



Design and Performance Assessment of Photovoltaic Building Envelopes for a Prototype Office Building in the Mediterranean

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ABSTRACT

In recent years, with the depletion of energy resources, studies on the use of renewable and clean energy sources have increased rapidly. The use of renewable energy sources is particularly prominent in the construction sector, which has a high energy consumption. This study examines the energy performance of Building-Integrated Photovoltaic (BIPV) systems applied to different façade designs in a prototype office building in the Mediterranean climate, specifically designed for renewable energy use in buildings. Four different PV façade design scenarios were determined for the prototype building, and energy performance analyses were conducted using the DesignBuilder simulation program. In this context, energy performance values such as Energy Coverage Ratio (ECR) and Self-Consumption Ratio (SCR) of the scenarios were compared. As a result of the comparison, the S2 inclined PV façade demonstrated the highest ECR (42.92%) and the lowest SCR (70.9%). The findings show that facade designs and the application of PV systems are important elements in determining the building energy performance and can meet a significant portion of the energy consumption. The study contributes to the evaluation of energy performance arising from differences in PV system applications in façade designs during the building's preliminary design process.

Akdeniz'deki Prototip Ofis Binası için Fotovoltaik Bina Kabuğu Tasarımı ve Performans Değerlendirmesi

MAKALE BİLGİSİ

Anahtar Kelimeler:

BIPV
Ofis binası
Cephe tasarımı
Yapı kabuğu
Enerji performansı

ÖZET

Son yıllarda enerji kaynaklarının tükenmesi ile birlikte yenilenebilir ve temiz enerji kaynaklarının kullanılmasına yönelik çalışmalar hızla artmıştır. Özellikle yüksek enerji tüketimine sahip olan yapı sektöründe yenilenebilir enerji kaynaklarının kullanımı ön plana çıkmaktadır. Çalışmada, binalarda yenilenebilir enerji kullanımına yönelik Akdeniz ikliminde prototip ofis binasına farklı cephe tasarımları ile uygulanan BIPV (Building Integrated Photovoltaic) sistemlerin enerji performansları incelenmektedir. Prototip bina üzerinden dört farklı PV cephe tasarım senaryosu belirlenerek enerji performans analizleri DesignBuilder simülasyon programı aracılığıyla gerçekleştirilmiştir. Bu bağlamda senaryoların enerji karşılama oranı (Energy Coverage Ratio - ECR), öz tüketim oranı (Self-Consumption Ratio - SCR) gibi enerji performans değerleri karşılaştırılmıştır. Karşılaştırma sonucunda, S2 eğimli PV cephe en yüksek ECR (%42,92) ve en düşük SCR (%70,9) değerlerini göstermiştir. Ulaşılan bulgular, cephe tasarımları ve PV sistemlerinin uygulanma biçimlerinin bina enerji performansını belirlemede önemli bir unsur olduğunu ve enerji tüketiminin önemli bir kısmını karşılayabileceğini göstermektedir. Çalışma bina ön tasarım sürecinde, cephe tasarımlarında PV sistem uygulamalarındaki farklılıklardan kaynaklı enerji performansının değerlendirilmesine yönelik katkı sunmaktadır.

NOMENCLATURE

AC	alternating current
ASHRAE	american society of heating, refrigerating and air-conditioning engineers
BAPV	building attached photovoltaic
BIPV	building integrated photovoltaic
CdTe	cadmium telluride
DC	direct current
DDS	design decision step
ECR	energy coverage ratio

HVAC	heating, ventilation and air conditioning
LSC	luminescent solar concentrator
NOCT	nominal operating cell temperature
NZEB	nearly zero energy building
PV	photovoltaic
SCR	self-consumption ratio
U-value	overall heat transfer coefficient
ZEB	zero energy building

INTRODUCTION

With Industry 4.0, the increasing energy needs of technologically mechanized cities have caused major global energy problems in recent years (Hasan & Trianni, 2023; Kaya & Beyhan, 2025). In addition to energy poverty, issues such as rising carbon emissions, climate change (Abu Qadourah, 2022), and escalating costs of fossil-based resources have brought energy generation and consumption to the forefront (Yilmazoglu, 2017). The construction sector significantly contributes to these challenges, accounting for approximately 39% of global carbon dioxide emissions and 36% of total energy consumption in 2018. When construction and demolition processes are included, this share increases to nearly 50% (Santamouris & Vasilakopoulou, 2021). The International Energy Agency (IEA) reported that in 2021, energy demand in buildings increased by approximately 4% compared to the previous year, marking the highest rise in the last two decades, especially following the COVID-19 pandemic (IEA, 2022). Furthermore, it is projected that energy consumption in the built environment will double by 2050 (Roy et al., 2020). In response to these challenges, numerous protocols and targets have been established at both EU and global levels to enhance energy efficiency and reduce carbon emissions in buildings with high energy consumption. However, it has been recognized that implementing energy conservation measures alone is insufficient to classify such buildings as energy-efficient. In addition to reducing energy demand, the integration of low-carbon, alternative renewable energy sources for clean energy generation in buildings is of critical importance (Kaya et al., 2025). In this context, alongside energy-efficient building design approaches, the concepts of nearly zero energy building (NZEB) and positive energy building (PEB) have gained significant prominence globally (Barrutieta et al., 2023; European Parliament and the Council, 2018; Özer Yaman, 2025). These concepts emphasize energy generation from renewable energy sources within the framework of energy efficiency and are increasingly integrated into the design principles of the built environment (Wang et al., 2016; Elghamry et al., 2020; Kürüm Varolgüneş, et al., 2023). Furthermore, these approaches are increasingly being incorporated into legislation around the world. Among renewable energy technologies used in buildings, solar-based systems stand out as the most prevalent due to their inexhaustible nature, high energy efficiency, and ease of use (Shi et al., 2022; Khan et al., 2023; Kaya & Beyhan, 2021).

Solar energy is utilized in buildings through two main systems: energy-generating systems (Photovoltaic-PV) and heat-generating systems (solar collectors) (Basnet, 2012; Kaya, 2022). Among these systems, the use of PV systems that generate energy is becoming increasingly widespread

(Michailidis, et al., 2025). The global investment rate in PV systems that generate energy has increased significantly in recent years, rising from 38% in 2019 to 60% in 2022 and reaching 73% in 2023 (IRENA, 2024). The increase in PV system-related studies in both the construction sector and other sectors, as well as the spread of international incentives and investments and the mandatory implementation of NZEB standards in many countries, has resulted in a rapid increase in PV system applications and potential (Maduta et al., 2025). As PV system applications become more widespread in buildings, the need for additional land is decreasing, thereby enabling cost optimization (Khun et al., 2020).

In this context, energy policies require that building integrated PV (BIPV) systems, which are considered a fundamental component of building envelopes, particularly in NZEB design approaches, be integrated into architectural design and implementation processes using integrated design methods, creating a unique and innovative field of research. This study aims to examine the energy performance of different design applications of BIPV systems in the building envelope, taking into account integrated design methods. This examination is based on the hypothesis that BIPV system applications can be incorporated more extensively into architecture and energy efficiency can be improved by considering them comprehensively from the outset of the design process.

Background of Photovoltaic in Building Envelope

With the advancement of technologies, significant progress has been made in maximizing energy generation through building envelope applications of PV systems (Mandalaki et al., 2012). In this context, factors influencing the energy generation efficiency of PV systems, such as PV cell type (Reddy et al., 2020; Basnet, 2012), orientation and tilt angle (Sanchez & Izad, 2015; Gweshia et al., 2019; Minelli et al., 2023), as well as temperature and shading conditions (Dabbagh, 2015; Asfour, 2018; Bayrak et al., 2025), have been extensively studied. These studies highlight a strong correlation between considering these factors in the application of PV systems on building envelopes and achieving optimal energy efficiency.

PV system applications in buildings are predominantly implemented as technical elements on roofs (Abu Qadourah, 2023; Wijeratne et al., 2022). However, in recent years, facade applications have gained prominence due to the insufficiency of roof areas in urban settings and the high potential offered by building facades with large surface areas for PV system integration (Zhang et al., 2018; Youssef et al., 2015). In addition to research focusing on the efficiency of facade-applied PV systems, studies addressing architectural design

integration and cost implications have also been conducted (Marinos et al., 2014; Debbarma et al., 2017; Tablada et al., 2020). These studies have led to the increased adoption of BIPV systems, a contemporary and innovative approach to building envelope design. BIPV systems are a relatively new technology that was first implemented in Germany in 1985 by integrating them into roofs (Crassard & Rode, 2007). When considered in a general framework, BIPV systems offer lower costs compared to building attached PV (BAPV) systems due to their ability to replace traditional materials and their optimal life cycle costs, while also providing aesthetically superior solutions for buildings (Ghosh, 2020; Debbarma et al., 2017). BIPV systems can perform various functions simultaneously by being integrated into the building envelope from the outset with appropriate details, in addition to energy generation (Kirimtat et al., 2022; Tabakovic, et al., 2016; Yang & Zou, 2016). These functions include reducing structural damage, providing aesthetic integration, creating a high-quality architectural appearance, enabling innovative designs, and protecting the structure from adverse weather conditions by providing insulation and shading as part of the

building envelope (Abu Qadourah, 2020; Bukker & Riffat, 2015; Biloria et al., 2023).

