's higher altitude and increased radiation intensity.

In the afternoon, the south orientation achieves its highest generation at an 80° tilt from 2:00pm to 5:00pm. This steep angle is optimal for capturing the sun's lower elevation as it moves towards the western horizon. Similarly, as the solar altitude declines towards the evening, optimal generation transitions to 20° in the north, north-east and south-east orientations around 5:00pm, marking the final hour of energy generation for the day as illustrated in Figure 13.

Despite the absence of solar generation during the pre-dawn hours (before 6:00am) and the post-sunset period (after 6:00pm), as well as a relatively lower generation at 4:00pm due to declination and the solar irradiance during late afternoon hours, the total energy produced throughout the day has the potential to offset about 34% of the building's energy demand, demonstrating the potential for net-positive energy performance during autumnal equinox.

The second scenario is quite different both in generation and dynamism across all the six orientations. With the explicit dynamism across orientations, optimal generations were recorded at diverse angles, with maximum generation in the south orientation being recorded at 30° throughout the day, making it static as shown in Figure 14. The generation in this scenario illustrates the potential to offset up to 27% of the energy needed by the building.

The energy consumption recorded during non-generative hours is primarily attributed to the operation of essential lighting, cooling systems, and other equipment that remain active beyond solar generation hours, ensuring continuity in indoor environmental quality and occupant comfort.

Nevertheless, the energy generated during peak hours compensates for the partial building energy consumption, illustrating the effectiveness of the dynamic PV system in meeting the building's energy needs. These findings reaffirm the efficacy of an adaptive PV system in optimizing solar energy utilization, particularly during transitional seasonal periods such as the equinoxes. The capacity to dynamically adjust tilt angles not only enhances energy capture efficiency but also contributes to sustainability. Furthermore, the ability of the system to partially meet daily energy demands despite intermittent shortfalls in specific hours demonstrates the potential of dynamic building-integrated photovoltaics (dBIPV) in achieving energy self-sufficiency, even in scenarios with varying seasonal solar angles.

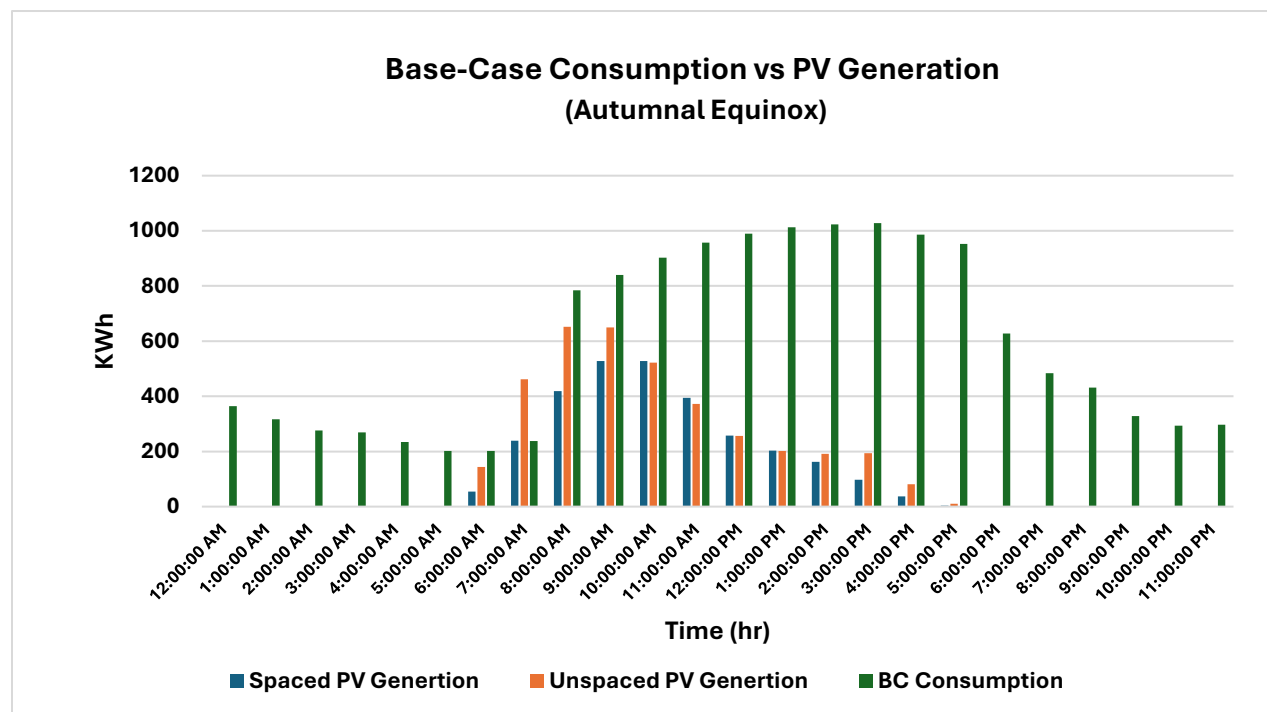


Figure 16 Hourly Comparison of Base-Case Energy Consumption vs Dynamic PV-Generation (Spaced & Unspaced) – Autumnal Equinox

4.2.3 Analysis of Solar Energy Generation During the Summer Solstice

The summer solstice exhibits distinct energy generation patterns compared to the other representative days, primarily due to the extended daylight hours and the sun's higher trajectory in the sky. As illustrated in Figure 17, the early onset generation was recorded around 5:00am in the first scenario, a phenomenon primarily driven by the early sunrise in the northeast, which results in significant advantage and immediate energy capture by the panels orientated towards the north, east, northeast, and southeast during the early morning hours.

Between 6:00am and 8:00am, the 10° angle dominates energy generation across all six orientations, reflecting the low solar elevation during this period. This consistency in optimal angle in this scenario shows the efficiency of shallow tilt angles for capturing early morning sunlight. By 9:00am, the optimal tilt angle shifts, with the south-facing PV panels achieving peak generation at 50° , aligning with the increasing solar altitude. Between 10:00am and 2:00pm, a distinctly similar generation pattern is observed in the north and south orientations, with maximum output recorded a tilt angle of 70° and 80° respectively. These steeper tilt angles are optimal for capturing the high solar elevation during midday. The south orientation's slate angle is adjusted to 60° to maximize energy generation, while other orientations achieve their peak output at 10° , benefitting from lower incidence angles as the sun moves westward. This divergence in optimal angle illustrates the importance of orientation-specific adjustments to account for the sun's azimuth and elevation during the afternoon. Unlike other seasonal days, solar generation extends up to 6:00pm, but only in the north and south orientations, due to their favorable alignment with the sun's prolonged trajectory during the summer solstice.

Although the first scenario (closely installed PV slates) achieved a higher total energy generation of approximately 600KW surpassing the second scenario by 21% during the autumnal equinox and summer solstice, other critical trade-offs must be considered when selecting the optimal design.

The spaced PV slates configuration (second scenario), despite having only half the PV density of the first scenario, demonstrated a significant capacity for dynamic energy generation by harnessing solar energy from multiple angles throughout the day. With tilt angles varying between 10° and 70° , this configuration effectively offset 86% of the building's total energy demand. In contrast, the closely installed PV slates (first scenario) achieved 108% offset, fully meeting and exceeding the building's energy needs on this representative day. This portrays the importance of PV adaptiveness, where dynamic tilt adjustments enhance energy capture efficiency and contribute to a more flexible and responsive solar energy harvesting strategy.

During the early hours of the day, the solar generation reaches approximately 400kwh, covering roughly 50% of the hourly operational energy demand. However, the generation falls drastically after 10:00 am, making shift in the energy balance. This decline in generation efficiency can be attributed to several interrelated factors such as elevated atmospheric temperature, which can have a negative impact on photovoltaic efficiency, reducing power output due to increase semiconductor resistance and reduced voltage performance. Another possible justification is the shading effects in the closely installed PV slates – as the sun moves higher in the sky, self-shading from PV slates may partially obstruct direct solar exposure, diminishing generation capacity. The low wall window-to-wall ratio (WWR) in the west orientation of the studied building can also reduce the system's ability to capture and convert solar energy effectively during late afternoon hours.

However, despite all these challenges, the total energy generated during the summer solstice remains significant, proving the system's overall effectiveness in harnessing solar energy during

periods of extended daylight. The findings show the importance of accounting for seasonal variations in solar geometry and environmental conditions when designing and operating dynamic PV systems. The ability to adjust slate angles dynamically in response to the sun’s position and to mitigate efficiency losses due to temperature and shading effects is significant for enhancing energy yield.

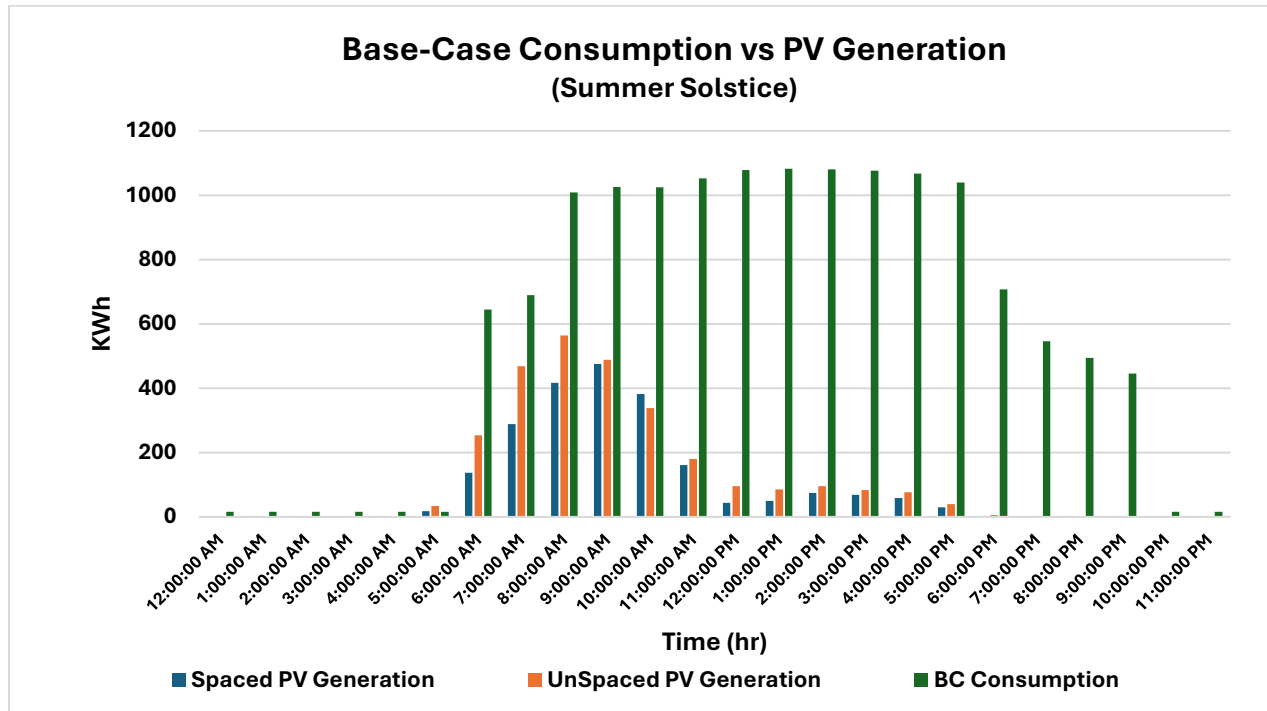


Figure 17 Hourly Comparison of Base-Case Energy Consumption vs Dynamic PV-Generation (Spaced & Unspaced) – Summer Solstice

4.2.4 Analysis of Solar Energy Generation During the Winter Solstice

As established, the winter solstice represents the seasonal period with the shortest daylight hours and the longest night. However, despite this constraint, the analysis in both scenarios reveals that the highest cumulative solar energy generation with the dynamic PV was achieved on this representative day. The findings show the effectiveness of adaptive tilt optimization in maximizing energy yield even under suboptimal solar conditions.

As illustrated in Figure 18, no energy generation was recorded across all six orientations between 5:00am and 6:00am in both scenarios, reflecting the absence of sunlight during these early hours. The first instance of energy generation in the close PV slate scenario was recorded at 7:00am, with optimal PV performance in the north and south orientations at a tilt angle of 10° , effectively aligning with the low winter sun angle.

The dynamism of the PV system is further demonstrated by the orientation-specific adjustments required to maximize energy generation throughout the day. For instance, the east orientation achieved optimal generation at a 20° angle between 8:00am and 11:00am. Similarly, the northeast orientation recorded optimal generation at 20° angle at 9:00am, while the southeast orientation achieved its peak output at 40° angle around 3:00pm. The east and west orientation also demonstrate dynamic optimization, with optimal generation recorded at 50° and 30° angles respectively, around 12:00pm, aligning with the sun's midday position. These variations in optimal slate angles show the importance of real-time adjustments to align with the sun's low and variable trajectory during the winter months, though the system ceases energy generation at 4:00pm, marking the end of the daily solar energy harvesting period.

Similar to the scenario with closely installed PV slates, no energy generation was recorded across all six orientations between 5:00 am and 6:00 am. The first instance of energy generation occurred at 7:00 am, with the northeast-facing PV slates tilting to 30° , while the remaining five orientations maintained a tilt angle of 10° . Although the second scenario (spaced PV slates) followed the same general energy generation pattern as the first scenario throughout the day (Figure 18), key differences emerged in the optimal generation angles and tilt dynamism. Notably, the second scenario exhibited greater tilt variability. Enhancing overall energy harvesting efficiency. However,

in the north-facing orientation, the PV slates consistently maintained a tilt angle of 10° throughout the day (Figure 14).

While building energy consumption did not extend beyond the active solar generation window in the first scenario, the second scenario achieved an energy offset of up to 74% of the total building energy demand. Despite operational loads being recorded more than five hours before the first-generation event and continuing beyond the final generation period, the total daily solar output was substantial enough to partially meet the building's energy needs in the second scenario. However, under the first scenario (closely installed PV slates), the higher overall energy yield allowed for the complete fulfillment of total energy demand, demonstrating the superior performance of this configuration in achieving full energy self-sufficiency. This indicates that the energy harvested during the winter solstice has the potential to offset substantial building energy required. The excess energy produced in the first scenario explains the efficacy of seasonal adaptability in dynamic PV integration, ensuring consistent performance even during periods of limited daylight.

The unexpectedly high cumulative generation observed during the winter solstice can be attributed to several key factors. Firstly, the lower solar incidence angles in winter result in more consistent and prolonged exposure to optimally titled PV panels, particularly at steeper angles. The dynamic PV system effectively aligns with these angles, ensuring maximum perpendicular irradiance capture, which enhances efficiency. Another major factor contributing to this trend is improved photovoltaic efficiency at lower temperatures. Unlike in summer, where high ambient temperatures lead to increased semiconductor resistance and reduced voltage output, winter conditions provide an optimal cooling effect on PV modules, thereby enhancing power conversion efficiency.

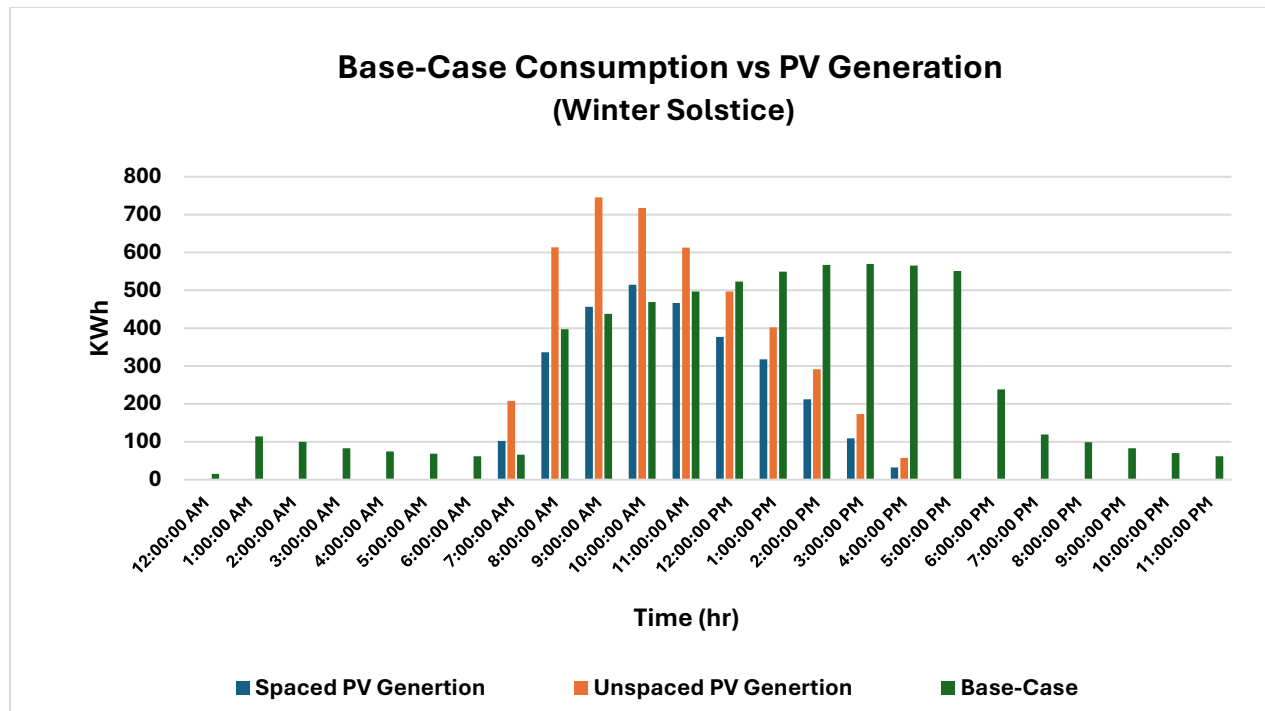


Figure 18 Hourly Comparison of Base-Case Energy Consumption vs Dynamic PV-Generation (Spaced & Unspaced) – Winter Solstice

4.3 Impact of Dynamic PV Shading on Building Energy

Performance

The energy performance assessment of the building integrated with dynamic PV (dPV) technology encompasses two critical aspects: the generation potential of the dPV system and the shading effects resulting from the installation of PV slates. While the generation potential of the dPV technology has been extensively discussed, it is equally important to examine the passive effects of PV-induced shading on indoor cooling loads, daylighting, and overall building energy performance.