The building envelope serves multiple visual and structural functions within a building. Consequently, the integration of BIPV systems into the building envelope often involves complex detailing (Martin-Chivelet et al., 2025). To achieve optimal results, it is crucial to employ efficient integration solutions and develop visually appealing, innovative designs. BIPV systems are classified according to cell technologies, BIPV design and market (Gholami et al., 2021; Shukla et al., 2017). With recent developments, nano-based fourth-generation PV cells have been added to cell technologies, and these cells are highly efficient, flexible, and have advanced functionality (Rehman et al., 2023). However, nano-based cells are not widely used in applications due to their recent development. The most commonly used cells in applications are first-generation silicon-based cells (monocrystalline silicon and polycrystalline silicon). Within the scope of BIPV design, the basic design concepts and applications (according to EN 50583) are grouped (Martín-Chivelet et al., 2022; Kiss, 1993; Dabbagh, 2015; IEA-PVPS, 2023) (Figure 1).

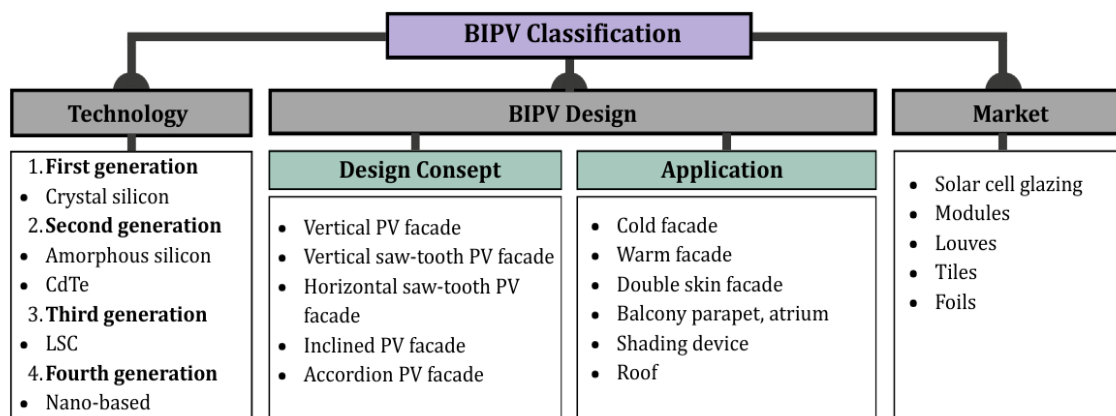


Figure 1. BIPV system classification

Integrated building design has gained significant importance with the concurrent use of technological systems from the early stages of building design, alongside the rise of sustainable building approaches (Düzgün & Aladağ, 2016). To effectively integrate BIPV system applications into the building envelope, an integrated building design process must be applied. This process ensures that all components of the system are considered simultaneously, resulting in a reduction of the building's energy requirements, enhanced efficiency from technological applications, and cost optimization. By involving all teams at every stage of the process, optimal conditions are achieved, and the integrated approach throughout the life cycle facilitates evaluation and team formation (Yao, 2017; Attia et al., 2013). As a result, the use of integrated renewable energy systems and other components becomes a necessity for building concepts such as NZEB and PEB in architecture. However, despite its advantages, integrated building design may present challenges, such as unclear boundaries compared to traditional design processes and an emphasis on technical aspects over architectural considerations (Koch & Buh, 2013). This study aims to maximize the efficiency of integrating architectural building envelope systems with active solar systems by minimizing the negative aspects of the integrated design approach.

As a result of achieving high energy efficiency, the subject has begun to feature prominently in academic studies. In a study by Kaftan et al. (2019) on the holistic design of PV systems, it was emphasized that individuals without expertise in PV systems should be provided with guidance on material selection and usage planning during the early design phase to ensure the effective integration of BIPV systems. Additionally, the study developed a calculation method to determine the optimum quantity and location of PV systems based on building energy demand. In the context of retrofitting buildings with PV systems, Ascione et al. (2021) conducted an analysis to investigate high-cost situations and the criteria contributing to the elevated costs of sensitive elements, as well as the lower efficiency of transparent photovoltaics compared to conventional photovoltaics, which also carry the risk of overheating. Regarding the application of PV systems in buildings, Sayın & Koç (2011) analyzed system components, materials, and types, offering insights into the practical implementation of PV systems in architectural contexts.

Debbarma et al. (2017) analyzed the cost, functionality, and aesthetic characteristics of both systems, assessing their potential for integration into buildings. Aelenei et al. (2019) investigated the electrical energy performance of the Solar XXI office building in Lisbon, where polycrystalline BIPV was installed on the south façade for

electricity generation, and a PV roof system was placed on the adjacent parking facility. Despite high-level energy efficiency measures, the building could not meet annual energy consumption or NZEB criteria. In a study conducted in Taiwan, the economic benefits of BIPV systems were evaluated by examining the net present value and payback period of BIPV systems applied to the facade of a shopping center. Over a 20-year life cycle, the payback period for BIPV systems was calculated to be 10 years, and the net present value was calculated to be 16 years (Wu et al., 2018). Kaya & Beyhan (2024) study showed that PV system efficiencies integrated with various tilt angles and designs in Mediterranean climates varied, with the highest energy generation (26.59%) achieved from the inclined PV façade system, optimally integrated with the façade at a horizontal tilt angle. Tachir et al. (2024) concluded that emissions were reduced by 30% through energy consumption and environmental impact assessments of a boutique hotel building in Greece using active solar systems. Finally, Abu Qadourah (2022), study analyzed the energy generation and economic viability of PV systems on roofs in Jordan. It was determined that rooftop PV systems could meet 76% to 86% of the building's electricity consumption in the best-case scenario (azimuth 90° and -90°, slope: 7°), and 25% to 29% over 25 years, depending on building location.

In all of these studies in the literature, PV systems have not been applied to the structure from the outset of the design, taking into account integrated design methods. Taking this shortcoming in existing studies into account, this article integrates PV systems into the building envelope using integrated design methods and different façade design concepts, and then evaluates the energy performance of the façade design concepts. The study focused on meeting the energy needs of buildings through PV systems and evaluated different design integration forms of the relevant systems into the building envelope. In this context, the aim was to systematically examine integrated design approaches related to the use of active solar systems in architecture, identify application methods, and

create a design decision system that would be beneficial in architectural design processes.

METHODOLOGY

Antalya, one of Turkey's provinces with the highest solar radiation potential and located in the Mediterranean climate zone, was selected as the study area. The Mediterranean climate is of great importance for energy generation through PV systems in buildings due to the high amount of solar energy and the large number of sunny days per year (Abu Qadourah, 2023; Abu Qadourah et al., 2022). In this context, many studies have been conducted on the subject (Mandalaki et al., 2012; Mandalaki et al., 2014; Gonçalves et al., 2012; Karteris et al., 2013; Freitas & Serra, 2015; Peng et al., 2016).

The aim of this study is to evaluate the energy generation of PV systems applied to a prototype office building in Antalya, located in the Mediterranean climate, with different designs, and to calculate the energy consumption of the building with different designs. In this study, which aims to develop a design guide for this region, which is extremely advantageous for the use of PV systems, the first step was to identify the building specifications, location, and climate data for the prototype building that will form the basis of the design. The modelling of the developed prototype was carried out using the DesignBuilder simulation software, a building energy performance analysis tool (DesignBuilder Software Ltd., 2024). In the second phase of the study, design decision steps were established within the context of integrated design. In this phase, the locations, applications, angles, integration type, and connection type of PV panels on roofs and facades were determined based on four different design concept scenarios. In the third phase, energy generation and consumption comparisons of the four different BIPV façade design scenarios developed were evaluated through DesignBuilder simulation on the prototype building and in relation to each other, and the final result was obtained (Figure 2).