The shading effect of the integrated PV slates primarily results from the dynamic movement influencing solar penetration through windows and, consequently, the indoor thermal environment. Figure 19-22 illustrates the impact of shading on the energy consumption of the studied building

across the four representative seasonal periods. The analysis reveals that the extent of energy reduction due to shading varies based on the mode of PV installation, seasonal solar angles, duration of daylight exposure, and the extent of coverage provided by the PV panels at different times of the day.

With the consideration of only the shading effect on the building energy consumption, the reduction in the building energy consumed during the vernal equinox is observed to be relatively low before 8:00am, but becomes significant between 8:00am and 5:00pm, with an average reduction of approximately 25% when the PV slates were closely installed, and 26% when they were spaced. This trend suggests that the PV shading effect is more pronounced during peak solar radiation hours, reducing the thermal load on the building by minimizing direct solar heat gain through glazed surfaces. The cumulative daily energy reduction due to shading during this representative period is estimated to be around 27%.

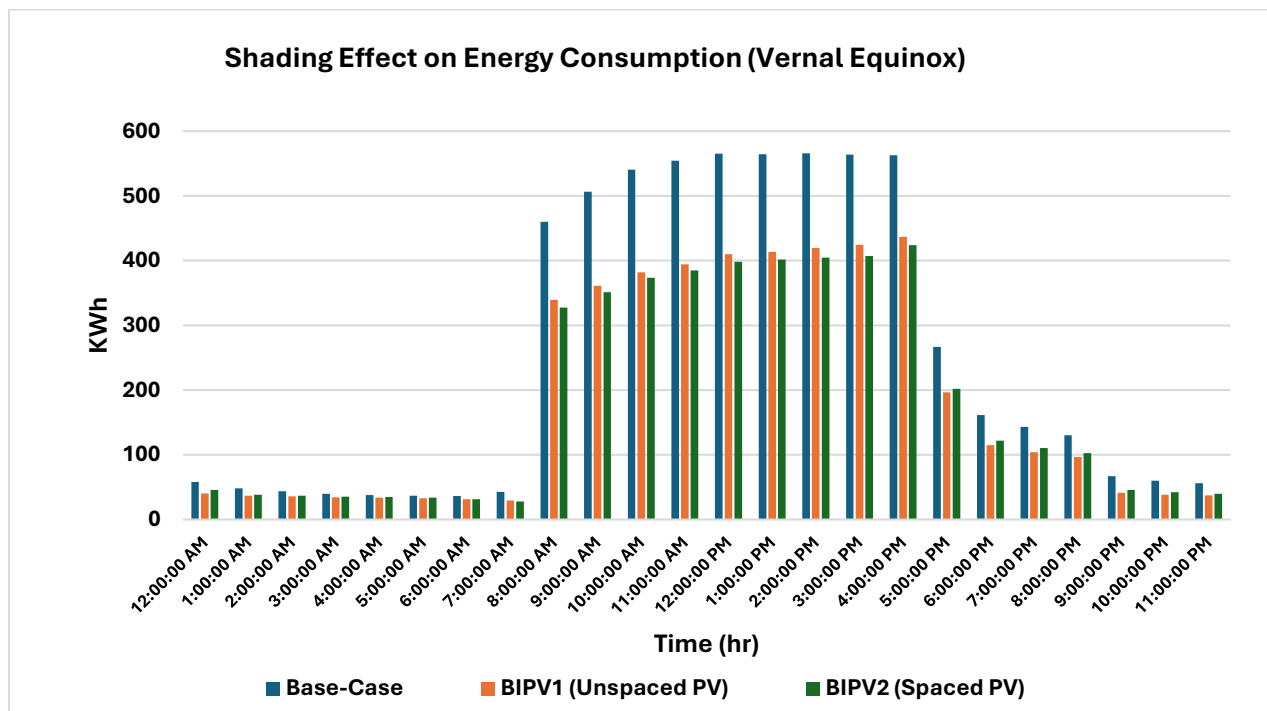


Figure 19 Reduction in Energy Consumption due to Shading Effect – (Vernal Equinox)

A similar trend is observed during the autumnal equinox and summer solstice, where the cumulative energy savings due to shading effects are 24% and 26% respectively in the first scenario (closely installed PV slates), and 22% and 27% reduction in the second scenario. The reduction observed in the summer solstice is likely due to extended daylight hours and higher solar intensities, which increase the overall cooling demand despite the shading effect. Research by (Zomorodian et al., 2016) explained that while shading devices reduce peak cooling loads, building with extensive exposure to solar radiation in summer may still require additional passive or active cooling strategies to achieve optimal indoor thermal comfort.

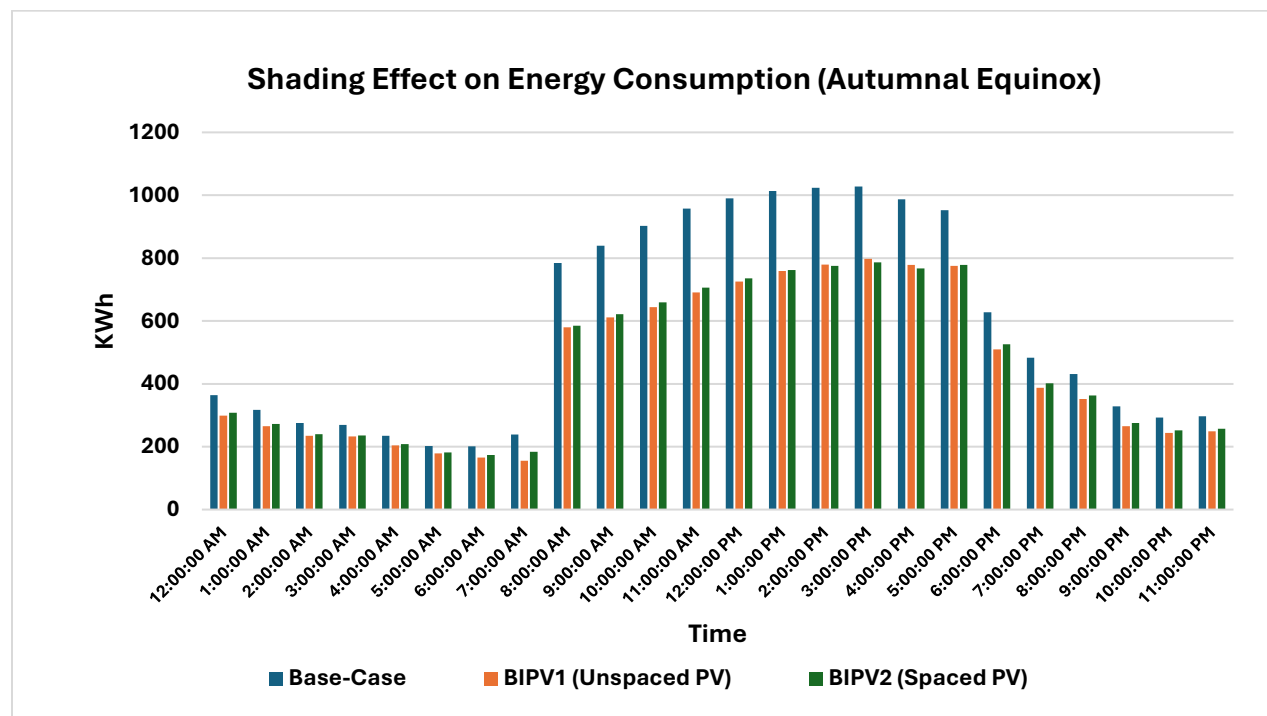


Figure 20 Reduction in Energy Consumption due to Shading Effect – (Autumnal Equinox)

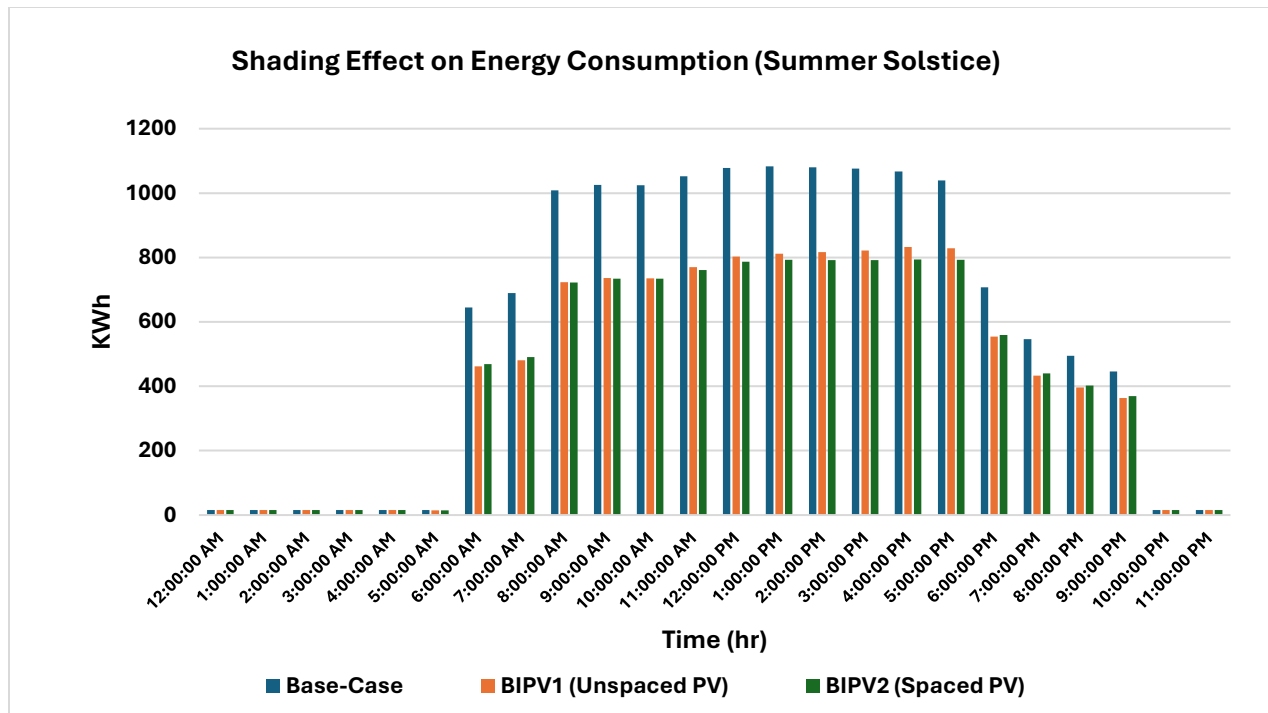


Figure 21 Reduction in Energy Consumption due to Shading Effect – (Summer Solstice)

However, the winter solstice exhibits a unique energy reduction pattern, where the average hourly energy savings due to shading reached 42% and 47% in both the first and second scenario respectively, with the cumulative daily reduction approximately around 41% and 39% which is very significant. To provide clearer insight beyond the relative percentages, the energy savings were also assessed using absolute consumption (kWh). For instance, at 10am and 11am, the energy consumed by the base-case considering the first scenario was recorded at 469.34 kWh and 497.12 kWh respectively. With the integration of the dynamic PV slates, these values were reduced to 272.65 kWh and 288.46 kWh, demonstrating the substantial savings at the stated hours. Over the entire winter solstice, the base-case (closely installed PV) accounted for a cumulative energy consumption of 6381 kWh, whereas, with the integration of the dynamic PV slates, the total consumption reduced 3766 kWh. The slightly higher reduction observed in the winter solstice as shown in Figure 22 can be attributed to lower angles, which result in longer shadow projections.

This effect aligns with findings in prior research, which suggests that dynamic shading strategies can significantly reduce solar heat gains in winter without compromising daylight access when properly controlled (Tzempelikos & Athienitis, 2007). This is supported by the observed data; although winter presents lower solar irradiance, the shading further contributes to a measurable reduction in heating or cooling loads, especially in climates where solar overheating is a concern even during cooler seasons due to glazing orientation or internal gains.

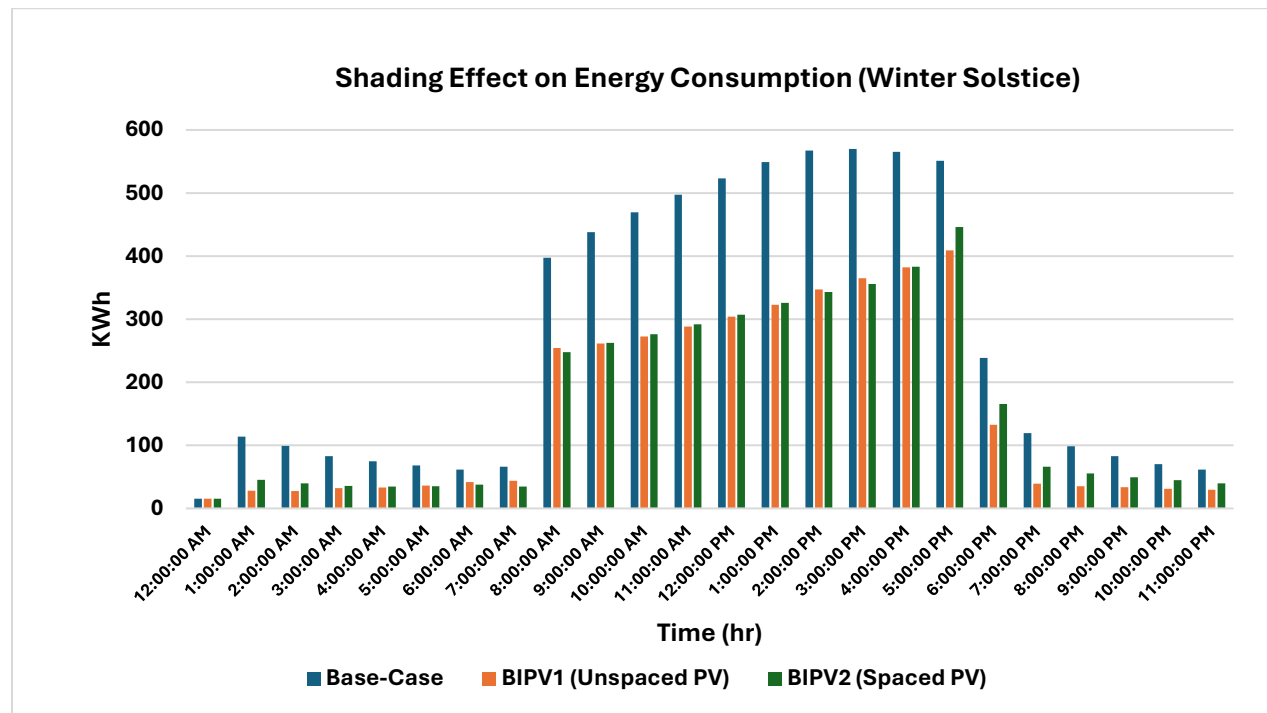


Figure 22 Reduction in Energy Consumption due to Shading Effect – (Winter Solstice)

Furthermore, the energy consumption trend observed 5 hours before sunrise (approximately 5:00am) remains nearly identical for both the base-case building and the building integrated with dPV technology. This consistency indicates that shading effects are primarily relevant during daylight hours, reinforcing the importance of considering dynamic PV shading as a part of an overall energy efficiency strategy.

In general, the findings emphasize the dual benefits of dynamic PV technology; not only as an active energy generation system but also as a passive shading device that contributes to energy demand reduction. The effectiveness of shading in lowering energy consumption varies seasonally, with higher percentage savings during periods of moderate daylight exposure (vernal equinox and solstices), and relatively lower cumulative savings during the approximate equal day and night periods (autumnal equinox). The integration of dynamic PV shading in buildings, when optimized, can lead to substantial reductions in cooling energy demand, mitigating overheating risks and enhancing overall building energy efficiency.

4.3.1 Shading Impact on Cooling and Lighting Energy Demand

The impact of shading on building energy requirements for cooling and lighting was analyzed comprehensively. In the base case, where no prior daylight obstructions were present, the installation of PV slates introduced variations in artificial lighting demand. As expected, the artificial lighting energy requirement increased in both shading scenarios due to the obstruction of natural daylight. However, the extent of this increase varied depending on the spacing of the PV slates and the seasonal period. When the PV slates were installed in close proximity, the reduction in daylight penetration was more significant, leading to a higher increase in artificial lighting demand. Conversely, when the PV slates were spaced apart, daylight penetration was less obstructed, resulting in a comparatively lower increase in lighting energy demand.