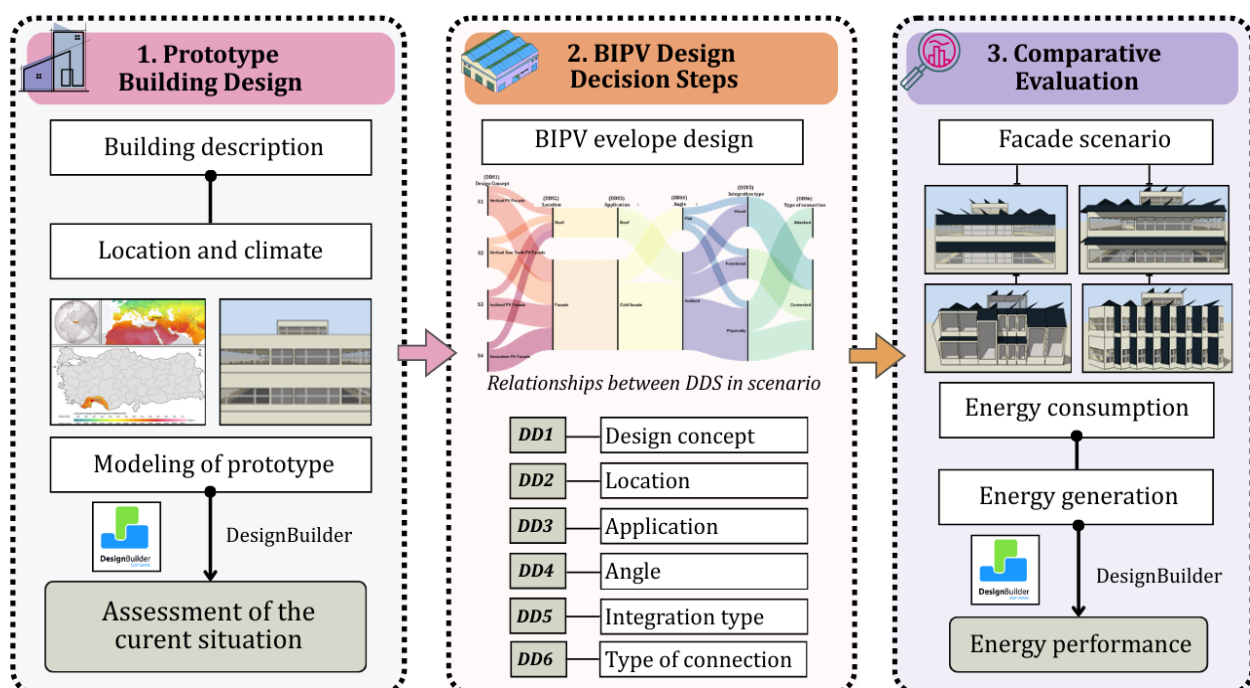


Figure 2. Flowchart of BIPV design methodology

Prototype Office Building

In the prototype building design phase, which constitutes the first stage of the fieldwork, building specifications, location and climate data were transferred to DesignBuilder simulation software to develop a prototype office model.

Building description

A prototype office building was developed for the field study. Office buildings, due to their function, are primarily designed for daytime use and demand high levels of daylight as well as optimal thermal performance (Li & Tsay, 2008; Yan et al., 2022). This characteristic presents a range of opportunities, particularly for the design and integration of PV systems into the building envelope. Taking these design considerations into account, the office prototype was positioned in a rectangular form along the east-west axis, maximizing the south-facing surface area to achieve the greatest efficiency from natural daylight. The prototype consists of a two-story open office layout with dimensions of 18x30 meters, encompassing a floor area of 540 m². The floor plans include office spaces, vertical circulation areas, wet zones, archive and storage rooms, as well as ventilation and installation shafts. Notably, there is no external shading around the prototype.

Location and climate

Antalya, located in Turkey's Mediterranean climate zone, was selected for the simulation study, which incorporates integrated design decisions in line with the guidelines developed. The climate of the region is characterized by hot and humid conditions, coupled with high solar radiation potential (approximately 4 kWh). Annual data indicates that Antalya experiences an average of 300 sunny days per year, with an average annual sunshine duration of 8.2 hours (MGM, 2024). Due to the elevated temperatures, the demand for cooling is significant during the summer months. The study area is situated at 36° 87' north latitude and 30° 73' east longitude (Figure 3).

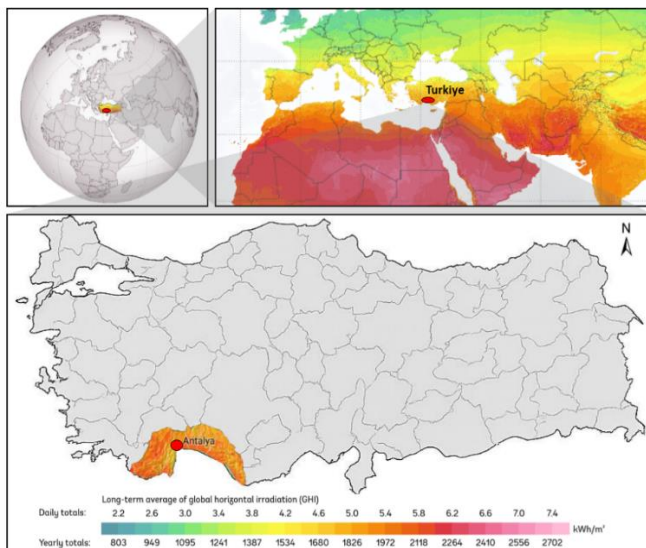


Figure 3. Location of case study area and global horizontal irradiation (World Bank, 2026)

BIPV Design Decision Step (DDS)

In the BIPV design decision step process, which constitutes the second phase of the study, six steps have been identified for the application of different PV system integrated design methods in prototype building scenarios. In the first phase of the design decision steps (DDS1), developed by considering all connections in the application of PV systems to the building envelope, the design concepts of PV systems to be applied to the facade have been determined. In this context, four different PV façade design concepts commonly used in the literature were selected as scenarios (Kiss, 1993; Dabbagh, 2015). In the second stage (DDS2), the positioning of PV systems on the building envelope was carried out on roofs and façades for all scenarios. In the third stage (DDS3), the PV systems were considered in the context of design applications to the building envelope as described in the literature, and the cold facade PV application, which achieves the highest energy efficiency in facade integrations, was applied in all scenarios (SUPSI, 2017). In the fourth stage (DDS4), the angles of the PV systems applied to the building envelope were determined as either inclined or flat. In the fifth stage (DDS5), the integration forms of PV systems in roof and facade applications in the scenarios were determined. Here, the visual, functional, and physical integration forms of PV systems were identified according to the applications. In the sixth stage (DDS6), the connection forms of PV systems were determined as either modular or connected, depending on their roof and facade applications (Figure 4). Following the design decision-making process, all scenarios were compared with the prototype building.

PV systems were applied to the south, east and west facades in the four scenarios created, while no PV systems were applied to the north facade due to its low efficiency. In the scenarios, PV technology utilised monocrystalline silicon cells due to their highest cell efficiency within silicon-based cells and their widespread use (Tyagi et al, 2013; Sugianto, 2020). The energy efficiencies obtained from the PV systems for each prototype were analysed in the scenarios. The implementation statuses of the reference office building and all PV facade scenarios are shown in Table 1.

In the S1 vertical PV scenario, energy consumption values and building materials were kept the same as in the existing prototype. In this scenario, PV systems were vertically integrated above windows on the south, east, and west facades, which show high efficiency in terms of solar radiation (Li et al., 2023). In S1, a total of 52 PV modules were used on each floor, with 26 modules on the west and east facades. On the south facade, which has a large surface area, a total of 86 PV modules were used, with 43 modules on each floor. In the S2 inclined PV scenario, the PV systems integrated into the south, west, and east facades are integrated at an angle of 35 degrees, which is the optimal angle for Antalya in relation to the sun (Kazemzadehmarand & Sözen, 2024). The total number of PV modules used in S2 is kept equal to that in S1. In the S3 vertical gear PV scenario, a total of 120 PV modules were applied on the south facade, with 60 modules on each floor, and a total of 70 PV modules were applied on the east and west facades, with 35 modules on each floor. In this scenario, the facades differ from the prototype building facades due to the vertical gear PV facade design concept.

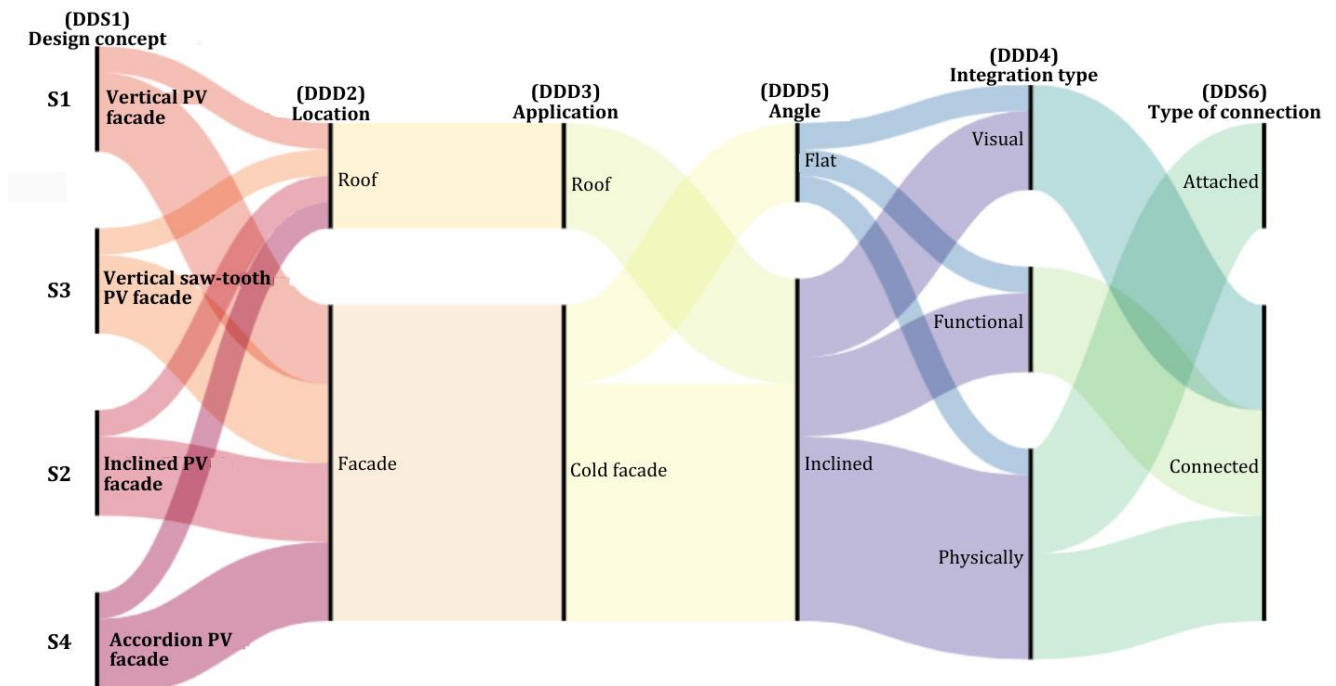


Figure 4. BIPV design decision step for scenarios sankey diagram

In the S4 accordion PV scenario, 22 PV systems were installed on the ground floor and 62 PV systems on the first floor of the south facade, for a total of 84 PV systems. On the east and west facades, 14 PV systems were installed on the ground floor and 38 PV systems on the first floor, for a total of 52 PV systems. Three different angles (17.5°, 35°, and 70°) were determined for the PV systems used on the

accordion facades, which are multiples of 35°. Similarly, in this scenario, the facades differ from the prototype building due to the accordion PV facade design concept. The number of PV modules used on the roof is the same in all scenarios, with 212 PV modules installed at an optimal angle of 35 degrees relative to the sun in each scenario.

Table 1. Prototype and PV design configurations

	<i>Sun path diagram</i>	<i>South façade</i>	<i>East/West façade</i>
<i>Prototype</i>			
<i>S1 Vertical PV system</i>			
<i>S2 Inclined PV system</i>			
<i>S3 Vertical Saw-tooth PV system</i>			
<i>S4 Accordion PV system</i>			

Building energy consumption estimation

The data for the prototype office building was transferred to version 7.0.1.004 of DesignBuilder simulation software, a graphical interface of the EnergyPlus 8.9 simulation tool, and energy consumption values were calculated. In the next stage, the energy generation values of the scenarios were calculated (DesignBuilder Software Ltd., 2024). As a result of transferring the prototype data to the simulation tool, the prototype's U-values were first calculated and compared with the U-values specified for the relevant climate class according to the national regulation TS 825 Building Thermal Insulation Rules. As a result of this evaluation, it was determined that the U-values of the elements were below the maximum limits specified in the regulation.

The energy values and parameters consumed by the prototype for annual heating, cooling, lighting, and electrical equipment, as calculated by the DesignBuilder simulation, are presented in Table 2. In the simulation program, all energy loads in the building, heating, cooling, interior lighting, and electric equipment are defined as electrical energy. For this reason, within the scope of the study, all energy consumption values were considered as site electricity consumption. Heating and cooling systems are provided by an electrically powered "Fan coil unit (4-pipe) Air Cooled Chiller". Interior lighting is defined as a fixed electrical load "Office_Open-off_Light schedule". Office lighting loads were applied taking into account the 500 lux illuminance level in accordance with the EN 12464-1 standard. Daylight-dependent dimming control has not been implemented in the building. The impact of façade designs on building energy performance was evaluated separately from lighting control and as a result, no sensors were defined in the simulation. For other electrical equipment, devices such as computers and printers that consume electricity, except for fan coils and LED luminaires, were identified.

The operating hours of the systems were defined in the simulation software as 08:00-18:00 on weekdays, based on typical office usage hours. In the simulation analysis results, the annual energy consumption (8,760 h) in the prototype building was calculated as 293,406 kWh in kWh and 271.67 kWh/m²y in kWh/m²y (Energy use intensity - EUI). Due to the hot and humid climate characteristics of the work area, the office cooling system accounts for a very large portion of the total energy consumption, at 173,152 kWh (59.01%). The interior lighting in the office ranks second in energy consumption after the cooling system.

Table 2. Simulation parameters and annual energy consumption

<i>Parameter</i>	<i>Value</i>
Total area	1,080 m ²
Wall U-value	0.465 W/m ² K
Floor U-value	0.542 W/m ² K
Roof U-value	0.237 W/m ² K
Ground floor U-value	0.439 W/m ² K
Heating- Cooling set point	22 °C - 28 °C
Operating hours	Weekdays (08.00-18.00)
Interior lighting load	67,525 kWh (23.02%)
Other electric equipment load	46,720 kWh (15.92%)
Cooling load	173,152 kWh (59.01%)
Heating load	6,009 kWh (2.05%)
Total load	293,406 kWh

PV system energy generation estimation

The results of the energy generation scenarios in the study were obtained by calculating the PV system data belonging to a solar energy company and transferring it to the DesignBuilder simulation. All PV systems used in the scenarios have a module efficiency of 21.97% and consist of 36 monocrystalline silicon cells. Each panel has an installed power of 200W, a module size of 1506x685x35 mm, and each cell has a size of 158.78x158.75 mm.

The performance of the PV model in the simulation was established using the "Equivalent One-Diode" model. The cell temperature was calculated using the NOCT method, and the inverter efficiency was taken as "Simple inverter 95%". Shading was considered in relation to the building geometry, and cable-related losses were not included in the simulation models. The basic PV model parameters used are listed in Table 3.

Table 3. PV model parameters

<i>Parameter</i>	<i>Value</i>
PV performance model	Equivalent one-diode
Temperature model	NOCT (20°C amb., 46 °C cell)
Module type	Monocrystalline silicon
Installed power	200 W
Module efficiency	21.97%
Inverter efficiency	95%
Shading/ wiring losses	Geometric shading included, wiring losses not included

The number of PV modules used on the roofs in all scenarios is fixed, with 212 modules used for each. On the facades, PV systems were installed on the east, west, and south facades, except for the north facade, where low efficiency is expected. While the number of modules used on the facades is the same in S1 and S2, the number of modules used in S3 and S4 scenarios differs due to facade design concepts (Table 4).

Table 4. Façade scenarios with PV module and installed power information

<i>Façade scenario</i>		<i>Façade</i>			<i>Façade total</i>	<i>Roof</i>	<i>Envelope total</i>	<i>Installed power</i>
		<i>Sought</i>	<i>East</i>	<i>West</i>				
S1	Vertical PV	88 m ²	52 m ²	52 m ²	192 m ²	214 m ²	404 m ²	80.4 kW
		86 module	52 module	52 module	190 module	212 module	402 module	
S2	Inclined PV	88 m ²	52 m ²	52 m ²	192 m ²	214 m ²	404 m ²	80.4 kW
		86 module	52 module	52 module	190 module	212 module	402 module	
S3	Vertical saw-tooth pv	120 m ²	70 m ²	70 m ²	260 m ²	214 m ²	474 m ²	94.4 kW
		120 module	70 module	70 module	260 module	212 module	472 module	
S4	Accordion PV	84 m ²	52 m ²	52 m ²	188 m ²	214 m ²	402 m ²	80.4 kW
		84 module	52 module	52 module	188 module	212 module	400 module	

Energy performance indicators

In this study, energy performance calculations were performed by considering the PV energy generation and building energy consumption values of all PV façade design scenarios. The energy coverage ratio (ECR) and self consumption ratio (SCR) values of the design scenarios were taken into account for energy performance calculations. In this context, ECR is the rate at which the energy produced by PV systems meets the building's site electrical energy needs on an annual basis (Eq.1). SCR represents the rate at which the energy generated by PV systems is used directly within the site, without being transferred to the grid (Eq.2).

$$ECR = \frac{\sum PV_{AC}}{\sum Enduse} \quad (1)$$

$$SCR = \frac{\sum SelfConsumption}{\sum PV_{AC}} \quad (2)$$

The term “PV_{AC}” indicates that the energy generation of PV systems is measured using AC values. “End use” refers to the building's site electricity consumption, and “self-consumption” refers to the amount of energy used directly by the PV energy generation within the building.