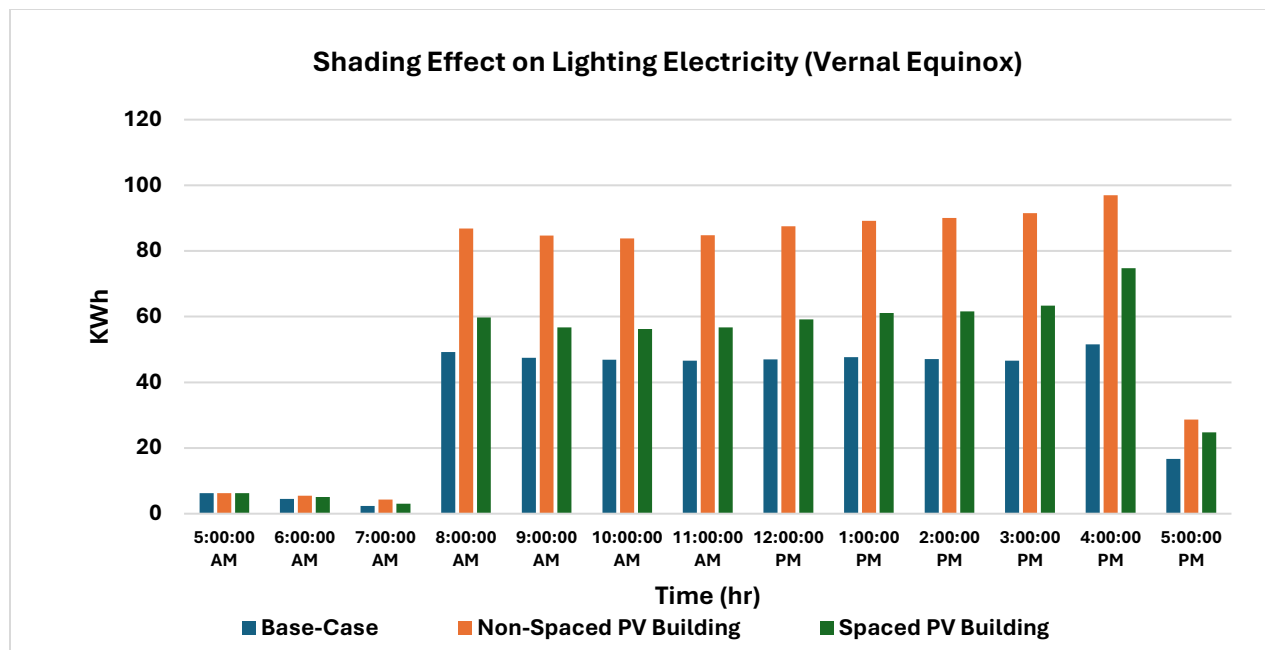


Figure 23 Increment in Lighting Electricity due to Shading Effect - (Vernal Equinox)

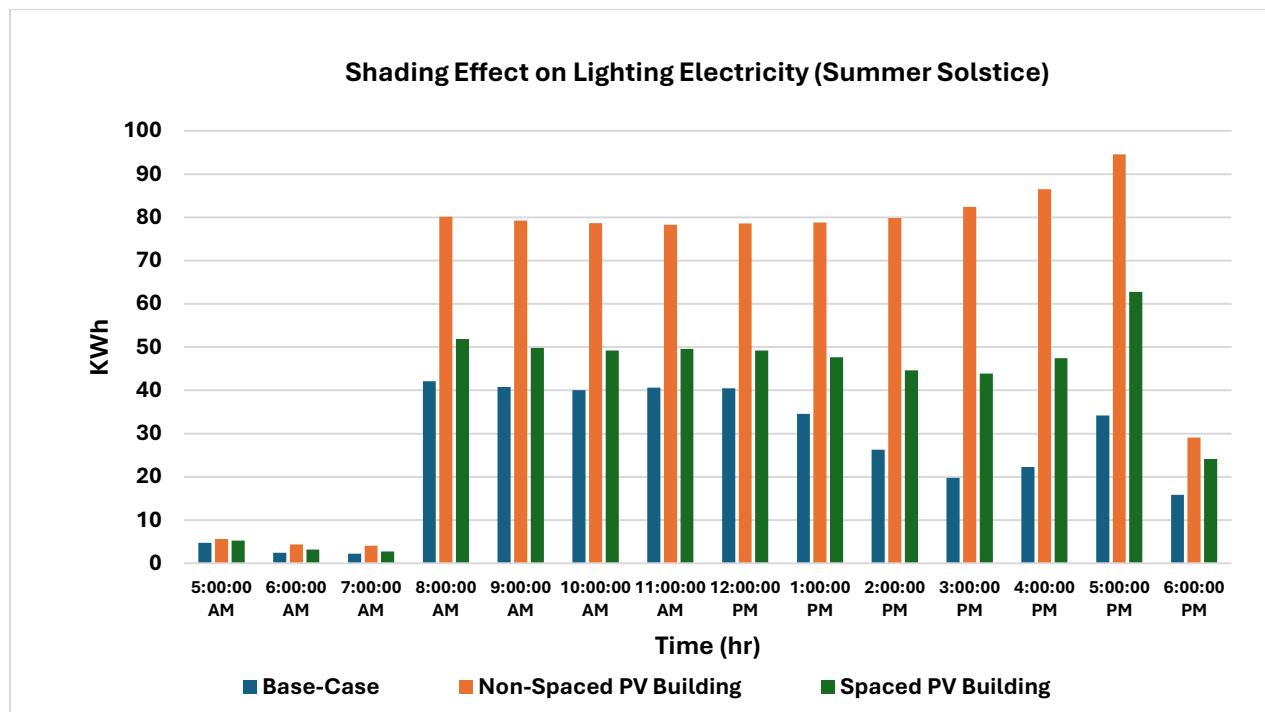


Figure 24 Increment in Lighting Electricity due to Shading Effect - (Summer Solstice)

For instance, during the vernal equinox, the artificial lighting energy demand increased by 45% and 22% in the first (closely installed PV slates) and second (spaced PV slates) scenarios, respectively. Similarly, lighting demand increased by 49% and 26% in the autumnal equinox, 57% and 31% in the summer solstice, and 56% and 24% in the winter solstice. These variations indicate that while PV shading effectively reduces heat gain, it may inadvertently increase artificial lighting needs, especially in scenarios with denser PV slate arrangements. Figure 23 - 26 presents the percentage increase in lighting energy demand for both scenarios across the four representative seasonal periods.

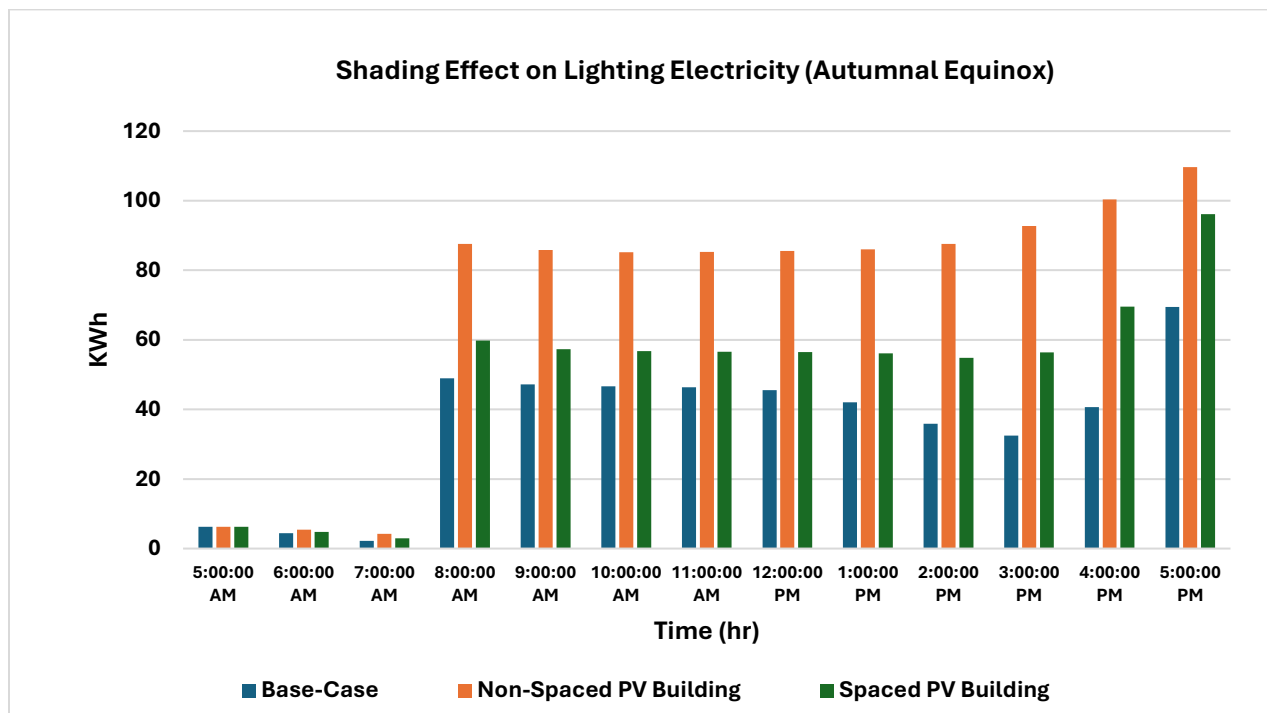


Figure 25 Increment in Lighting Electricity due to Shading Effect - (Autumnal Equinox)

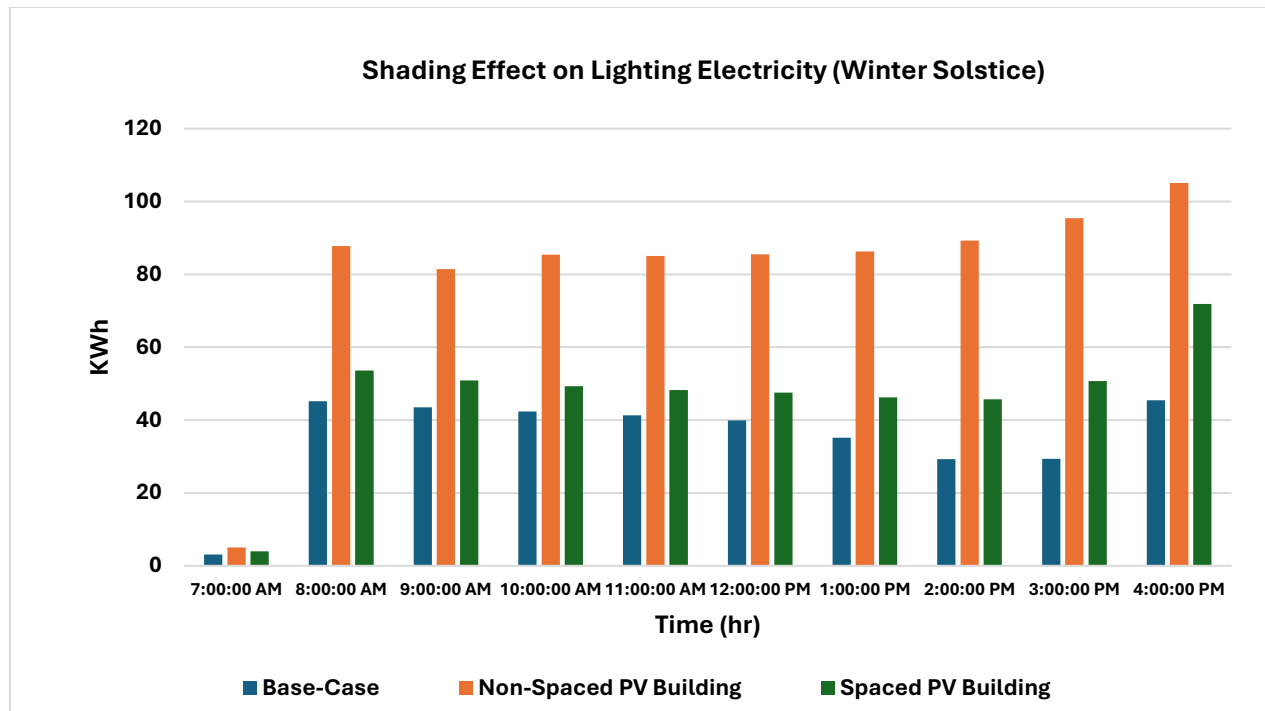


Figure 26 Increment in Lighting Electricity due to Shading Effect - (Winter Solstice)

In contrast, the cooling energy requirement exhibited an inverse trend. Significant reductions in cooling energy demand were observed in both shading scenarios due to reduced solar heat gain through the glazed areas. When the PV slates were closely installed, the cooling energy savings were more pronounced, suggesting a more effective reduction in direct solar exposure. In comparison, the spaced PV slates allowed partial solar penetration, leading to a relatively lower cooling energy reduction. For example, during the vernal equinox, cooling energy consumption decreased by 48% and 39% in the first and second scenarios, respectively. The reduction was 29% and 25% in the autumnal equinox, 28% and 27% in the summer solstice, and 68% and 52% in the winter solstice. The more substantial cooling energy reduction observed in the first scenario is attributable to the minimized heat gain due to the denser PV slate arrangement, effectively blocking solar radiation. However, in the second scenario, some degree of solar radiation still penetrates through the exposed glazed sections, contributing to a less cooling energy reduction.

While the percentage reductions offer useful insights, they are relative to the total energy use, which varies significantly between seasons. For instance, during the summer solstice, the base-case cooling energy demand reached 8638.58 kWh, and was reduced to 6220.1 kWh and 6326.1 kWh in both Unspaced and spaced PV scenarios, respectively- indicating absolute savings of over 2300 kWh. In contrast, during the winter solstice, although the percentage reduction reached 68% and 52%, the base-case consumption was notably lower at 2098.08 kWh, with the closely installed PV reducing it to 677.27 kWh and the spaced configuration to 1008.15 kWh. These figures illustrate that while the winter percentage savings appear higher, the absolute cooling energy reduction was more significant during summer, further emphasizing the seasonal variation in cooling demand.

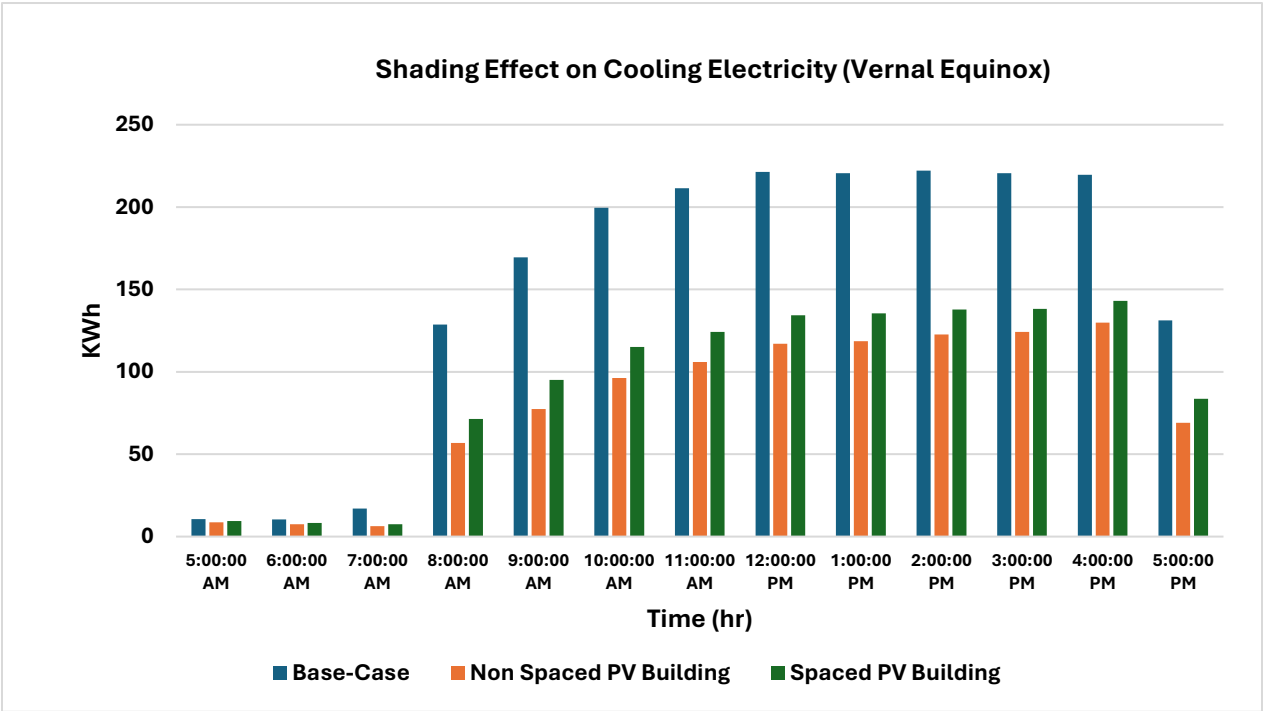


Figure 27 Reduction in Cooling Electricity due to Shading Effect - (Vernal Equinox)

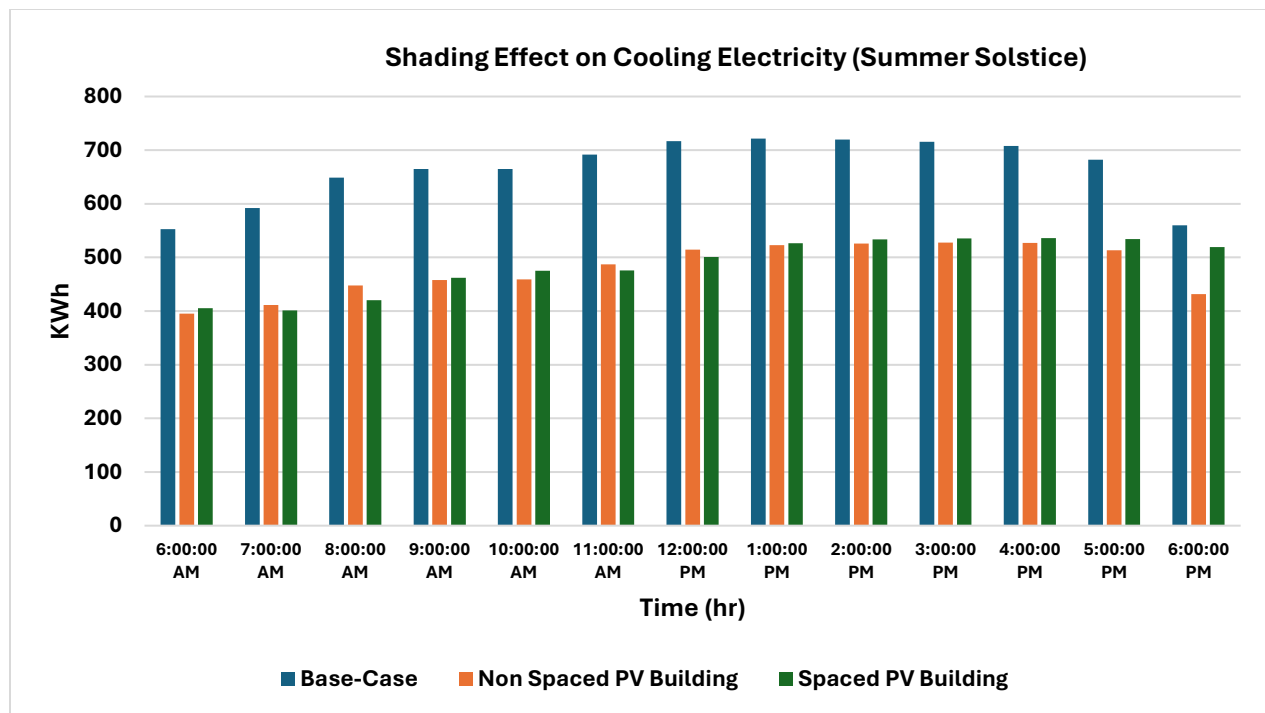


Figure 28 Reduction in Cooling Electricity due to Shading Effect - (Summer Solstice)

To moderate the increased artificial lighting energy demand while maximizing cooling energy savings, an optimized balance between daylight utilization and shading ought to be explored. A potential improvement includes incorporating high-performance glazing with a high R-value and low U-value, which would further enhance thermal insulation while maintaining adequate daylight levels. Additionally, the use of electrochromic glazing could offer adaptive control over daylight admission and thermal comfort, improving overall energy efficiency. Figure 27 – 30 illustrates the extent of cooling energy reduction observed in both scenarios across the four seasonal periods.