RESULT AND DISCUSSION

In this section of the study, a comparative evaluation of the energy performance of different PV façade systems applied in the office prototype is carried out. Within the scope of the evaluation, comparisons were made based on the energy consumption and generation values of different scenarios created in the field study, and in this context, the best building energy performance was calculated among the façade design scenarios through PV systems.

Façade scenario energy consumption

Table 5 presents the annual energy consumption values and the energy consumption per m² for all PV façade design scenarios. The energy consumption values in each scenario are influenced by the increase in surface area due to the varying façade designs and the potential of these designs to allow in intense daylight. Among all scenarios, the highest energy consumption per m² is observed in the S4 accordion PV façade (290.88 kWh/m²y), which has a large surface area, while the lowest energy consumption occurs in the S3 vertical saw-tooth PV façade (240.33 kWh/m²y). Although S1 and S2 scenarios have the same building design, heating and cooling energy consumption values differ due to the differences in the inclination angle of the PV systems integrated into the façade.

Table 5. Energy consumption values per m² of façade scenarios

	<i>Building energy consumption (kWh)</i>	<i>Total area of the building (m²)</i>	<i>Annual energy consumption (kWh/m²y)</i>
S1	291,960	1,078	270.84
S2	279,377	1,078	259.16
S3	280,880	1,168.75	240.33
S4	318,530	1,095.08	290.88

The energy consumption values for the façade scenarios per consumption area in the building are illustrated in Figure 5. Among all the scenarios, the highest energy use intensity (EUI) occurred in the cooling systems, with the S4 accordion PV

façade showing the highest cooling load (177.93 kWh/m²y). This was due to the uncontrolled intake of sunlight into the building as a result of the façade design. The lowest cooling load was observed in the S3 vertical saw-tooth PV façade (127.11 kWh/m²y), which showed lower EUI compared to the prototype building (Table A1). Daylight dimming control was not implemented in all façade scenarios. The interior lighting system was simulated with a fixed electrical load. Differences in energy loads across scenarios are due to the effects of daylight and interior thermal loads created by façade geometry. Heating systems had the lowest energy consumption across all scenarios (Table A2).

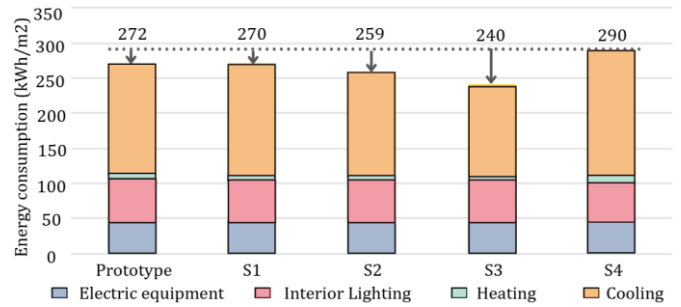


Figure 5. Energy consumption scope of façade scenarios according to place of use

Façade scenario PV system energy generation

As a result of the simulation study, the energy generation values (kWh) for the PV façade design scenarios on the roof and facades were calculated (Table 6). In the S1 and S2 scenarios, 190 PV modules were used, while 260 PV modules were used in S3. Despite the higher number of PV modules in S3, it ranked third in terms of façade energy generation (37,540 kWh). The highest energy generation from the PV façade was observed in S2 (56,281 kWh), where PV systems were placed at the optimum angle. Although the number of PV modules used on the facades in S1 and S2 was the same, the difference in energy generation resulted from the varying integration angles. Energy generation from the roof in all scenarios was consistent at 62,798 kWh, which was higher than the energy generation from the facades. Inverter efficiency is 95%, and in scenario comparisons, the energy generation of PV systems is calculated based on AC values, not DC values.

Table 6. Improvement scenarios roof and façade PV energy generation

<i>Façade Scenario</i>	<i>Energy generation</i>		
	<i>Façade (kWh)</i>	<i>Roof (kWh)</i>	<i>Total (kWh)</i>
S1 Vertical PV	14,012	62,798	76,810
S2 Inclined PV	56,281	62,798	119,079
S3 Vertical saw-tooth PV	37,540	62,798	100,338
S4 Accordion PV	53,960	62,798	116,758

Energy performances of façade scenarios

The energy performance of the façade scenarios was obtained by comparatively evaluating the PV energy generation and the building's energy needs. In this context, the energy performance assessments were conducted in two stages. First, the total energy generation of the roof and façade PV systems was compared with their total energy consumption (Figure 6). Then, a comparison was made based on the annual ECR, SCR, grid import, and grid export values, taking into account the PV AC generation of the façade scenarios.

The S4 accordion PV façade, due to its layout affecting the building envelope and increasing the surface area, resulted in the highest energy requirement, reaching approximately 300,000 kWh. Despite this, it still met a significant portion of the energy demand, producing around 116,758 kWh of energy.

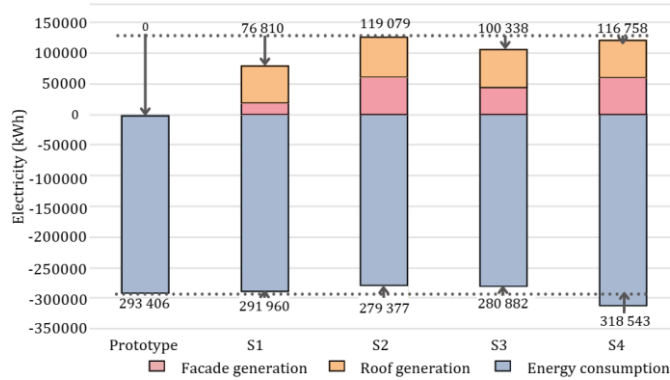


Figure 6. Energy generation and consumption percentages across scenarios

When comparing the annual energy generation values of PV facade scenarios with their energy consumption values, the highest efficiency was achieved in the S2 inclined PV facade with a rate of 42.92%. The lowest ECR was 26.31% in the S1 vertical PV facade scenario. The S4 Accordion PV facade, which has the highest energy consumption value, ranks second in terms of ECR, covering 36.65% of total energy consumption from PV systems (Figure 7).

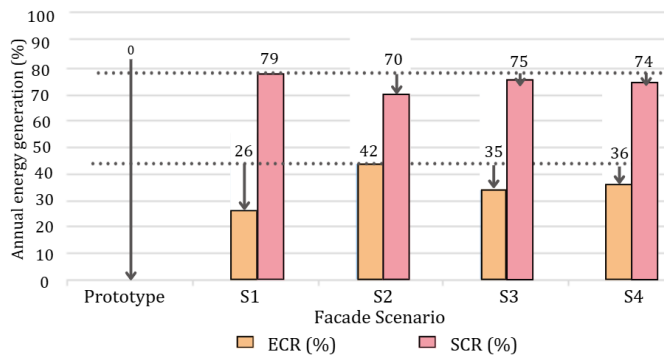


Figure 7. Percentages of energy demand met by PV systems across scenarios

Table 7 shows the annual ECR, SCR, grid import, and export values for all façade scenarios. The evaluation results show that scenario S2, which achieved the highest ECR value (42.62%), can meet a larger portion of the building's annual electricity needs than the other scenarios. However, the higher generation capacity also increased the amount of energy exported to the grid (34,643 kWh), resulting in a lower self-consumption rate (70.91%) than the other scenarios. In contrast, although lower ECR values (26–37%) were achieved in scenarios S1, S3, and S4, higher self-consumption rates (75–80%) were achieved. This indicates that a greater portion of the generated PV electrical energy is directly consumed within the building, reducing grid dependency.

Table 7. Annual energy performance indicators of facade design scenarios

	ECR (%)	SCR (%)	Grid import (kWh)	Grid export (kWh)
S1	26.31	79.66	230,774	15,624
S2	42.62	70.91	194,941	34,643
S3	35.72	75.46	205,168	24,624
S4	36.65	74.92	231,068	29,283

Validation and sensitivity

To ensure the reliability of the simulation results for the energy performance of the prototype and façade design models created in the study, a validation step was carried out. In this context, a baseline model was created within the same climate file (Antalya) by preserving the geometry, internal gains, and building occupancy conditions. In the created model, heat transfer coefficients (U-value) and HVAC system efficiencies, in conjunction with the building envelope material properties, were revised in accordance with the ASHREA 90.1 standard. The "Turkey-medium weight" templet was used for the building envelope material, and U-values were determined as U_{wall} : 0.361 W/m²K, U_{floor} : 0.373 W/m²K, U_{roof} : 0.346 W/m²K, and U_{window} : 1.514 W/m²K respectively. The HVAC system was implemented as "VAV, air-cooled chiller, reheat" in accordance with the ASHRAE 90.1 standard.

The comparison of the annual energy consumption values of the baseline model created for prototyping and validation is presented in Table 8. Energy consumption from internal lighting and equipment showed a deviation of approximately 1%, indicating the compatibility of the models' internal gains and operating profiles. The cooling load is 9.2% lower in the prototype model, which is linked to the high performance of the envelope insulation. Although there is a 50.3% increase in heating energy, this has a limited effect on total energy consumption. Total energy consumption was calculated as 293,406 kWh for the prototype and 307,727 kWh for the baseline model, a total difference of 4.7%. The results demonstrate the proportionality of the model's energy calculations and the reliability of the prototype values.

Table 8. Annual energy consumption comparison of prototype and baseline models

End-use	Prototype (kWh)	Baseline (kWh)	Deviation (%)
Interior lighting	67,525	66,766	+1.1
Other electric equipment	46,720	46,198	+1.1
Cooling	173,152	190,763	-9.2
Heating	6,009	3,999	+50.3
Total	293,406	307,727	-4.7

A sensitivity analysis was conducted on two main parameters affecting PV system performance in order to evaluate the reliability of the model. The analysis was performed on the S2 configuration, which achieved the highest energy performance. Sensitivity analysis is designed to reveal the effect of changes in module and inverter efficiency on annual PV generation. In this context, module efficiency was examined in the ranges of 19%, 21.97% (base) and 24%; inverter efficiency was examined in the ranges of 93%, 95% (base) and 97%. For all cases, climate data, façade geometry, and building loads were held constant. The results show that increasing module efficiency increases the annual AC generation of the PV system approximately linearly, with changes between 19% and 24% producing a difference of -13.9% and +9.1% in energy output. The $\pm 2\%$ change in inverter efficiency resulted in a $\pm 2.1\%$ deviation in PV generation. Total building energy consumption remained constant, and it was observed that only these variables on the generation side affected the energy generation performance of the PV system (Table 9).

The findings demonstrate that the model provides physically consistent responses to efficiency parameters and that PV system performance is stable to small parameter changes. Thus, the model's prediction accuracy is determined to be reliable.

Table 9. Variable sensitivity analysis for scenario S2

Table 9: Variable sensitivity analysis for scenario S2				
Drives/ Value		Annual PV-DC (kWh)	Annual PV-AC (kWh)	Δ vs Base (%)
Module efficiency	19%	107,817	102,426	-13.9
	21.97% (base S2)	125,346	119,079	-
	24%	136,769	129,931	+9.1
Inverter efficiency	93%	125,346	116,572	-2.1
	95% (base S2)	125,346	119,079	-
	97%	125,346	121,586	+2.1

CONCLUSION

In this study, the energy performance of different PV façade design scenarios applied to a prototype office building in the Mediterranean climate, an area with high solar radiation potential, was evaluated. The energy performance of these scenarios was compared with the energy data of the reference prototype. Upon analysis, it was found that the S3 vertical saw-tooth PV façade scenario, which features controlled daylight design, resulted in the lowest energy consumption for cooling loads. In contrast, the S4 accordion PV façade scenario, with its larger façade area and uncontrolled daylight intake, exhibited the highest energy consumption.

As a result of the comparison, it was observed that integrating PV systems into the prototype's envelope, which has a high cooling load, using integrated design methods significantly contributes to the building's energy performance. The ECR values of PV systems vary between a minimum of 26.31% (S1 vertical PV façade) and a maximum of 42.62% (S2 inclined PV façade) across the façade scenarios. The reason for this difference between the two scenarios, which have equal numbers of PV systems on the building envelope, is that the PV systems in the S2 scenario are integrated into the building

envelope at an optimal angle, thus receiving high solar radiation. When evaluating the façade scenarios based on energy performance (energy generation and consumption), the most favorable result was achieved in the S2 inclined PV façade scenario, where integrated design methods were considered. However, the SCR value of the S2 scenario is 70.9%, and compared to the other front scenarios, the rate of energy generated transferred to the grid is seen to be the highest. This is a result of the high energy generation capacity of the S2 scenario.

The study found that when roof space is insufficient for energy generation in buildings, integrating PV systems into facades with large surface areas and high solar radiation potential using integrated design methods can be effective in achieving high energy efficiency. It was found that a substantial portion of the building's energy consumption could be met by renewable energy technologies when PV systems are appropriately integrated into the building envelope, particularly in regions with similar climates (e.g., high solar radiation and extended sunshine hours). This study, which analyzed the energy performance of PV systems integrated into the building envelope, concludes that adopting integrated design methods should be prioritized in the building design process.

In addition to simulation software, energy generation and consumption calculations can be performed in existing buildings using experimental measurements for future studies that address the integration of PV systems with buildings. At the same time, the number of different façade design concepts can be increased using machine learning, and energy performance calculations can be performed. This study, conducted on a two-story office building, can be applied in the future to different building typologies (residential, school, etc.) and high-rise buildings. Conducted in the Mediterranean climate, where cooling loads are high, this study can be carried out in the future in different climates. Finally, the integration of PV systems with buildings can be examined in future studies in the context of cost optimization within the framework of the life cycle process.

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APPENDICES

Table A1. Annual consumption intensity values of prototype and façade design scenarios by category

	<i>Lighting (kWh/m²)</i>	<i>Equipment (kWh/m²)</i>	<i>Cooling (kWh/m²)</i>	<i>Heating (kWh/m²)</i>	<i>Total consumption (kWh/m²)</i>
Prototype	62.64	43.34	160.62	5.57	272.17
S1	62.64	43.34	158.22	6.64	270.84
S2	62.64	43.34	147.18	6.00	259.16
S3	62.64	43.34	127.11	7.24	240.33
S4	62.64	43.34	177.93	6.97	290.88

Table A2. Annual energy generation and consumption values of prototype and facade design scenarios by category

	<i>Lighting (kWh)</i>	<i>Equipment (kWh)</i>	<i>Cooling (kWh)</i>	<i>Heating (kWh)</i>	<i>Total consumption (kWh)</i>	<i>PV generation DC (kWh)</i>	<i>PV generation AC (kWh)</i>
Prototype	67,525	46,720	173,152	6,009	293,406	0	0
S1	67,525	46,720	171,634	6,080	291,960	80,852	76,810
S2	67,525	46,720	158,653	6,474	279,377	125,346	119,079
S3	73,210	50,657	148,565	8,449	280,882	105,619	100,338
S4	68,595	47,464	194,847	7,636	318,543	122,903	116,758