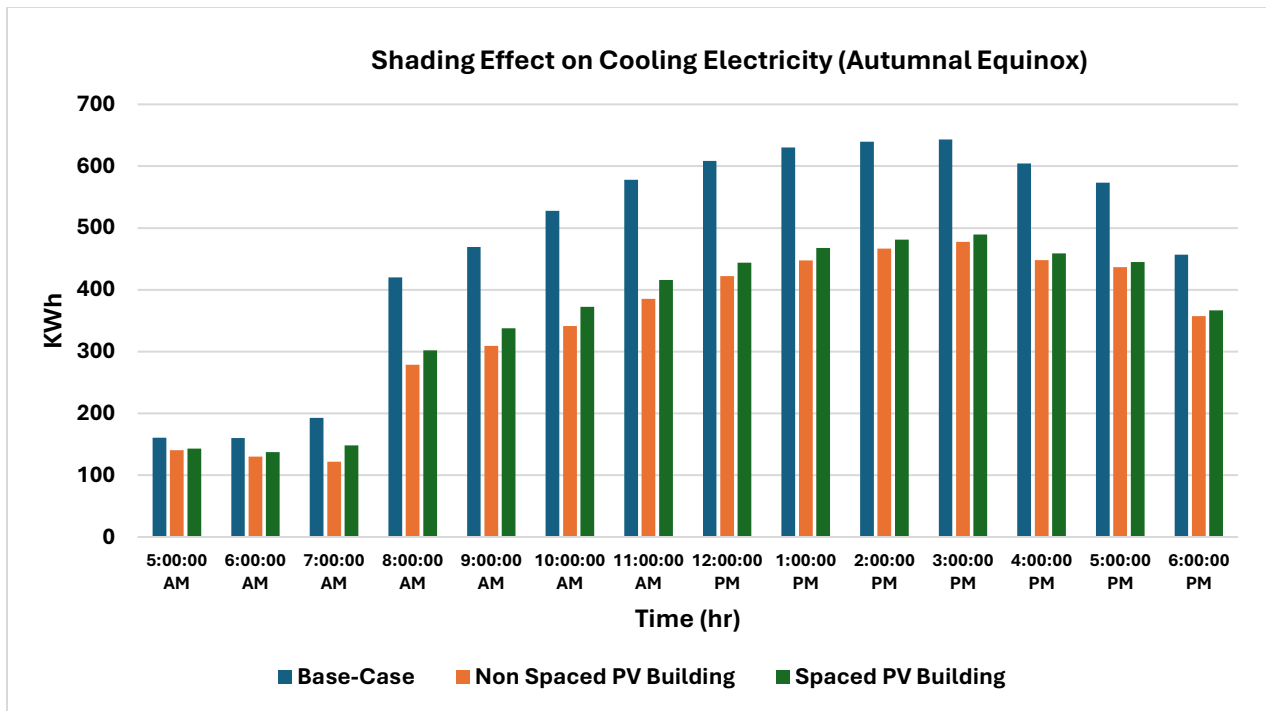


Figure 29 Reduction in Cooling Electricity due to Shading Effect - (Autumnal Equinox)

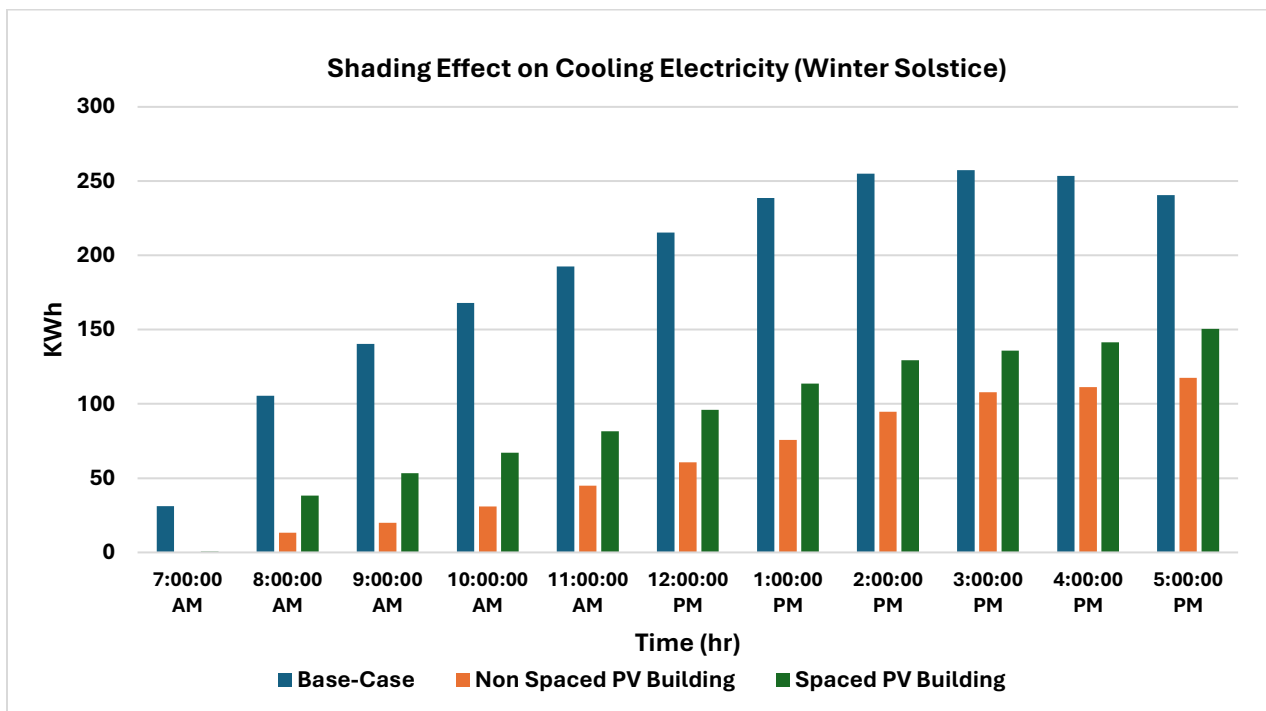


Figure 30 Reduction in Cooling Electricity due to Shading Effect - (Winter Solstice)

4.4 Visual Performance Analysis

Visual Performance in any habitable space is a key factor, not only for energy efficiency but also the well-being, productivity, and comfort of occupants. This fact was reinforced by (Reinhart et al., 2006), stating that daylighting has proven to reduce reliance on artificial lighting, enhance occupant productivity, and thereby contributing to energy savings and sustainability in building design. Beyond reducing reliance in artificial lighting, studies have also established that daylight exposure has profound benefits, including improved cognitive function, mood enhancement, and overall health (Boyce, 2003). Similarly, it has been consistently demonstrated that access to natural daylight offers significant psychological and psychological benefits, including improved mood, reduced eye strain, and enhanced performance (Boyce, 2003).

As a result. Daylight analysis has become an integral part of modern architectural design, particularly in high-performance and sustainable buildings. Effective daylight strategies influence space usage, visual comfort, and occupant satisfaction, while also addressing critical issues such as direct sunlight exposure, illumination levels, discomfort glare, and the uniform distribution of light across the working plane (IES, 2013). A well-designed building that incorporates daylighting analysis can significantly reduce artificial lighting usage, leading to substantial energy savings and improved occupant sat (IES, 2012; LEED v4.1, 2020).

The integration of dynamic photovoltaic (PV) systems on glazed areas of building envelopes introduced a complex trade-off between energy generation and daylighting availability. While dynamic PV serves as energy-generating components, they also act as solar shading devices, modulating daylight penetration into the interior space. This shading effect influences the sDA, a metric that quantifies daylight sufficiency in indoor environments (IES, 2013).

Spatial Daylight Autonomy (sDA) describes the percentage of an analyzed space that receives a minimum illuminance level for a specified fraction of annual operating hours. According to LEED v4 guidelines, a space meets the daylighting credit if at least 50% of the occupied area receives 300 lux of daylight for at least 50% of the annual occupied hours (sDA_{300, 50%}) (USGBC, 2013). This metric helps evaluate the effectiveness of daylight utilization and determines whether a space requires supplementary artificial lighting. LEED v4 .1 outlines specific threshold for sDA to award daylighting credits, as detailed in Table 10.

Table 10 LEED v4.1 Thresholds for Spatial Daylight Autonomy (sDA) Credits (U.S. Green Building Council's (USGBC) LEED v4 guidelines)

sDA (300/50%)	LEED Daylighting Credit	Description
≥ 55%	1 Point	At least 55% of the regularly occupied floor area achieves sDA 300/50%, meaning it receives at least 300 lux for 50% of the annual occupied hours.
≥ 75%	2 Points	At least 75% of the regularly occupied floor area meets the same sDA 300/50% criteria.
≥ 90%	3 Points	At least 90% of the regularly occupied floor area meets the sDA 300/50% requirement, maximizing daylight access.

Note: sDA 300/50% indicates that a space receives a minimum of 300 lux for at least 50% of the annual occupied hours, as per LEED v4.1 daylighting credit requirements.

4.4.1 Impact of PV Tilt Angles on Daylighting Performance

The visual performance analysis of the studied building when the PV were closely installed indicates that PV tilt angles of 10°, 20°, and 30° fail to meet the minimum sDA threshold as depicted in Table 11. These tilt angles position the PV panels nearly vertical, leading to significant daylight obstruction and suboptimal indoor illumination levels. Consequently, the space experiences near-dark conditions, failing to achieve the 300 lux for at least 50% of occupied hours requirement

(Figure 31). This finding shows the daylight-energy trade-off, where maximizing solar energy generation compromises interior daylighting performance.

At a 40° tilt, partial compliance with sDA requirements is observed, particularly in south, east and southeast orientations. However, this compliance is orientation-dependent, with north and south orientations achieving 40° tilts during the early hours of the vernal equinox. A higher window-to-wall ratio (WWR) in west-facing facades may improve sDA compliance, but artificial lighting remains necessary to maintain adequate illumination. However, even with the increment in lighting energy when the PV slates were spaced, the design still complies with the sDA requirements, with the least accessed tilt angle meeting the minimum illuminance requirement for least 50% of the occupied hours as shown in Figure 32.

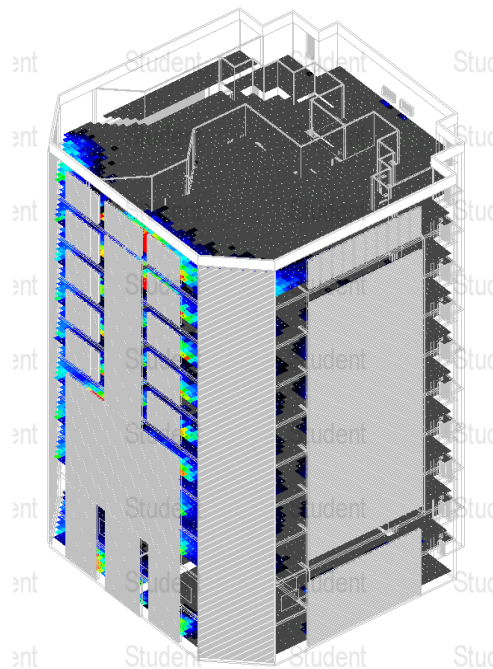


Figure 31 Suboptimal Daylight Performance: sDA and UDI Criteria Unmet

Conversely, tilt angles of 50°, 60°, 70°, and 80° when the PV were closely installed exhibit full sDA compliance across all orientations, ensuring sufficient daylighting within the space. However, these

angles come at the expense of solar energy generation, as the incident solar radiation on the PV slate decreases with increasing tilt angles (Duffie & Beckman, 2013). This reduction in solar exposure directly impacts energy yield, presenting a challenging trade-off between daylight accessibility and energy performance.

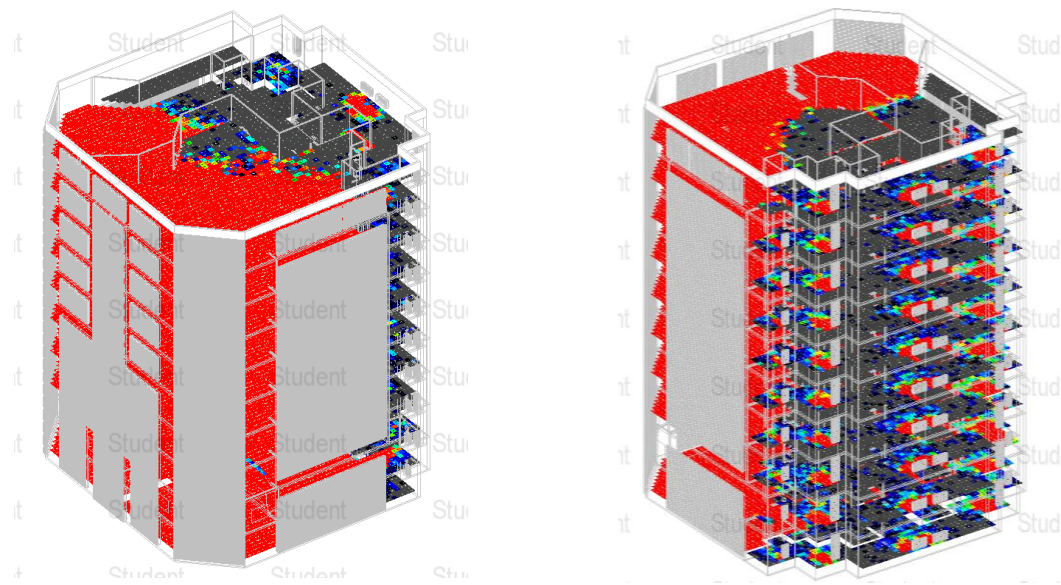


Figure 32 Optimized Daylight Distribution: Fulfilment of sDA and UDI Criteria

4.4.1.1 Useful Daylight Illuminance (UDI) Analysis

Useful Daylight Illuminance (UDI) is a robust and occupant-centric metric for evaluating the annual distribution of Daylight levels within an indoor space. It categorizes daylight illuminance levels into ranges that reflect occupant comfort, visual usability, and energy efficiency. The concept was first introduced by (Nabil & Mardaljevic, 2006) as an enhancement to traditional daylight performance metrics, providing a more occupant-centric approach to daylight evaluation.

Unlike static illuminance metrics, UDI acknowledges the dynamic nature of daylight availability and its implications for visual comfort, productivity, and artificial lighting demand. It classifies daylight exposure into three distinct bands, namely.

UDI-f (fell short), this range represents an illuminance level below 100 lux, which is generally considered insufficient for most visual tasks. Spaces with a high percentage of UDI-f may require supplemental artificial lighting to meet occupant needs, leading to increased energy consumption and reduced visual comfort (Nabil & Mardaljevic, 2006). The second category of the metric is the UDI-s (supplementary). The UDI-s range encompasses illuminance levels between 100 and 2000lux, which are deemed optimal for occupant comfort and usability. This range is associated with comfortable daylighting conditions that support a wide range of activities without causing glare or visual discomfort. Achieving a high percentage of UDI-s indicates that space is effectively daylit during occupied periods, reducing the need for artificial lighting and enhancing energy efficiency (Nabil & Mardaljevic, 2006).

UDI-e (Excessive) is the last category of the UDI, this range includes illuminance levels above 2000 lux, which may lead to glare, visual discomfort, or thermal discomfort due to excessive solar heat gain. High levels of UDI-e can negatively impact occupant productivity and well-being, necessitating the use of shading devices or other glare control strategies to mitigate these effects (Reinhart et al., 2006)

The integration of dynamic photovoltaic PV slates within the glazed area of the studied building showcases an interplay between daylight accessibility and energy generation. The analysis of the UDI in relation to different PV tilt angles highlights the trade-offs between solar energy optimization and visual comfort when the PV slates were closely installed and when they were spaced.