REFERENCES

- Abu Qadourah, J. (2020). *Architectural integration of photovoltaic and solar thermal technologies in multi-family residential buildings in the Mediterranean area*. (Doctor of Philosophy). Berlin University of the Arts, Berlin.
- Abu Qadourah, J. (2022). Energy and economic potential for photovoltaic systems installed on the rooftop of apartment buildings in Jordan. *Results in Engineering*, 16, 100642. <https://doi.org/10.1016/j.rineng.2022.100642>.
- Abu Qadourah, J. (2023). Evaluating solar-active shading solutions: a study of energy performance in Mediterranean residential architecture. *Architectural Engineering and Design Management*, 1-16. <https://doi.org/10.1080/17452007.2023.2267570>.
- Abu Qadourah, J., Al-Falahat, A. A. M., & Alrwashdeh, S. S. (2022). Assessment of solar photovoltaics potential installation into multi-family building's envelope in Amman, Jordan. *Cogent Engineering*, 9(1). <https://doi.org/10.1080/23311916.2022.2082059>.
- Aelenei, D., Lopes, R. A., Aelenei, L., & Gonçalves, H. (2019). Investigating the potential for energy flexibility in an office building with a vertical BIPV and a PV roof system. *Renewable Energy*, 137, 189-197. <https://doi.org/10.1016/j.renene.2018.07.140>
- Ascione, F., Bianco, N., Iovane, T., Mastellone, M., & Mauro, G. M. (2021). The evolution of building energy retrofit via double-skin and responsive façades: A review. *Solar Energy*, 224, 703-717. <https://doi.org/10.1016/j.solener.2021.06.035>
- Asfour, O. (2018). Solar and Shading Potential of Different Configurations of Building Integrated Photovoltaics Used as Shading Devices Considering Hot Climatic Conditions. *Sustainability*, 10, 4373. <https://doi.org/10.3390/su10124373>.
- Attia, S., Andersen, M., & Walter, E. (2013). *Identifying And Modeling The Integrated Design Process Of Net Zero Energy Buildings* Paper presented at the High Performance Buildings - Design and Evaluation Methodologies, Belgium.
- Barrutieta, X., Kolbasnikova, A., Irulegi, O., & Hernández, R. (2023). Decision-making framework for positive energy building design through key performance indicators relating geometry, localization, energy and PV system integration. *Energy and Buildings*, 297, 113442. <https://doi.org/10.1016/j.enbuild.2023.113442>
- Basnet, A. (2012). *Architectural Integration of Photovoltaic and Solar Thermal Collector Systems into buildings*. (Master Thesis). Norwegian University of Science and Technology, Trondheim.
- Bayrak, F., Gönül, A., & Camci, M. (2025). Thermal management of photovoltaic panels using configurations of spray cooling systems. *Applied Thermal Engineering*, 274, 126656. <https://doi.org/10.1016/j.applthermaleng.2025.126656>
- 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>
- Buker, M. S., & Riffat, S. B. (2015). Building integrated solar thermal collectors – A review. *Renewable and Sustainable Energy Reviews*, 51, 327-346. <https://doi.org/10.1016/j.rser.2015.06.009>
- Crassard, F., & Rode, J. (2007). *The evolution of building integrated photovoltaics (BIPV) in the German and French technological innovation systems for solar cells*. (Master Degree). Chalmers University Of Technology, Göteborg.
- Dabbagh, N. (2015). *Football Stadium: Solar Envelope As An Architectural Tool*. (Master Thesis). Delft University of Technology, Delft, The Netherlands.
- Debbarma, M., Sudhakar, K., & Baredar, P. (2017). Comparison of BIPV and BIPVT: A review. *Resource-Efficient Technologies*, 3(3), 263-271. <https://doi.org/10.1016/j.reffit.2016.11.013>
- DesignBuilder Software Ltd. (2024). *DesignBuilder (Version 7.0)* [Computer software]. <https://designbuilder.co.uk>
- Düzgün, H., & Aladağ, H. (2016). A Roadmap For Sustainable Buildings : Integrated Design. *Academic Journal of Science*. 04(02). 233-248.
- Elghamry, R., Hassan, H., & Hawwash, A. A. (2020). A parametric study on the impact of integrating solar cell panel at building envelope on its power, energy consumption, comfort conditions, and CO2 emissions. *Journal of Cleaner Production*, 249, 119374. <https://doi.org/10.1016/j.jclepro.2019.119374>
- European Parliament and the Council. (2018). *Directive (EU) 2018/844 of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*. *Official Journal of the European Union*, L 156, 75–91. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L0844>
- Freitas, S., & Serra, F. (2015). *Multi-Objective Genetic Algorithm for the Optimization of a PV System Arrangement*. ISES Solar World Congress (SWC2015), South Korea.
- Gholami, H., Nils Røstvik, H., & Steemers, K. (2021). The Contribution of Building-Integrated Photovoltaics (BIPV) to the Concept of Nearly Zero-Energy Cities in Europe: Potential and Challenges Ahead. *Energies*, 14(19). <https://doi.org/10.3390/en14196015>.
- Ghosh, A. (2020). Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive review. *Journal of Cleaner Production*, 276, 123343. <https://doi.org/10.1016/j.jclepro.2020.123343>

- Gonçalves, H., Aelenei, L., & Rodrigues, C. (2012). Solar XXI: A Portuguese Office Building towards Net Zero-Energy Building. *Rehva Journal*, 34-40.
- Gweshia, A. O., Alfulayyih, Y. M., & Li, P. (2019). *Optimization of Fixed PV Panel "Tilt" Angles for Maximal Energy Harvest Considering Year-Around Sky Coverage Conditions*. Paper presented at the ASME 2019 International Mechanical Engineering Congress and Exposition, Utah, USA. <https://doi.org/10.1115/IMECE2019-10391>
- Hasan, A. S. M. M., & Trianni, A. (2023). Boosting the adoption of industrial energy efficiency measures through Industry 4.0 technologies to improve operational performance. *Journal of Cleaner Production*, 425, 138597. <https://doi.org/10.1016/j.jclepro.2023.138597>
- International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS). (2023). *Guide for Technological Innovation System Analysis for Building Integrated Photovoltaics 2023*. IEA-PVPS. <https://iea-pvps.org/>
- International Energy Agency (IEA). (2022). *Energy Efficiency 2022*. IEA. <https://www.iea.org/reports/energy-efficiency-2022>
- International Renewable Energy Agency (IRENA). (2024). *Tripling renewable power by 2030: The role of the G7 in turning targets into action*. IRENA. Abu Dhabi. <https://www.irena.org/Publications>
- Kaftan, M., Sautter, S., & Kubicek, B. (2019). *Integrating BIPV during Early Stages of Building Design*. Paper presented at the 37 Education and Research in Computer Aided Architectural Design in Europe and XXIII Iberoamerican Society of Digital Graphics.
- Karteris, M., Slini, T., & Papadopoulos, A. M. (2013). Urban solar energy potential in Greece: A statistical calculation model of suitable built roof areas for photovoltaics. *Energy and Buildings*, 62, 459-468. <https://doi.org/10.1016/j.enbuild.2013.03.033>
- Karteris, M., Theodoridou, I., Mallinis, G., & Papadopoulos, A. M. (2014). Façade photovoltaic systems on multifamily buildings: An urban scale evaluation analysis using geographical information systems. *Renewable and Sustainable Energy Reviews*, 39, 912-933. <https://doi.org/10.1016/j.rser.2014.07.063>
- Kaya, G. N. (2022). *Yapı Kabuğunda Aktif Güneş Sistemleri Odaklı Bütünleşik Tasarım Yaklaşımlarının Simülasyon Tabanlı Analizi* (Master Thesis). Gazi Üniversitesi, Ankara.
- Kaya, G. N., & Beyhan, F. (2021). Integrated design approaches with photovoltaic panel and solar collectors in building envelope. *World Journal of Environmental Research*, 11(2), 49-61. <https://doi.org/10.18844/wjer.v11i2.7232>
- Kaya, G. N., & Beyhan, F. (2024). A Study on the Potential of Photovoltaic Panels in Existing Buildings: Housing Example in the Mediterranean. *Online Journal of Art and Design*, 12(1), 73-87.
- Kaya, G. N., & Beyhan, F. (2025). Yapılarda Güneş Enerjisi Sistem Uygulamalarının Enerji Verimliliği Bağlamında Değerlendirilmesi. *Tesisat Mühendisliği*, 33(208), 31 - 40.
- Kaya, G. N., Beyhan, F., İlerisoy, Z. Y., & Cudzik, J. (2025). Evaluation of machine learning applications in building life cycle processes for energy efficiency: A systematic review. *Energy Reports*, 13, 4900-4916. <https://doi.org/10.1016/j.egyr.2025.04.034>
- Khan, S., Sudhakar, K., & bin Yusof, M. H. (2023). Building integrated photovoltaics powered electric vehicle charging with energy storage for residential building: Design, simulation, and assessment. *Journal of Energy Storage*, 63, 107050. <https://doi.org/10.1016/j.est.2023.107050>
- Kirimtat, A., Tasgetiren, M. F., Brida, P., & Krejcar, O. (2022). Control of PV integrated shading devices in buildings: A review. *Building and Environment*, 214, 108961. <https://doi.org/10.1016/j.buildenv.2022.108961>
- Kiss, C. A. (1993). *Building-Integrated Photovoltaics*. (Technical Report). National Renewable Energy Laboratory (NREL). Golden, Colorado.
- Koch, C., & Buhl, H. (2013). Integrated Design Process: A Concept for Green Energy Engineering. *Engineering*, 05, 292-298. doi:10.4236/eng.2013.53039.
- Kuhn, T., Erban, C., Heinrich, M., Eisenlohr, J., Ensslen, F., & Neuhaus, D. (2020). Review of Technological Design Options for Building Integrated Photovoltaics (BIPV). *Energy and Buildings*, 217, 110381. doi:10.1016/j.enbuild.2020.110381.
- Kürüm Varolgüneş, F., Varolgüneş, S., Rama, D., & Durán-Sánchez, A. (2023). A proposal for the Selection of Green Building Standards through the Analytical Hierarchy Process (AHP): A Roadmap for Green Hotels in Turkey. *Quality & Quantity*. doi:10.1007/s11135-023-01756-y.
- Li, D. H. W., Aghimien, E. I., & Alshaibani, K. (2023). An Analysis of Real-Time Measured Solar Radiation and Daylight and Its Energy Implications for Semi-Transparent Building-Integrated Photovoltaic Façades. *Buildings*, 13(2), 386. doi:10.3390/buildings13020386.
- Li, D. H. W., & Tsang, E. K. W. (2008). An analysis of daylighting performance for office buildings in Hong Kong. *Building and Environment*, 43(9), 1446-1458. <https://doi.org/10.1016/j.buildenv.2007.07.002>
- Maduta, C., D'Agostino, D., Tsemekidi-Tzeiranaki, S., & Castellazzi, L. (2025). From Nearly Zero-Energy Buildings (NZEBS) to Zero-Emission Buildings (ZEBs): Current status and future perspectives. *Energy and Buildings*, 328, 115133. <https://doi.org/10.1016/j.enbuild.2024.115133>
- 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>

- Mandalaki, M., Zervas, K., Tsoutsos, T., & Vazakas, A. (2012). Assessment of fixed shading devices with integrated PV for efficient energy use. *Solar Energy*, 86(9), 2561-2575. <https://doi.org/10.1016/j.solener.2012.05.026>
- Martín Chivelet, N., Kapsis, C., & Frontini, F. (2025). *Building-Integrated Photovoltaics: A Technical Guidebook*. (IEA-PVPS Task 15 Report). International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS), 2025. <https://iea-pvps.org/>
- Martín-Chivelet, N., Kapsis, K., Wilson, H. R., Delisle, V., Yang, R., Olivieri, L., Polo, J., Eisenlohr, J., Roy, B., Maturi, L., Otnes, G., Dallapiccola, M., & Upalakshi Wijeratne, W. M. P. (2022). Building-Integrated Photovoltaic (BIPV) products and systems: A review of energy-related behavior. *Energy and Buildings*, 262, 111998. <https://doi.org/10.1016/j.enbuild.2022.111998>
- Meteoroloji Genel Müdürlüğü (MGM). (25 February 2026). Antalya Hava Durumu Verileri. <https://www.mgm.gov.tr>
- Michailidis, P., Michailidis, I., & Kosmatopoulos, E. (2025). Reinforcement Learning for Optimizing Renewable Energy Utilization in Buildings: A Review on Applications and Innovations. *Energies*, 18, 1724. doi:10.3390/en18071724
- Minelli, F., D'Agostino, D., Migliozi, M., Minichiello, F., & D'Agostino, P. (2023). PhloVer: A Modular and Integrated Tracking Photovoltaic Shading Device for Sustainable Large Urban Spaces—Preliminary Study and Prototyping. *Energies*, 16, 5786. <https://doi.org/10.3390/en16155786>
- Özer Yaman, G. (2025). Investigation of the Relationship Between Building Functions and Energy Performance Using BIM/BES Methods Across Different Climate Types. *İsı Bilimi ve Tekniği Dergisi*, 45, 172-192. <https://doi.org/10.47480/isibted.1622706>
- Peng, J., Curcija, D. C., Lu, L., Selkowitz, S. E., Yang, H., & Zhang, W. (2016). Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate. *Applied Energy*, 165, 345-356. <https://doi.org/10.1016/j.apenergy.2015.12.074>
- Reddy K, P., Gupta, S., Nundy, S., Karthick, A., & Ghosh, A. (2020). Status of BIPV and BAPV System for Less Energy-Hungry Building in India-A Review. *Applied Sciences*, 10, 2337. doi:10.3390/app10072337.
- Rehman, F., Syed, I. H., Khanam, S., Ijaz, S., Mehmood, H., Zubair, M., Massoud, Y., & Mehmood, M. Q. (2023). Fourth-generation solar cells: a review. *Energy Advances*, 2(9), 1239-1262. <https://doi.org/10.1039/d3ya00179b>
- Roy, A., Ghosh, A., Bhandari, S., Sundaram, S., & Mallick, T. K. (2020). Perovskite Solar Cells for BIPV Application: A Review. *Buildings*, 10(7). <https://doi.org/10.3390/buildings10070129>
- Sánchez, E., & Izard, J. (2015). Performance of photovoltaics in non-optimal orientations: An experimental study. *Energy and Buildings*, 87, 211-219. <https://doi.org/10.1016/j.enbuild.2014.11.035>
- Santamouris, M., & Vasilakopoulou, K. (2021). Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, 1, 100002. <https://doi.org/10.1016/j.prime.2021.100002>
- Sayın, S., & Koç, İ. (2011). Güneş Enerjisinden Aktif Olarak Yararlanmada Kullanılan Fotovoltaik(PV) Sistemler Ve Yapılarda Kullanım Biçimleri. *S.Ü. Müh.-Mim. Fak. Dergisi*, c.26, s.3.
- Scuola universitaria professionale della Svizzera italiana (SUPSI). (2017). *Building Integrated Photovoltaics: Product overview for solar building skins*. SUPSI. Switzerland. <https://www.supsi.ch/>
- Shi, S., Sun, J., Liu, M., Chen, X., Gao, W., & Song, Y. (2022). Energy-Saving Potential Comparison of Different Photovoltaic Integrated Shading Devices (PVSDs) for Single-Story and Multi-Story Buildings. *Energies*, 15(23). doi:10.3390/en15239196.
- Shukla, A. K., Sudhakar, K., & Baredar, P. (2017). Recent advancement in BIPV product technologies: A review. *Energy and Buildings*, 140, 188-195. <https://doi.org/10.1016/j.enbuild.2017.02.015>
- Sugianto, S. (2020). Comparative Analysis of Solar Cell Efficiency between Monocrystalline and Polycrystalline. *INTEK: Jurnal Penelitian*, 7, 92-100. <https://doi.org/10.31963/intek.v7i2.2625>
- Tabakovic, M., Fechner, H., & Knoebl, K. (2016). *Framework and Requirements' Analysis: Development of innovative educational material for Building-integrated PV*. Utrecht, the Netherlands.
- Tablada, A., Kosorić, V., Huang, H., Lau, S. S. Y., & Shabunko, V. (2020). Architectural quality of the productive façades integrating photovoltaic and vertical farming systems: Survey among experts in Singapore. *Frontiers of Architectural Research*, 9(2), 301-318. <https://doi.org/10.1016/j.foar.2019.12.005>
- Tachir, G., Altınöz, M., & Mıhlayanlar, E. (2024). Energy Consumption at Accommodation Buildings: A Case Study of a Boutique Hotel-Abdera. *Kocaeli Journal of Science and Engineering*, 7(1), 71-80. doi:10.34088/kojose.1095837.
- Tyagi, V. V., Rahim, N. A. A., Rahim, N. A., & Selvaraj, J. A. L. (2013). Progress in solar PV technology: Research and achievement. *Renewable and Sustainable Energy Reviews*, 20, 443-461. <https://doi.org/10.1016/j.rser.2012.09.028>
- Wang, W., Liu, Y., Wu, X., Xu, Y., Yu, W., Zhao, C., & Zhong, Y. (2016). Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai. *Energy and Buildings*, 130, 98-106.

<https://doi.org/10.1016/j.enbuild.2016.07.066>

Wijeratne, W. M. P. U., Samarasinghalage, T. I., Yang, R. J., & Wakefield, R. (2022). Multi-objective optimisation for building integrated photovoltaics (BIPV) roof projects in early design phase. *Applied Energy*, 309, 118476.

<https://doi.org/10.1016/j.apenergy.2021.118476>

World Bank. (25 February 2026). *Global Solar Atlas: Global horizontal irradiation – World dataset (2019)*. World Bank Group. <https://globalsolaratlas.info/download/world>

Yan, H., Zhang, Y., Liu, S., Cheung, K. M., & Ji, G. (2022). *Optimization of Daylight and Thermal Performance of Building Façade: A Case Study of Office Buildings in Nanjing*. 2021 DigitalFUTURES. https://dx.doi.org/10.1007/978-981-16-5983-6_16

Yang, R. J., & Zou, P. X. W. (2016). Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy. *International Journal of Construction Management*, 16(1), 39-53. <https://doi.org/10.1080/15623599.2015.1117709>.

Yao, J. (2017). *The application of natural ventilation of residential architecture in the integrated design*. Paper presented at the IOP Conference Series: Earth and Environmental Science.

Yılmazoğlu, M. Z., (2017). Decreasing energy consumption and carbon footprint in a school building: a comparative study on energy audits. *International Journal of Global Warming*, vol.13, no.2, 237-257.

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, T., Wang, M., & Yang, H. (2018). A Review of the Energy Performance and Life-Cycle Assessment of Building-Integrated Photovoltaic (BIPV) Systems. *Energies*, 11, 3157. <https://doi.org/10.3390/en11113157>.