For the closely installed PV slates, tilt at 10° in most orientations fails to meet the useful daylighting illuminance threshold, aligning with findings from the Spatial Daylight Autonomy (sDA) analysis, where the near-vertical alignment of the PV slates at 10° caused almost total blockage of daylight as illustrated in Table 11. Consequently, there is little to no daylight available for distribution within space, resulting in illuminance levels that predominantly fall within the UDI-F range (below 100lux). This outcome shows the challenges of achieving adequate daylighting at lower tilt angles, despite their potential for maximizing solar energy generation.

PV tilt at 20° and 30° angles partially fulfil the UDI threshold, with illuminance levels falling within the moderate range of UDI-s. While daylight penetration improves compared to the 10° tilts, the distribution of daylight remains suboptimal, particularly in orientations where the PV slates still block significant amounts of natural light. This partial compliance highlights the need for careful consideration of tilt angles to balance energy generation and daylighting performance. However, just as the accessed sDA, the least accessed tilt angle when the PV was spaced meets up with the useful daylight illuminance requirement as depicted in Figure 14, showcasing the advantage the spaced PV slates design has over the closed PV installation.

The tilt angles that demonstrated compliance with the UDI-s (supplementary) threshold even when the PV slates were closely installed are 40°, 50°, 60°, 70°, and 80°, indicating effective distribution of daylight within the office space as illustrated in Table 12. As the tilt angle increases, the PV slate allows more daylight to penetrate the interior, resulting in illuminance levels that are both comfortable and usable for occupants. While energy generation may decrease at higher tilt angles due to reduced solar radiation incidence, the improved daylighting performance represents a favorable trade-off, particularly in occupant-centric spaces where visual comfort is a priority.

Table 11 Daylighting Performance: sDA & UDI Evaluation (Scenario 1)

Floor	Tilt Angle (°)	Floor Area (m²)	sDA Area (%)	UDI Area (%)	Acceptable Criteria (sDA) 55%, UDI 50-80%	Comment
Second	10	787.456	0%	14.56%	✗ both below	Poor daylighting
	20		0%	42.33%	✗ both below	Poor daylighting
	40		29.40%	60.48%	sDA below	Partially Satisfactory
	50		55.90%	62.76%	sDA below	Satisfactory
	70		58.55%	64.76%	✓ meet both	Satisfactory
	80		60.79%	66.49%	✓ meet both	Satisfactory
Fifth	10	787.456	0%	24.85%	✗ both below	Poor daylighting
	20		0.32%	46.15%	✗ both below	Poor daylighting
	40		37.67%	60.90%	sDA below	Partially Satisfactory
	50		57.19%	62.79%	✓ meet both	Satisfactory
	70		58.5%	64.86%	✓ meet both	Satisfactory
	80		60.79%	67.25%	✓ meet both	Satisfactory
Eight	10	794.29	3.98%	23.17%	✗ both below	Poor daylighting
	20		3.13%	35.05%	✗ both below	Poor daylighting
	40		20.98%	51.54%	sDA below	Partially satisfactory
	50		31.34%	59.86%	sDA below	Partially Satisfactory
	70		44.48%	67.2%	sDA below	Partially Satisfactory
	80		47.89%	69.57%	sDA below	Partially Satisfactory
Mezzanine	10	553.29	0.49%	7.02%	✗ both below	Poor daylighting
	20		0.93%	10.03%	✗ both below	Poor daylighting
	40		3.10%	25.83%	✗ both below	Poor daylighting
	50		6.11%	34.70%	✗ both below	Poor daylighting
	70		20.76%	59.03%	sDA below	Partially Satisfactory
	80		24.75%	66.66%	sDA below	Partially Satisfactory

Table 12 Daylighting Performance: sDA & UDI Evaluation (Scenario 2)

Tilt Angle (°)	Floor Area (m²)	Acceptable Criteria (sDA) 55%,	Acceptable Criteria UDI 50-80%
10	787.456	✓	✓
20		✓	✓
40		✓	✓
50		✓	✓
70		✓	✓
80		✓	✓

4.5 Economic Feasibility Assessment of the Dynamic BIPV

Even with the imperative shift toward renewable energy sources that have placed building-integrated photovoltaic at the center of sustainable building strategies and the continuous exponential growing rate of photovoltaic (PV) installations, their wide adoption is often constrained by economic feasibility concern and a better understanding of the costs is necessary to assess the competitiveness with the conventional energy sources (Diestelmeier, 2019). Irrespective of how promising the solar photovoltaic (PV) technologies can be, the economic viability is a critical factor influencing their large-scale adoption and long-term sustainability, determining return on investment, and overall cost-effectiveness. While the technical (energy and visual) performance of the proposed dynamic PV façade system has been comprehensively assessed, it is equally essential to evaluate its economic feasibility.

Unlike the conventional PV systems, dynamic BIPV solutions require specialized design, installation, and maintenance strategies, leading to higher upfront cost Elshurafa et al., (2020). Also, the developers, policymakers, and investors require robust economic indicators to compare BIPV with conventional energy sources and make informed investment choices (IRENA, 2020).

Various economic metrics have been developed in literature to assess the financial performance of solar energy technologies. Among the most widely utilized indicators are the Levelized Cost of

Energy (LCOE), Payback Period (PBP), and Net Present Value (NPV) (Diestelmeier, 2019). However, for the scope of this study, the analysis will focus on LCOE and PBP, as they provide an all-inclusive yet practical evaluation of the cost-effectiveness and financial payback timeline of the proposed dynamic PV system. The exclusion of NPV is justified by its inherent reliance on uncertain future cash flows and discount rate variability, which may introduce significant subjectivity and inconsistencies in evaluating long-term economic viability (Bazilian et al., 2013). By contrast, LCOE and PBP offer a more objective, standardized, and transparent assessment, making them highly relevant for this study.

4.5.1 Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is a fundamental and one of the most widely used metrics in assessing the cost-effectiveness of energy generation technologies by calculating the per-unit cost of electricity produced over a system's lifetime. The LCOE accounts for both capital expenditures (CapEx) and operation expenditures (OpEx), making it a comprehensive measure of the economic sustainability of renewable energy projects. It also enables a fair comparison between solar PV and conventional energy sources such as fuel (Sinaga et al., 2019 & Elshurafa et al., 2020). The LCOE of a PV system is calculated using the following equation, as defined in (Elshurafa et al., (2020):

$$\text{LCOE} = \frac{I + \sum_{t=1}^n \frac{O_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \dots\dots\dots \text{equation 1}$$

Where:

- I = initial Investment Cost (Sar)
- O_t = Operating Cost in year t (Sar)
- M_t = Maintenance Cost in year t (Sar)
- F_t = Fuel Cost in year t (not applicable for solar PV but relevant for hybrid or grid-dependent systems)
- E_t = Energy generated in year t (kWh)
- r = Discount rate (%)
- n = Project Lifespan (years)

Each parameter is critical in evaluating the cost-effectiveness of the dynamic PV façade system:

- Initial Investment Cost (I): also referred to as CapEx, capital expenditures, or overnight costs specific to the initial investment required for the set-up of a new energy producing system. It includes the cost of PV panels, inverters, mounting structures, installation, and associated electrical components. The investment cost is often the largest component in solar PV projects and can significantly impact the LCOE. Dynamic PV systems tend to have higher initial costs than fixed systems due to the need for adaptive control mechanisms (IRENA, 2020).
- Operating & Maintenance Costs (O&M): referred to as OpEx, or operational expenditure; these expenditures include fixed and variable costs for operation and maintenance (except fuel costs). It encompasses routine inspections, cleaning, system monitoring, and occasional component replacements such as inverters, which have a shorter lifespan than PV modules. Low maintenance requirements of solar PV systems contribute to a reduced LCOE compared to conventional energy sources. According to (KAPSARC, 2020), O & M for LCOE ranges from 1% - 1.5% of the renewable capital cost.

- Energy Generated (E_t): The total energy output over the system's lifetime is an important determinant of LCOE. Higher efficiency, optimal orientation, and minimal shading enhance energy yield, thereby lowering the LCOE (Elshurafa et al., (2020).
- Discount Rate (r): reflects the average cost of capital as it is used to discount values back to the current/present year. It represents the time value of money and varies depending on the economic conditions and financing structure of the project. A lower discount rate (common in government-subsidized projects) reduces LCOE, while a higher rate increases it, making financing costs a key consideration (Diestelmeier, 2019). The classic question of 'what discount rate should be used?' is one that is asked when performing any financial assessment and the case at hand is no exception. As stated by KAPSARC, the assumed discount rate is 5% as stated in Table 13.
- Project Lifespan (n): Typically ranges between 20-30years for solar PV systems. Longer lifespans reduce LCOE by spreading costs over a greater number for years (IRENA, 2020). The challenge that arises is to agree on the values that are to be used. Lifetimes of 25 years are considered typical, but that of 30 years and even longer are becoming increasingly accepted ((Dunlop et al., 2005.); Jordan and Kurtz, 2012).

Table 13 Key parameters for the economic analysis of unspaced and spaced PV systems

Parameters	Unspaced PV	Spaced PV
Capital Cost (C_o)	3,851,762.25 SAR	2,375,541.25 SAR
Annual O&M Cost (O_t) = 1.5% of the capital cost	57,776.43 SAR/year	35,633.12 SAR/year
Annual Energy Generation (E_t)	1,187,515.35 kWh/year	925,281.69 kWh/year
Discount Rate (r) = 5%	0.05	0.05
System Lifetime (years (T))	5, 10, 15, 20, 25, 30	5, 10, 15, 20, 25, 30

Calculating LCOE for different time periods

To compute the LCOE, we calculate the present value (PV) of costs and the PV of energy generation over various lifespans.

Step 1: Compute the present value of O&M costs

The present value (PV) of O&M costs over a period T is given by:

$$PV_{O\&M} = O_t \times \sum_{t=1}^T \frac{1}{(1+r)^t} \dots\dots\dots \text{Equation 2}$$

Using the summation formula for a geometric series:

$$PV_{O\&M} = O_t \times \left(\frac{1-(1+r)^{-T}}{r} \right) \dots\dots\dots \text{Equation 3}$$

Substituting values:

$$PV_{O\&M} = 57,776.43 \times \left(\frac{1-(1+1.05)^{-T}}{0.05} \right) \dots\dots\dots \text{Unspaced PV}$$

$$PV_{O\&M} = 35,633.12 \times \left(\frac{1-(1+1.05)^{-T}}{0.05} \right) \dots\dots\dots \text{Spaced PV}$$

Step 2: Compute the Present Value of Energy Generation

$$PV_E = E_t \times \sum_{t=1}^T \frac{1}{(1+r)^t} \dots\dots\dots \text{Equation 4}$$

$$PV_{O\&M} = 1,187,515.35 \times \left(\frac{1-(1+1.05)^{-T}}{0.05} \right) \dots\dots\dots \text{Unspaced PV}$$

$$PV_{O\&M} = 925,281.69 \times \left(\frac{1-(1+1.05)^{-T}}{0.05} \right) \dots\dots\dots \text{Spaced PV}$$

Table 14 LCOE value for the stated period of time

System Lifetime (years)	LCOE (SAR/kWh)- Unspaced PV	LCOE (SAR/kWh)- Spaced PV
5	0.648	0.671
10	0.415	0.395
15	0.329	0.304
20	0.286	0.261
25	0.260	0.236
30	0.244	0.220

The LCOE results for the dynamic PV- integrated façade system for both the spaced and unspaced PV exhibit a declining trend with an increase in systems lifetime as shown in Table 14. Initially, at 5 years, LCOE stands at 0.648SAR/kWh and 0.671SAR/kWh in each of the scenario respectively, which is significantly higher than conventional electricity tariffs in Saudi Arabia, currently averaging 0.30 SAR/kWh (ECRA., 2023). However, as the system operates over extended periods, the LCOE progressively decreases, reaching 0.286 SAR/kWh and 0.261 SAR/kWh by year 20 and further declining to 0.260, 0.244 SAR/kWh and 0.236, 0.220 SAR/kWh by 25th and 30th year respectively.

The downward trend is primarily driven by the amortization of capital costs over a long duration and the relatively low operation and maintenance (O&M) costs of photovoltaic systems. The gradual reduction in LCOE aligns with the established economic principle that longer operation periods lower the average unit cost of energy production (IRENA, 2021). In research by (Al-Saud et al. (2022), they analyzed a large-scale corporate building PV system in Riyadh, estimating an LCOE of 0.33 SAR/kWh. This value is comparable to the 15-year LCOE of the dynamic façade system, indicating that the proposed technology is approaching economic competitiveness with standard rooftop PV solutions. Similarly, Elshurafa et al., (2020) reported that the LCOE of rooftop PV systems in the Middle East ranged between 0.20 – 0.35 SAR/kWh for a 25-year lifetime, which

aligns closely with the 0.260 SAR/kWh and 0.236 SAR/kWh obtained in this study. Hosseini et al. (2018) also examined PV façade-integrated systems and reported an LCOE range of 0.27 – 0.37 SAR/kWh, which confirms that the proposed system performs within expectation. Additionally, the International Energy Agency (IEA, 2023) reports that global utility-scale solar PV LCOE averages around 0.20-0.35 SAR/kWh, depending on location and financial incentives. The 15th to 30th-year LCOE in this study falls within the established range, affirming that the dynamic PV-integrated façade can be financially viable in the long run.

However, it is worth noting that, despite both scenarios falling within the acceptable range of the LCOE, the second scenario (spaced PV) has a lower LCOE from 10th to 30th year. Even though it generates about 22% less energy than the closely installed PV. Relatively, the spaced PV indicates improvement in efficiency and shading reduction, while the closely installed PV increased shading and higher capital cost resulting in higher LCOE.

4.5.2 Payback Period (PBP)

The Payback Period (PBP) is another key metric used to evaluate the economic feasibility of PV systems. It measures the time required for the cumulative energy savings or revenue generated by the system to equal the initial investment cost (Bazilian et al., 2013). The PBP is determined using the following formula:

$$PBP = \frac{I}{A} \dots\dots\dots \text{equation 5}$$

Where:

- I = Initial Investment Cost (Sar)
- A = Annual Energy Cost Savings or Revenue Generated (Sar/year)

A shorter PBP is generally preferable, as it indicates a faster return on investment. Several factors influence the PBP:

- Initial Investment Cost (I): Higher capital costs extend the payback period unless offset by significant energy savings or subsidies.
- Annual Energy Savings (A): The higher the energy output and grid electricity savings, the shorter the PBP. Dynamic PV systems, which optimize energy generation throughout the day, can reduce PBP compared to static installations (Diestelmeier, 2019).
- Electricity Tariffs & Incentives: Regions with higher electricity prices experience faster PBP, as the cost savings from self-generated solar energy are more significant. Additionally, government incentives (feed-in tariffs, net metering, tax credits) can accelerate financial returns (IRENA, 2020).

Assumptions and Calculation

- $I_{(\text{unspaced PV})} = \text{Total Capital/Initial Cost} = 3,851,762.25 \text{ SAR}$
- $I_{(\text{Spaced PV})} = \text{Total Capital/Initial Cost} = 2,375,541.25 \text{ SAR}$
- Electricity Tariff: 0.30 SAR/kWh.

Annual Energy Savings:

- $A = \text{Energy generation} \times \text{Electricity tariff}$
- $A_{(\text{unspaced PV})} = 1,187,515.35 \times 0.30 = 356,254.61 \text{ SAR/year}$

$$PBP = \frac{3,851,762.25}{356,254.61} = 10.8 \text{ years}$$

- $A_{(\text{Spaced PV})} = 925,281.69 \times 0.30 = 277,584.51 \text{ SAR/year}$

$$PBP = \frac{2,375,541.25}{277,584.51} = 8.56 \text{ years}$$

The simple Payback Period (PBP) for the dynamic PV system in both scenarios were calculated at approximately 11 years and 8.6 years respectively, indicating that the system will recover its initial investment cost at the mentioned years through saving on electricity bills. Although, the payback period of the first scenario (closely installed PV) might relatively be longer than the conventional rooftop PV as reported by (Imam et al., 2019), but nearly two-third of its lifetime will generate pure financial savings after breakeven, with the operating period of 20 to 30 years. From year 12 onward, the system is expected to provide annual savings of 350, 643 SAR, amounting to a net positive return exceeding 5 million SAR over 30 years.

A study by Rehman & Bader (2021) on PV installation in commercial buildings in Saudi Arabia estimated PBPs ranging from 8 to 12 years, aligning closely with the PBP of both scenarios in this study. Similarly, (Hosseini et al., 2018) reported payback period of 10 - 12years for building – integrated PV facades in hot climate, which closely matches the obtained PBP in this study. A study by Fraunhofer ISE (2021) also found that PV façade systems in Europe had payback periods ranging from 9 – 13 years, indicating that the current studied system is within an acceptable economic range. Additionally, the international Renewable Energy Agency (IRENA, 2022), stated that the solar PV payback periods in developed markets range between 8-15years, depending on solar incentives and grid electricity price. The payback, the inclusion of practicable incentives in the calculation of the payback period would have made the obtained PBP even more competitive in an international

context. Nevertheless, the analysis portrays the long-term economic viability of the proposed technology. It was determined that the scenario with the lower capital cost results in faster investment recovery. The analysis indicates that including government incentives may significantly reduce the LCOE and PBP, making the technology even more competitive. Table 15 illustrates the comparison between the spaced and unspaced dynamic PV across key performance factors.

Table 15 Unspaced and Spaced PV Systems Comparison across key performance factors

Factor	Unspaced PV	Spaced PV	Best Option
Capital Cost	Higher	Lower	Spaced PV
Energy Output	Higher	Lower	Unspaced PV
Visual Performance	Poor	Excellent	Spaced PV
LCOE	0.244 SAR/kWh	0.220 SAR/kWh	Spaced PV
PBP	10.8 years	8.56 years	Spaced PV
Long-term Viability	Strong	Strong	Both Viable

CHAPTER 5

SUMMARY, CONCLUSION, AND RECOMMENDATIONS

5.1 Summary and Conclusion

This study has established the potential of dynamic photovoltaic integration into building facades as a sustainable and economically viable strategy for reducing energy consumption in hot climates. By assessing two configurations- spaced and unspaced PV systems- integrated into the vertical glazing of a representative office building in Al-Khobar, the research demonstrates how much such systems can deliver substantial improvements in building energy performance and economic returns.

The unspaced PV system produced approximately 1.19 million kWh/year, which enabled it to partially offset the base-case energy demand. The spaced system, though producing 925, 282 kWh/year which is less to the unspaced dynamic PV scenario but offered enhanced visual performance with better daylight penetration and less self-shading. These energy contributions translated into approximately 30% - 50% reduction in total annual electricity demand.

It is important to note that the differences between both configurations present a meaningful tradeoff that is worth critical consideration. While the unspaced system generated a higher amount of energy due to a large number of installed dynamic PV slates (approximately 4717 slates), the spaced configuration, despite utilizing about half of it, achieved an energy output that competes closely with its counterpart in relative terms, producing only approximately 22% less energy

annually as compared to the unspaced. This indicates a level of energy efficiency and sustainability that makes the spaced PV option promising.

In contrast, the unspaced configuration has a capital and operational cost that was approximately 38% greater than the spaced system's. These differences in cost show the economic advantage of the spaced configuration. Furthermore, the spaced dynamic PV system demonstrated superior performance in terms of visual comfort, providing more daylight access and better outward views; priceless features that enhance occupant well-being and satisfaction. When all factors are considered, the spaced PV system emerges as a relatively more viable option, offering a balanced solution that does not compromise occupant comfort for marginal energy gains.

From the economic perspective, both configurations presented competitive long-term performance. The Levelized Cost of Energy (LCOE) reduced over time as capital costs were reduced, ranging from 0.648 to 0.244 SAR/kWh (unspaced) and 0.671 to 0.220 SAR/kWh (spaced) across 5 to 30 years lifespan. These values align with regional and global averages, validating the feasibility of façade-integrated PV. The Payback Period was estimated at 10.8 years for the unspaced and 8.56 years for spaced PV, both well within acceptable investment recovery durations, especially in the presence of future incentives or subsidy schemes.

In addition to the technical and financial performance, the research demonstrated the effectiveness of dynamic PV in improving the indoor visual quality. The system allowed tilt angle flexibility, enhancing daylight autonomy and illuminance, as well as strengthening the dual benefit of energy generation and occupant comfort.

5.2 Limitation and Future Research

One major limitation observed was the reduced efficiency of the PV modules during peak summer months, where high ambient and surface temperatures caused performance degradation. Although Saudi Arabia enjoys abundant solar irradiance, extreme heat conditions significantly affect the output of PV systems. This issue could be addressed in future projects by integrating passive or active cooling strategies behind the panels, such as ventilated air gaps or phase change materials that absorb excess heat.

Another feasible limitation is the dust accumulation on the PV surfaces, a common issue in arid climates. The build-up of dirt can significantly reduce the efficiency of the system, especially for high-rise installations. To address this challenge, future designers should consider self-cleaning coatings, or automated façade maintenance systems that can safely and efficiently clean PV panels on tall buildings.

Additionally, the absence of dynamic movement modules in the simulation software meant that the system's adaptability was modeled under static assumptions. While orientation adjustments were conceptually included, they could not be simulated in real-time within DesignBuilder due to software restrictions. This simplification may have led to underestimation or overestimation of certain performance indicators. Collaborating with software developers or exploring advanced tools to provide more flexibility in future research.

5.3 Recommendations

To build on the findings of this research and also achieve a sustainable dynamic PV technology, the following recommendations could be adopted.

- Designers and manufacturers should incorporate hydrophobic coating or self-cleaning technologies into the dynamic PV designs to minimize dust accumulation and enhance energy output.
- Researchers and manufacturers should incorporate thermal buffers or phase-change materials (PCMs) behind PV modules to reduce surface temperature and enhance efficiency especially during peak summer months.
- Researchers should explore more flexible simulation platforms with energy modeling plugins, to overcome current software limitations related to dynamic features.
- National and local government should introduce financial incentives and subsidies that support the adoption of dynamic photovoltaic façade systems.
- For façade-integrated PV systems, especially in high-rise buildings, modular and automated cleaning solutions should be incorporated from the design phase.
- Research and government bodies should encourage and sponsor cross-regional studies; comparing the performance of dynamic PV in diverse or combine climates to establish more specific performance benchmarks.

REFERENCES

- Abdelhafez, M. H. H., Touahmia, M., Noaime, E., Albaqawy, G. A., Elkhayat, K., Achour, B., & Boukendakdji, M. (2021). Integrating solar photovoltaics in residential buildings: Towards zero energy buildings in hail city, ksa. *Sustainability (Switzerland)*, 13(4), 1–19. <https://doi.org/10.3390/su13041845>
- Abd-ur-Rehman, H. M., Al-Sulaiman, F. A., Mehmood, A., Shakir, S., & Umer, M. (2018). The potential of energy savings and the prospects of cleaner energy production by solar energy integration in the residential buildings of Saudi Arabia. *Journal of Cleaner Production*, 183, 1122–1130. <https://doi.org/10.1016/j.jclepro.2018.02.187>
- Ahmad, T., & Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: The story told so far. In *Energy Reports* (Vol. 6, pp. 1973–1991). Elsevier Ltd. <https://doi.org/10.1016/j.egyr.2020.07.020>
- Alanezi, A., & Naraghi, M. H. (2018, November 9). Solar Photovoltaic Power Plant Development for a Desert Climate. *Volume 6B: Energy*. <https://doi.org/10.1115/IMECE2018-86588>
- Alarenan, S., Gasim, A. A., & Hunt, L. C. (2020). Modelling industrial energy demand in Saudi Arabia. *Energy Economics*, 85. <https://doi.org/10.1016/j.eneco.2019.104554>
- Aldhubaib, H. A. (2022). Electrical energy future of Saudi Arabia: Challenges and opportunities. In *Frontiers in Energy Research* (Vol. 10). Frontiers Media S.A. <https://doi.org/10.3389/fenrg.2022.1005081>
- Alfaoyzan, F. A., & Almasri, R. A. (2023). Utilizing solar photovoltaic systems in educational facilities to achieve a zero bill campus: The Sulaiman Al-Rajhi University case. *Energy Exploration and Exploitation*, 41(4), 1415–1438. <https://doi.org/10.1177/01445987231174767>
- Al-Gahtani, S. F. (2024). Saudi Arabia’s Journey toward a Renewable Future. In *Energies* (Vol. 17, Issue 11). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/en17112444>
- Al-Ghamdi, S. A., & Alshaibani, K. (2018). The Potential of Solar Energy in Saudi Arabia: The Residential Sector. *Journal of Engineering and Architecture*, 6(1). <https://doi.org/10.15640/jea.v5n2a4>
- Alharthi, F. S., & Alamoud, A. M. (2023). Efficient utilization of solar PV for corporate building in Riyadh, Saudi Arabia. *Renewable Energy and Power Quality Journal*, 21, 97–102. <https://doi.org/10.24084/repqj21.232>

- AlHashmi, M., Chhipi-Shrestha, G., Nahiduzzaman, K. Md., Hewage, K., & Sadiq, R. (2021). Framework for Developing a Low-Carbon Energy Demand in Residential Buildings Using Community-Government Partnership: An Application in Saudi Arabia. *Energies*, 14(16), 4954. <https://doi.org/10.3390/en14164954>
- Alhashmi, M., Chhipi-Shrestha, G., Ruparathna, R., Nahiduzzaman, K. M., Hewage, K., & Sadiq, R. (2021). Energy performance assessment framework for residential buildings in Saudi Arabia. *Sustainability (Switzerland)*, 13(4), 1–25. <https://doi.org/10.3390/su13042232>
- Ali, A. (2023). Transforming Saudi Arabia's Energy Landscape towards a Sustainable Future: Progress of Solar Photovoltaic Energy Deployment. *Sustainability (Switzerland)*, 15(10). <https://doi.org/10.3390/su15108420>
- Almasoud, A. H., & Gandayh, H. M. (2015). Future of solar energy in Saudi Arabia. *Journal of King Saud University - Engineering Sciences*, 27(2), 153–157. <https://doi.org/10.1016/j.jksues.2014.03.007>
- Almasri, R. (n.d.). *Reality and challenges of solar energy in the Kingdom of Saudi Arabia (KSA)*.
- Almasri, R. A., Akram, R., Almarshoud, A. F., Omar, H. M., Alshitawi, M. S., & Khodary Esmaeil, K. (2023). Evaluation of the total exergy and energy consumptions in residential sector in Qassim Region, Saudi Arabia. *Alexandria Engineering Journal*, 62, 455–473. <https://doi.org/10.1016/j.aej.2022.07.041>
- Almulhim, T., Al Yousif, M., Mohammed, :, & Yousif, A. (2022). *An Analysis of Renewable Energy Investments in Saudi Arabia: A Hybrid Framework Based on Leontief and Fuzzy Group Decision Support Models An Analysis of Renewable Energy Investments in Saudi Arabia: A Hybrid Framework Based on Leontief and Fuzzy Group Decision Support Models **.
- Alrashed, F., & Asif, M. (2014). Trends in residential energy consumption in Saudi Arabia with particular reference to the Eastern province. *Journal of Sustainable Development of Energy, Water and Environment Systems*, 2(4), 376–387. <https://doi.org/10.13044/j.sdewes.2014.02.0030>
- Altun, A. F. (2022). Determination of Optimum Building Envelope Parameters of a Room concerning Window-to-Wall Ratio, Orientation, Insulation Thickness and Window Type. *Buildings*, 12(3), 383. <https://doi.org/10.3390/buildings12030383>
- AlYahya, S., & Irfan, M. A. (2016). Analysis from the new solar radiation Atlas for Saudi Arabia. *Solar Energy*, 130, 116–127. <https://doi.org/10.1016/j.solener.2016.01.053>

- Alyahya, S., & Irfan, M. A. (2016). Role of Saudi universities in achieving the solar potential 2030 target. *Energy Policy*, 91, 325–328. <https://doi.org/10.1016/j.enpol.2016.01.019>
- Al-Yasiri, A. J., & Journal, A. (n.d.). GLOBAL ENERGY DEMAND FOR DIFFERENT ENERGY SOURCES: CURRENT STATUS AND FUTURE PROSPECTS. *Contemporary Economic Studies*, 1(4), 2021.
- American Society of Heating, R. and A.-C. E. Inc. (n.d.). 2009 ASHRAE® HANDBOOK FUNDAMENTALS. In 2009.
- Anderson, J. S. (2019). ENERGY USE EXCELLENCE AND THE BUILDING ENVELOPE. *Journal of Green Building*, 14(3), 179–204. <https://doi.org/10.3992/1943-4618.14.3.179>
- Bayomi, N., & Fernandez, J. E. (2018). Trends of energy demand in the Middle East: A sectoral level analysis. *International Journal of Energy Research*, 42(2), 731–753. <https://doi.org/10.1002/er.3861>
- Bazilian, M., Onyeji, I., Liebreich, M., MacGill, I., Chase, J., Shah, J., Gielen, D., Arent, D., Landfear, D., & Zhengrong, S. (2013). Re-considering the economics of photovoltaic power. *Renewable Energy*, 53, 329–338. <https://doi.org/10.1016/j.renene.2012.11.029>
- Bergero, S., & Chiari, A. (2021). Validation and calibration of dynamic energy models: energy audit of a public building. *Journal of Physics: Conference Series*, 2116(1), 012107. <https://doi.org/10.1088/1742-6596/2116/1/012107>
- Biloria, N., Makki, M., & Abdollahzadeh, N. (2023). Multi-performative façade systems: The case of real-time adaptive BIPV shading systems to enhance energy generation potential and visual comfort. *Frontiers in Built Environment*, 9. <https://doi.org/10.3389/fbuil.2023.1119696>
- Bollino, C., Asdrubali, F., Polinori, P., Bigerna, S., Micheli, S., Guattari, C., & Rotili, A. (2017). A Note on Medium- and Long-Term Global Energy Prospects and Scenarios. *Sustainability*, 9(5), 833. <https://doi.org/10.3390/su9050833>
- Bot, K., Aelenei, L., da Glória Gomes, M., & Silva, C. S. (2022). A literature review on Building Integrated Solar Energy Systems (BI-SES) for façades – photovoltaic, thermal and hybrid systems. *Renewable Energy and Environmental Sustainability*, 7, 7. <https://doi.org/10.1051/rees/2021053>
- Boyce, P. R. (2003). *Human Factors in Lighting*. CRC Press. <https://doi.org/10.1201/9780203426340>

- Building envelope. (2021). In *Construction* (pp. 80–293). De Gruyter.
<https://doi.org/10.1515/9783035622294-003>
- Chaudhary, G., New, J., Sanyal, J., Im, P., O'Neill, Z., & Garg, V. (2016). Evaluation of “Autotune” calibration against manual calibration of building energy models. *Applied Energy*, 182, 115–134. <https://doi.org/10.1016/j.apenergy.2016.08.073>
- Chen, X., Qiu, Y., & Wang, X. (2024). A systematic review of research methods and economic feasibility of photovoltaic integrated shading device. In *Energy and Buildings* (Vol. 311). Elsevier Ltd. <https://doi.org/10.1016/j.enbuild.2024.114172>
- Chong, A., Lam, K. P., Pozzi, M., & Yang, J. (2017). Bayesian calibration of building energy models with large datasets. *Energy and Buildings*, 154, 343–355.
<https://doi.org/10.1016/j.enbuild.2017.08.069>
- Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43(4), 661–673. <https://doi.org/10.1016/j.buildenv.2006.10.027>
- Dada, M., & Popoola, P. (2023). Recent advances in solar photovoltaic materials and systems for energy storage applications: a review. In *Beni-Suef University Journal of Basic and Applied Sciences* (Vol. 12, Issue 1). Springer Science and Business Media Deutschland GmbH. <https://doi.org/10.1186/s43088-023-00405-5>
- Darandary, A., Mikayilov, J., & Soummane, S. (2023). *Regional Fuel Consumption and Carbon Dioxide Emissions in Saudi Arabia: Impacts of Electricity Price Reforms*.
<https://doi.org/10.30573/KS--2022-DP14>
- Demchyk Savage, M., & Savage, D. (n.d.). *Global Energy Consumption: An Analysis of Variables That Shape Global Energy Consumption: An Analysis of Variables That Shape Per Capita Usage, or How Pump Price, Urbanization, and Fossil Per Capita Usage, or How Pump Price, Urbanization, and Fossil Fuels Imports Impact Fossil Fuels Consumption Per Capita Fuels Imports Impact Fossil Fuels Consumption Per Capita Across OECD Countries Across OECD Countries Recommended Citation Recommended Citation*. <https://doi.org/10.25777/6mtn-gz27>
- Diestelmeier, L. (2019). Changing power: Shifting the role of electricity consumers with blockchain technology – Policy implications for EU electricity law. *Energy Policy*, 128, 189–196. <https://doi.org/10.1016/j.enpol.2018.12.065>
- Duffie, J. A., & Beckman, W. A. (2013). *Solar Engineering of Thermal Processes*. Wiley.
<https://doi.org/10.1002/9781118671603>

- Dunlop, E. D., Halton, D., & Ossenbrink, H. A. (n.d.). 20 years of life and more: where is the end of life of a PV module? *Conference Record of the Thirty-First IEEE Photovoltaic Specialists Conference, 2005.*, 1593–1596. <https://doi.org/10.1109/PVSC.2005.1488449>
- Elomari, Y., Norouzi, M., Marín-Genescà, M., Fernández, A., & Boer, D. (2022). Integration of Solar Photovoltaic Systems into Power Networks: A Scientific Evolution Analysis. In *Sustainability (Switzerland)* (Vol. 14, Issue 15). MDPI. <https://doi.org/10.3390/su14159249>
- Fahmy, M. S. Eid., Ahmed, F., Durani, F., Bojnec, Š., & Ghareeb, M. M. (2023). Predicting Electricity Consumption in the Kingdom of Saudi Arabia. *Energies*, 16(1). <https://doi.org/10.3390/en16010506>
- Felimban, A., Prieto, A., Knaack, U., Klein, T., & Qaffas, Y. (2019). Assessment of current energy consumption in residential buildings in Jeddah, Saudi Arabia. *Buildings*, 9(7). <https://doi.org/10.3390/buildings9070163>
- Gajdzik, B., Wolniak, R., Nagaj, R., Žuromskaitė-Nagaj, B., & Grebski, W. W. (2024). The Influence of the Global Energy Crisis on Energy Efficiency: A Comprehensive Analysis. *Energies*, 17(4). <https://doi.org/10.3390/en17040947>
- Gan, V. J. L., Lo, I. M. C., Ma, J., Tse, K. T., Cheng, J. C. P., & Chan, C. M. (2020). Simulation optimisation towards energy efficient green buildings: Current status and future trends. *Journal of Cleaner Production*, 254, 120012. <https://doi.org/10.1016/j.jclepro.2020.120012>
- Gasim, A. (2020). *Commentary Industrial Energy Consumption in Saudi Arabia*.
- Goia, F., Perino, M., Serra, V., & Zanghirella, F. (n.d.). *TOWARDS AN ACTIVE, RESPONSIVE, AND SOLAR BUILDING ENVELOPE* (Vol. 5, Issue 4). http://meridian.allenpress.com/jgb/article-pdf/5/4/121/2193526/jgb_5_4_121.pdf
- Hassan, Q., Algburi, S., Sameen, A. Z., Jaszczur, M., Salman, H. M., Mahmoud, H. A., & Awwad, E. M. (2024). Saudi Arabia energy transition: Assessing the future of green hydrogen in climate change mitigation. *International Journal of Hydrogen Energy*, 55, 124–140. <https://doi.org/10.1016/j.ijhydene.2023.11.117>
- Hu, Y., Peng, L., Li, X., Yao, X., Lin, H., & Chi, T. (2018). A novel evolution tree for analyzing the global energy consumption structure. *Energy*, 147, 1177–1187. <https://doi.org/10.1016/j.energy.2018.01.093>
- Huang, Y. (2014). Drivers of rising global energy demand: The importance of spatial lag and error dependence. *Energy*, 76, 254–263. <https://doi.org/10.1016/j.energy.2014.07.093>

- Imam, A. A., Abusorrah, A., & Marzband, M. (2024). Potentials and opportunities of solar PV and wind energy sources in Saudi Arabia: Land suitability, techno-socio-economic feasibility, and future variability. *Results in Engineering*, 21. <https://doi.org/10.1016/j.rineng.2024.101785>
- Imam, A. A., Al-Turki, Y. A., & R., S. K. (2019). Techno-Economic Feasibility Assessment of Grid-Connected PV Systems for Residential Buildings in Saudi Arabia—A Case Study. *Sustainability*, 12(1), 262. <https://doi.org/10.3390/su12010262>
- Jayathissa, P. , L. M. , S. J. , H. J. , N. Z. , & S. A. (2017). Optimising building net energy demand with dynamic BIPV shading. *Applied Energy*, 202. *Applied Energy*, 202, 726–735.
- Jones, D. W. (1991). How urbanization affects energy-use in developing countries. *Energy Policy*, 19(7), 621–630. [https://doi.org/10.1016/0301-4215\(91\)90094-5](https://doi.org/10.1016/0301-4215(91)90094-5)
- K, P., Govindarajan, U., Ramachandaramurthy, V. K., T, S. O. S., & Jeevarathinam, B. (2018). Integrating solar photovoltaic energy conversion systems into industrial and commercial electrical energy utilization—A survey. In *Journal of Industrial Information Integration* (Vol. 10, pp. 39–54). Elsevier B.V. <https://doi.org/10.1016/j.jii.2018.01.003>
- Kampelis, N., Papayiannis, G. I., Kolokotsa, D., Galanis, G. N., Isidori, D., Cristalli, C., & Yannacopoulos, A. N. (2020). An Integrated Energy Simulation Model for Buildings. *Energies*, 13(5), 1170. <https://doi.org/10.3390/en13051170>
- Kant, K., Shukla, A., & Sharma, A. (2018). Heating Ventilation and Air-Conditioning Systems for Energy-Efficient Buildings. In *Sustainability through Energy-Efficient Buildings* (pp. 165–180). CRC Press. <https://doi.org/10.1201/9781315159065-9>
- Khraisat, D., Taib, N., Sern, C. H. Y., & Al-Ruwaished, M. (2024). Application of Kinetic Facades and Its Impact on Daylighting Performance: A Systematic Literature Review. *Civil Engineering and Architecture*, 12(4), 2693–2704. <https://doi.org/10.13189/cea.2024.120415>
- Lan, J., Malik, A., Lenzen, M., McBain, D., & Kanemoto, K. (2016). A structural decomposition analysis of global energy footprints. *Applied Energy*, 163, 436–451. <https://doi.org/10.1016/j.apenergy.2015.10.178>
- Lazaroiu, A. C., Gmal Osman, M., Strejoiu, C. V., & Lazaroiu, G. (2023). A Comprehensive Overview of Photovoltaic Technologies and Their Efficiency for Climate Neutrality. In *Sustainability (Switzerland)* (Vol. 15, Issue 23). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/su152316297>

- Li, Z. (2023). Prospects of Photovoltaic Technology. In *Engineering* (Vol. 21, pp. 28–31). Elsevier Ltd. <https://doi.org/10.1016/j.eng.2022.07.008>
- Luo, Y., Zhang, L., Wang, X., Xie, L., Liu, Z., Wu, J., Zhang, Y., & He, X. (2017). A comparative study on thermal performance evaluation of a new double skin façade system integrated with photovoltaic blinds. *Applied Energy*, 199, 281–293. <https://doi.org/10.1016/j.apenergy.2017.05.026>
- Luther, M. B. (n.d.). *Dynamic and Responsive Building Envelopes*.
- Mandalaki, M., Tsoutsos, T., & Papamanolis, N. (2014). Integrated PV in shading systems for Mediterranean countries: Balance between energy production and visual comfort. *Energy and Buildings*, 77, 445–456. <https://doi.org/10.1016/j.enbuild.2014.03.046>
- Mesloub, A., Ghosh, A., Touahmia, M., Albaqawy, G. A., Noaime, E., & Alsolami, B. M. (2020). Performance Analysis of Photovoltaic Integrated Shading Devices (PVSDs) and Semi-Transparent Photovoltaic (STPV) Devices Retrofitted to a Prototype Office Building in a Hot Desert Climate. *Sustainability*, 12(23), 10145. <https://doi.org/10.3390/su122310145>
- Mikayilov, J. I., & Al Yamani, R. (n.d.). *The Surge in Riyadh's Population: Electricity Demand Implications*.
- Nabil, A., & Mardaljevic, J. (2006). Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings*, 38(7), 905–913. <https://doi.org/10.1016/j.enbuild.2006.03.013>
- Najid, M. A., & Al-Homoud, M. S. (2023). The Impact of HVAC Operational Strategies on Energy Use in an Office Building in a Hot Climate. *Journal of Architectural Engineering*, 29(2). <https://doi.org/10.1061/JAEIED.AEENG-1452>
- O'Neill, Z., & Eisenhower, B. (2013). Leveraging the analysis of parametric uncertainty for building energy model calibration. *Building Simulation*, 6(4), 365–377. <https://doi.org/10.1007/s12273-013-0125-8>
- Panagoda, S. S., Tilanka, G., Sandunika, I., Alwis, S., Panagoda, L. P. S. S., Sandeepa, R. A. H. T., Perera, W. A. V. T., Sandunika, D. M. I., Siriwardhana, S. M. G. T., Alwis, M. K. S. D., & Dilka, S. H. S. (2023). Advancements In Photovoltaic (Pv) Technology for Solar Energy Generation. In *J. Res. Technol. Eng* (Vol. 4, Issue 3). <https://www.researchgate.net/publication/372364724>
- Perino, M., & Serra, V. (2015). Switching from static to adaptable and dynamic building envelopes: A paradigm shift for the energy efficiency in buildings. *Journal of Facade Design and Engineering*, 3(2), 143–163. <https://doi.org/10.3233/fde-150039>

- Radwan, A., Olabi, A. G., Abo-Khalil, A. G., Yousef, B. A. A., Serageldin, A. A., Maghrabie, H. M., & Abdelkareem, M. A. (2023). Thermoelectric analysis of different vacuum-based photovoltaic semitransparent skylights. *Energy and Buildings*, 285. <https://doi.org/10.1016/j.enbuild.2023.112924>
- Rahman, S. M., Al-Ismail, F. S. M., Haque, Md. E., Shafiullah, Md., Islam, Md. R., Chowdhury, Md. T., Alam, Md. S., Razzak, S. A., Ali, A., & Khan, Z. A. (2021). Electricity Generation in Saudi Arabia: Tracing Opportunities and Challenges to Reducing Greenhouse Gas Emissions. *IEEE Access*, 9, 116163–116182. <https://doi.org/10.1109/ACCESS.2021.3105378>
- Raji, B., Tenpierik, M. J., & van den Dobbelsteen, A. (2016). An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: A case study in the Netherlands. *Energy and Buildings*, 124, 210–221. <https://doi.org/10.1016/j.enbuild.2015.10.049>
- Rashid, F. L., Eleiwi, M. A., Mohammed, H. I., Ameen, A., & Ahmad, S. (2023). A Review of Using Solar Energy for Cooling Systems: Applications, Challenges, and Effects. In *Energies* (Vol. 16, Issue 24). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/en16248075>
- Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS*, 3(1), 7–31. <https://doi.org/10.1582/LEUKOS.2006.03.01.001>
- Rotas, R., Fotopoulou, M., Drosatos, P., Rakopoulos, D., & Nikolopoulos, N. (2023). Adaptive Dynamic Building Envelopes with Solar Power Components: Annual Performance Assessment for Two Pilot Sites. *Energies*, 16(5). <https://doi.org/10.3390/en16052148>
- Saidi, A. S., Alhmoud, L., Alqahtani, A. A., Zemi, O. A., & Malike, M. U. (2024). Modeling, Integration, and Simulation of the 20 MW Photovoltaic Power Plant in the Saudi Arabia Distribution Network Considering LVRT Capability. In *J. Electrical Systems* (Vol. 20, Issue 3).
- Salam, M. A., & Khan, S. A. (2018). *Transition towards sustainable energy production – A review of the progress for solar energy in Saudi Arabia*. 36(1), 3–27. <https://doi.org/10.2307/90015705>
- Shin, M., & Haberl, J. S. (2019). Thermal zoning for building HVAC design and energy simulation: A literature review. *Energy and Buildings*, 203, 109429. <https://doi.org/10.1016/j.enbuild.2019.109429>

- Shukla, A. K., Sudhakar, K., & Baredar, P. (2017). Recent advancement in BIPV product technologies: A review. In *Energy and Buildings* (Vol. 140, pp. 188–195). Elsevier Ltd. <https://doi.org/10.1016/j.enbuild.2017.02.015>
- Sinaga, R., Tuati, N. F., Beily, M. D. E., & Sampeallo, A. S. (2019). Modeling and analysis of the solar photovoltaic levelized cost of electricity (LCoE) - case study in Kupang. *Journal of Physics: Conference Series*, 1364(1), 012066. <https://doi.org/10.1088/1742-6596/1364/1/012066>
- Sinopoli, J. (2010). Heating, Ventilating, and Air Conditioning Systems. In *Smart Building Systems for Architects, Owners and Builders* (pp. 31–46). Elsevier. <https://doi.org/10.1016/B978-1-85617-653-8.00003-X>
- Skandalos, N., & Tywoniak, J. (2019). Influence of PV facade configuration on the energy demand and visual comfort in office buildings. *Journal of Physics: Conference Series*, 1343(1). <https://doi.org/10.1088/1742-6596/1343/1/012094>
- Skandalos, N., Wang, M., Kapsalis, V., D'Agostino, D., Parker, D., Bhuvad, S. S., Udayraj, Peng, J., & Karamanis, D. (2022). Building PV integration according to regional climate conditions: BIPV regional adaptability extending Köppen-Geiger climate classification against urban and climate-related temperature increases. In *Renewable and Sustainable Energy Reviews* (Vol. 169). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2022.112950>
- Svetozarevic, B. , B. M. , J. P. , et al. (2019). *Dynamic photovoltaic building envelopes for adaptive energy and comfort management. Nature Energy*, 4. 671–682.
- Svetozarevic, B., Begle, M., Jayathissa, P., Caranovic, S., Shepherd, R. F., Nagy, Z., Hischier, I., Hofer, J., & Schlueter, A. (2019). Dynamic photovoltaic building envelopes for adaptive energy and comfort management. *Nature Energy*, 4(8), 671–682. <https://doi.org/10.1038/s41560-019-0424-0>
- Tlili, I. (2015). Renewable energy in Saudi Arabia: Current status and future potentials. *Environment, Development and Sustainability*, 17(4), 859–886. <https://doi.org/10.1007/s10668-014-9579-9>
- Torcellini, P., Pless, S., Deru, M., & Crawley, D. (2006). *Zero Energy Buildings: A Critical Look at the Definition; Preprint*. <http://www.osti.gov/bridge>
- Tzempelikos, A., & Athienitis, A. K. (2007). The impact of shading design and control on building cooling and lighting demand. *Solar Energy*, 81(3), 369–382. <https://doi.org/10.1016/j.solener.2006.06.015>

- Wang, G., Fang, J., Yan, C., Huang, D., Hu, K., & Zhou, K. (2024). Advancements in smart building envelopes: A comprehensive review. *Energy and Buildings*, 312. <https://doi.org/10.1016/j.enbuild.2024.114190>
- Wang, T., Zhao, Q., Gao, W., & He, X. (2023). Research on energy consumption in household sector: a comprehensive review based on bibliometric analysis. In *Frontiers in Energy Research* (Vol. 11). Frontiers Media SA. <https://doi.org/10.3389/fenrg.2023.1209290>
- Youssef, A. M. A., Zhai, Z. J., & Reffat, R. M. (2015). Design of optimal building envelopes with integrated photovoltaics. *Building Simulation*, 8(3), 353–366. <https://doi.org/10.1007/s12273-015-0214-y>
- Zhang, L., Zhang, Q., & Rafiq, M. A. (2022). The economic and environmental analysis of solar energy development under climate impacts. *Science Progress*, 105(3). <https://doi.org/10.1177/00368504221124065>
- Zhang, S., Ma, M., Xiang, X., Cai, W., Feng, W., & Ma, Z. (2022). Potential to decarbonize the commercial building operation of the top two emitters by 2060. *Resources, Conservation and Recycling*, 185, 106481. <https://doi.org/10.1016/j.resconrec.2022.106481>
- Zhang, X., Lau, S. K., Lau, S. S. Y., & Zhao, Y. (2018). Photovoltaic integrated shading devices (PVSDs): A review. *Solar Energy*, 170, 947–968. <https://doi.org/10.1016/j.solener.2018.05.067>
- Zhou, H., Cai, J., Zhang, T., Xu, L., Li, Q., Ren, H., Shi, Z., & Zhou, F. (2023). Performance analysis on the concentrated photovoltaic /thermal air collector with phase change material and vacuum double-glazing for temperature regulation. *Renewable Energy*, 207, 27–39. <https://doi.org/10.1016/j.renene.2023.03.012>
- Zou, W., Wang, Y., Tian, E., Wei, J., Peng, J., & Mo, J. (2024). A New Dynamic and Vertical Photovoltaic Integrated Building Envelope for High-Rise Glaze-Facade Buildings. *Engineering*. <https://doi.org/10.1016/j.eng.2024.01.014>

APPENDIX

Appendix A: Energy Generation and Consumption Details

VERNAL EQUINOX			
Time	Spaced PV Generation (kWh)	Unspaced PV Generation (kWh)	Base Case Consumption (kWh)
12:00:00 AM	0	0	58.03129
1:00:00 AM	0	0	48.17775
2:00:00 AM	0	0	43.45794
3:00:00 AM	0	0	39.46967
4:00:00 AM	0	0	37.81044
5:00:00 AM	0	0	36.74694
6:00:00 AM	22.76616547	43.29740781	36.15248
7:00:00 AM	88.79600753	162.8299736	42.64346
8:00:00 AM	224.5150993	360.5318451	459.7391
9:00:00 AM	386.7101794	504.2041546	506.4015
10:00:00 AM	487.6876232	501.5651135	540.6827
11:00:00 AM	478.7432101	418.8972416	554.2844
12:00:00 PM	355.9033193	304.6908191	565.1218
1:00:00 PM	274.6040658	239.2302782	564.1293
2:00:00 PM	215.097345	193.3656517	565.8657
3:00:00 PM	137.9310304	143.5600584	563.95
4:00:00 PM	62.40695421	80.14350769	562.7393
5:00:00 PM	14.05453941	21.65336574	266.8497
6:00:00 PM	0	0	161.453
7:00:00 PM	0	0	143.1463
8:00:00 PM	0	0	130.1137
9:00:00 PM	0	0	67.04757
10:00:00 PM	0	0	60.18763
11:00:00 PM	0	0	55.97032

SUMMER SOLSTICE			
Time	Spaced PV Generation (kWh)	Unspaced PV Generation (kWh)	Base Case Consumption (kWh)
12:00:00 AM	0	0	15.54902
1:00:00 AM	0	0	15.54902
2:00:00 AM	0	0	15.54902
3:00:00 AM	0	0	15.54902
4:00:00 AM	0	0	15.54902
5:00:00 AM	17.69028372	33.56892425	15.54902
6:00:00 AM	136.9514798	253.9120488	645.0134
7:00:00 AM	288.0759421	468.3476189	689.7741
8:00:00 AM	417.0089998	563.7854166	1008.736
9:00:00 AM	475.4868577	488.472834	1025.395
10:00:00 AM	382.4061233	337.8519492	1024.699
11:00:00 AM	160.8833281	179.7141092	1052.042
12:00:00 PM	44.00894473	95.82133629	1077.86
1:00:00 PM	49.68313972	85.19337336	1082.603
2:00:00 PM	74.77513456	95.7869873	1080.575
3:00:00 PM	68.33926416	83.97184131	1076.168
4:00:00 PM	58.97441267	76.12587365	1067.473
5:00:00 PM	29.71841229	40.17246467	1039.325
6:00:00 PM	3.30562678	5.60281005	707.6459
7:00:00 PM	0	0	546.2307
8:00:00 PM	0	0	494.537
9:00:00 PM	0	0	446.0426
10:00:00 PM	0	0	15.54902
11:00:00 PM	0	0	15.54902

AUTUMNAL EQUINOX			
Time	Spaced PV Generation (kWh)	Unspaced PV Generation (kWh)	Base Case Consumption (kWh)
12:00:00 AM	0	0	363.8892
1:00:00 AM	0	0	316.9668
2:00:00 AM	0	0	275.8654
3:00:00 AM	0	0	269.2154
4:00:00 AM	0	0	234.6683
5:00:00 AM	0	0	201.8504
6:00:00 AM	54.47870674	144.2611369	201.3334
7:00:00 AM	238.5901676	461.7680995	238.2706
8:00:00 AM	418.8161356	652.2105794	784.5366
9:00:00 AM	528.1311165	649.591242	839.4693
10:00:00 AM	527.9302324	521.8090852	902.4656
11:00:00 AM	393.9654393	372.5819456	957.3116
12:00:00 PM	257.6331008	255.9509744	989.8763
1:00:00 PM	202.8928978	201.5156761	1013.244
2:00:00 PM	161.8575308	191.3071411	1023.9
3:00:00 PM	97.15303738	193.9956288	1028.057
4:00:00 PM	37.06715801	81.06732556	986.5408
5:00:00 PM	3.88403924	10.10316203	952.4133
6:00:00 PM	0	0	627.6808
7:00:00 PM	0	0	483.4905
8:00:00 PM	0	0	431.3285
9:00:00 PM	0	0	328.694
10:00:00 PM	0	0	292.8915
11:00:00 PM	0	0	296.5557

WINTER SOLSTICE			
Time	Spaced PV Generation (kWh)	Unspaced PV Generation (kWh)	Base Case Consumption (kWh)
12:00:00 AM	0	0	15.54902
1:00:00 AM	0	0	113.7997
2:00:00 AM	0	0	99.33418
3:00:00 AM	0	0	82.9643
4:00:00 AM	0	0	74.74674
5:00:00 AM	0	0	68.36596
6:00:00 AM	0	0	61.60213
7:00:00 AM	102.1655	207.810468	66.0971
8:00:00 AM	336.4029	613.785635	397.6101
9:00:00 AM	456.5299	745.913554	437.7775
10:00:00 AM	514.4071	717.499513	469.3375
11:00:00 AM	466.939	612.632948	497.1183
12:00:00 PM	376.8989	496.794637	523.0458
1:00:00 PM	318.1882	402.068491	549.0702
2:00:00 PM	212.0457	291.461273	567.3425
3:00:00 PM	108.8454	173.325641	569.8805
4:00:00 PM	32.34322	57.1426703	565.5032
5:00:00 PM	0	0	550.8528
6:00:00 PM	0	0	238.4014
7:00:00 PM	0	0	119.5294
8:00:00 PM	0	0	98.66515
9:00:00 PM	0	0	82.62743
10:00:00 PM	0	0	70.26633
11:00:00 PM	0	0	61.53057

Appendix B: Cooling Energy Consumption

VERNAL EQUINOX			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
5:00:00 AM	10.65934	8.636666	9.3896
6:00:00 AM	10.40317	7.571587	8.280901
7:00:00 AM	16.93712	6.407907	7.419807
8:00:00 AM	128.6474	56.75358	71.4345
9:00:00 AM	169.4781	77.35877	95.08216
10:00:00 AM	199.5863	96.29066	115.0914
11:00:00 AM	211.4796	105.9953	124.2603
12:00:00 PM	221.3637	117.1015	134.2787
1:00:00 PM	220.6062	118.5473	135.51
2:00:00 PM	222.1307	122.5829	137.8767
3:00:00 PM	220.4823	124.1767	138.2606
4:00:00 PM	219.5484	129.8808	143.0869
5:00:00 PM	131.2956	69.10449	83.70461

SUMMER SOLSTICE			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
6:00:00 AM	552.8599	395.1286	405.1
7:00:00 AM	592.0137	411.4071	401.1753
8:00:00 AM	648.8329	447.591	420.4545
9:00:00 AM	664.8574	457.8807	462.0519
10:00:00 AM	664.7622	458.8207	475.3973
11:00:00 AM	691.5474	487.2906	475.8388
12:00:00 PM	716.8413	514.633	501.0207
1:00:00 PM	721.5665	522.6528	526.5353
2:00:00 PM	719.6925	525.7046	533.4968
3:00:00 PM	715.6732	527.5166	535.5144
4:00:00 PM	707.8129	526.8202	535.8461
5:00:00 PM	681.9089	513.1667	534.1672
6:00:00 PM	560.1667	431.4449	519.5015

AUTUMNAL EQUINOX			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
5:00:00 AM	160.6127	140.6309	142.9887
6:00:00 AM	160.0507	130.0924	137.4589
7:00:00 AM	192.4883	122.0065	148.2914
8:00:00 AM	420.2421	278.5648	302.0942
9:00:00 AM	469.4438	309.4279	337.6372
10:00:00 AM	527.4711	341.5648	372.6152
11:00:00 AM	578.0931	385.2473	415.9279
12:00:00 PM	608.5901	422.2775	443.5976
1:00:00 PM	630.2312	447.4673	467.669
2:00:00 PM	639.6593	466.8163	481.0557
3:00:00 PM	643.0357	477.7122	489.4077
4:00:00 PM	604.5594	448.1613	458.9094
5:00:00 PM	573.1071	436.5082	444.9963
6:00:00 PM	456.6678	357.4597	366.6013

WINTER SOLSTICE			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
7:00:00 AM	31.06815	0.22256	0.657602
8:00:00 AM	105.3834	13.30934	38.2719
9:00:00 AM	140.4668	19.88581	53.4522
10:00:00 AM	168.0605	30.98076	67.14657
11:00:00 AM	192.489	45.01593	81.66999
12:00:00 PM	215.4078	60.59075	95.93727
1:00:00 PM	238.6656	75.85028	113.6585
2:00:00 PM	255.0938	94.6615	129.4982
3:00:00 PM	257.396	107.8365	135.8597
4:00:00 PM	253.476	111.3526	141.4734
5:00:00 PM	240.5714	117.5653	150.5246

Appendix C: Lighting Energy Consumption

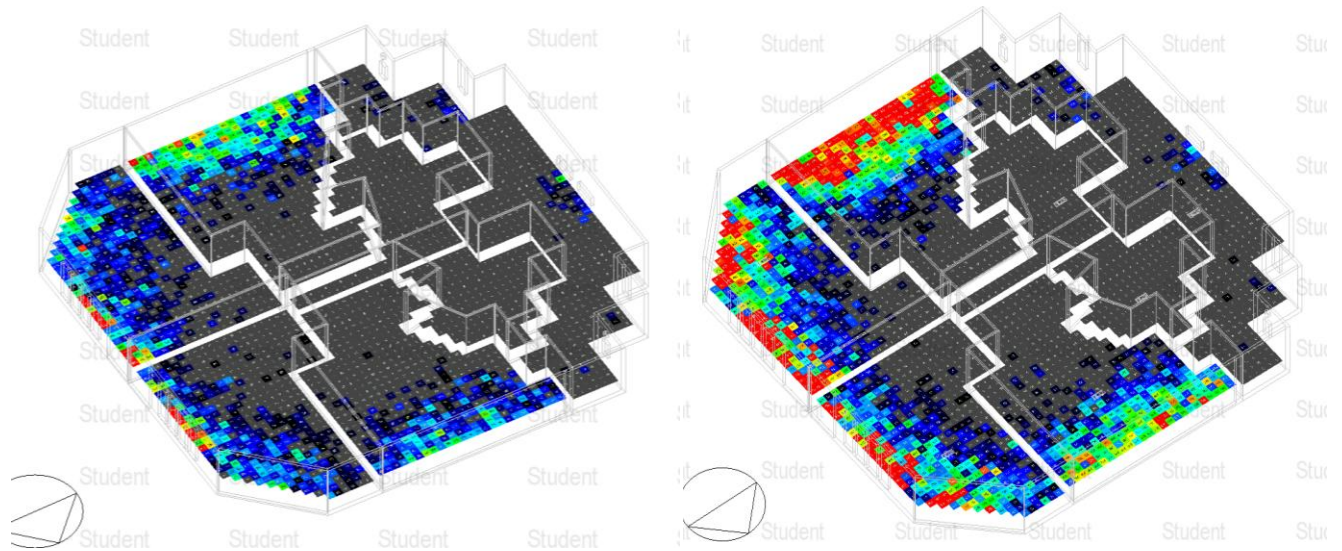
VERNAL EQUINOX			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
5:00:00 AM	6.297373	6.297373	6.297373
6:00:00 AM	4.506119	5.497817	5.033696
7:00:00 AM	2.320807	4.282067	2.994135
8:00:00 AM	49.24389	86.83179	59.76005
9:00:00 AM	47.4629	84.65648	56.74192
10:00:00 AM	46.85056	83.85664	56.25463
11:00:00 AM	46.5575	84.78199	56.74816
12:00:00 PM	47.00356	87.50523	59.204
1:00:00 PM	47.62603	89.21835	61.15167
2:00:00 PM	47.09688	90.0949	61.63334
3:00:00 PM	46.60202	91.52793	63.39006
4:00:00 PM	51.54863	97.0178	74.79576
5:00:00 PM	16.67483	28.70541	24.74014

SUMMER SOLSTICE			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
5:00:00 AM	4.724268	5.610292	5.275094
6:00:00 AM	2.454603	4.330806	3.185788
7:00:00 AM	2.193891	4.082739	2.713754
8:00:00 AM	42.07344	80.15961	51.89556
9:00:00 AM	40.75555	79.24727	49.78487
10:00:00 AM	40.00287	78.65293	49.17941
11:00:00 AM	40.64333	78.32082	49.59801
12:00:00 PM	40.46601	78.5629	49.2173
1:00:00 PM	34.53301	78.76884	47.64157
2:00:00 PM	26.23919	79.8335	44.59961
3:00:00 PM	19.77086	82.45118	43.9119
4:00:00 PM	22.247	86.50347	47.44661
5:00:00 PM	34.20915	94.57239	62.77903
6:00:00 PM	15.84145	29.04816	24.14786

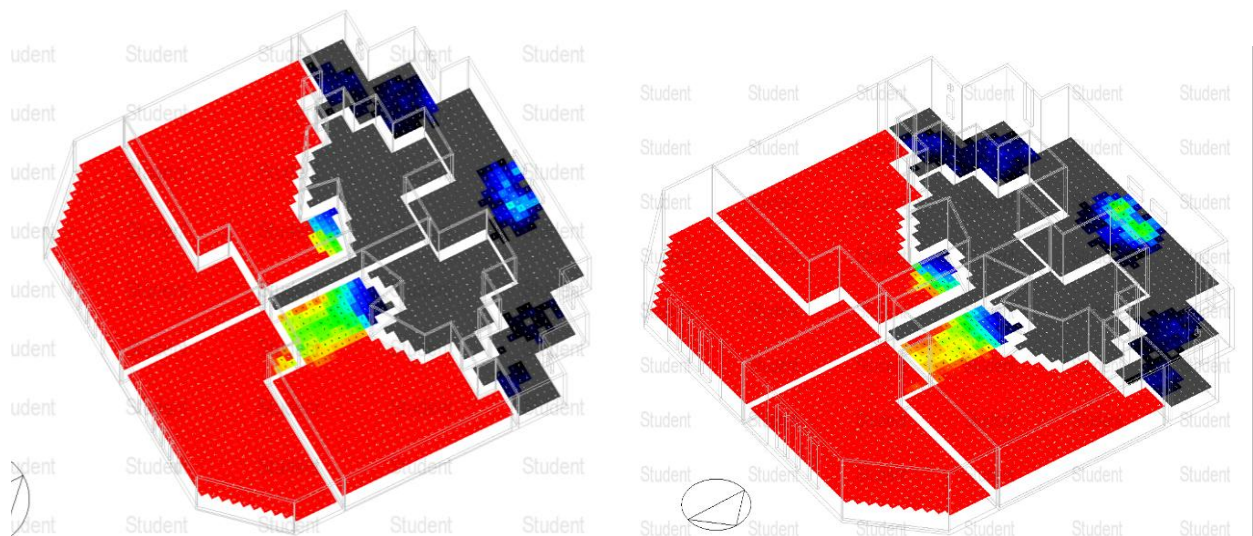
AUTUMNAL EQUINOX			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
5:00:00 AM	6.297373	6.297373	6.297373
6:00:00 AM	4.393932	5.390331	4.825256
7:00:00 AM	2.230745	4.215103	2.906912
8:00:00 AM	48.97742	87.53284	59.82735
9:00:00 AM	47.22137	85.86266	57.2822
10:00:00 AM	46.6095	85.15251	56.74538
11:00:00 AM	46.34184	85.29214	56.55322
12:00:00 PM	45.50504	85.52976	56.45961
1:00:00 PM	42.03275	86.03098	56.12497
2:00:00 PM	35.84835	87.52954	54.79423
3:00:00 PM	32.44674	92.70071	56.38034
4:00:00 PM	40.62489	100.3804	69.58868
5:00:00 PM	69.46035	109.6461	96.15879

WINTER SOLSTICE			
Time (hr.)	Base-Case (kWh)	Unspaced PV (kWh)	Spaced PV (kWh)
7:00:00 AM	3.061564	5.018083	3.93296
8:00:00 AM	45.17088	87.7823	53.62823
9:00:00 AM	43.51418	81.49897	50.92051
10:00:00 AM	42.33105	85.38995	49.29003
11:00:00 AM	41.27579	85.1038	48.24579
12:00:00 PM	39.8653	85.52285	47.552
1:00:00 PM	35.17631	86.26051	46.22783
2:00:00 PM	29.27605	89.24808	45.67819
3:00:00 PM	29.32015	95.47115	50.74332
4:00:00 PM	45.40189	105.0739	71.90874

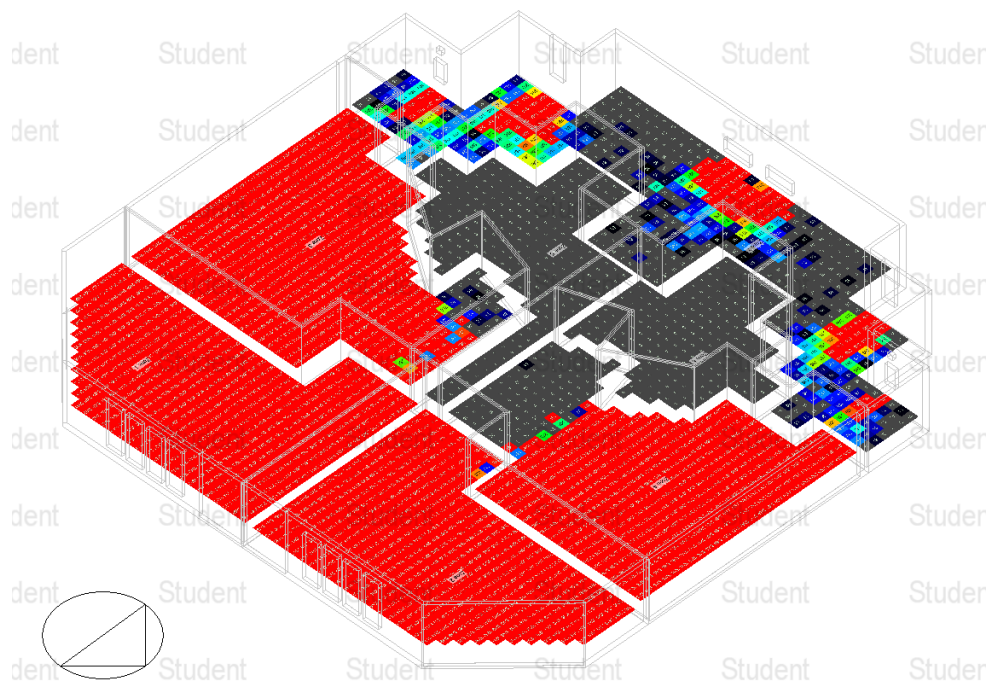
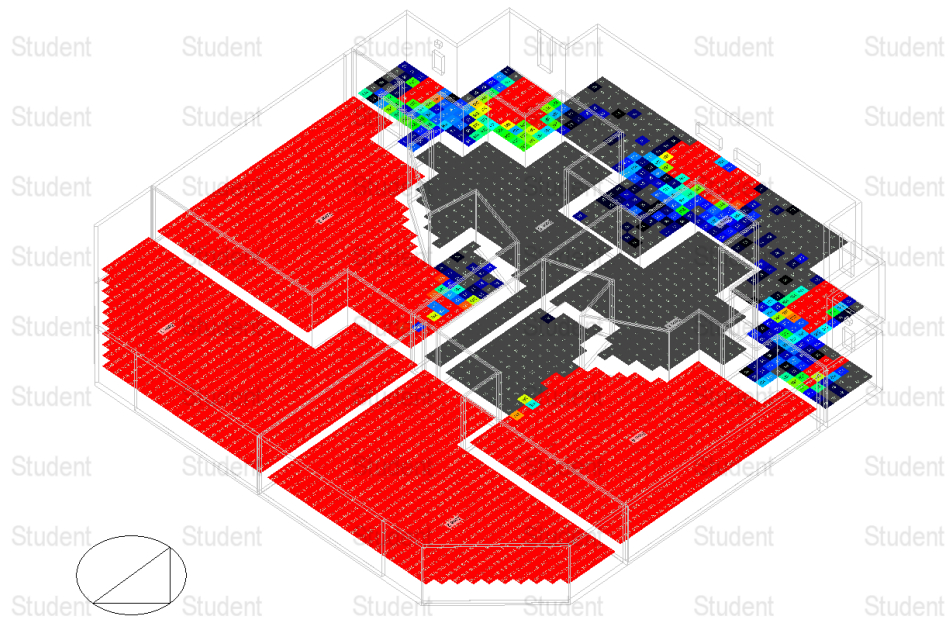
Appendix D: Daylighting Analysis Showing Non-Compliance of Unspaced PV Configurations (10°-50° Tilt) with Standard Metrics



Appendix E: Daylighting Analysis Showing Compliance of Unspaced PV Configurations (60°-90° Tilt) with Standard Metrics



Appendix F: Daylighting Analysis Showing Compliance of Spaced PV Configurations (10°-90° Tilt) with Standard Metrics



Vitae

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Conference Publication	A. Opeyemi Bello, A. Adefemi, M. Semiu, A. Yusuff Adelabu. 2022. “Assessing the impact of urban renewal on the built environment in Nigeria.” International Korkut Ata Scientific Researches Conference At: Turkey (Published). (ISBN–978- 625- 8323-69-6)