HYDROGEN, FUEL CELL & ENERGY STORAGE

Enhancing Solar Energy Utilization in Buildings: Integrating Transparent Solar Panels and BIPV/T Systems for Optimal Energy Efficiency in Tabriz, Iran

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Article Information

Article Type
RESEARCH ARTICLE

Article History
RECEIVED: *18 Oct 2024*
REVISED: *30 Nov 2024*
ACCEPTED: *20 Dec 2024*
PUBLISHED ONLINE: *04 Jan 2025*

Keywords

BIPV/T systems
Solar thermal system
Transparent photovoltaic
Energy analysis

Abstract

One challenge of utilizing solar panels is the potential impact on a building's aesthetic. Building-integrated photovoltaics/thermal (BIPV/T) systems and transparent solar panels, integrated into windows, offer viable solutions for optimal solar energy utilization. This research evaluates the feasibility of integrating these technologies within the specific climatic conditions of Tabriz, Iran, employing transient simulation. Three distinct building configurations were analyzed and compared in this study. The simulation results revealed that integrating transparent solar panels with BIPV/T systems can significantly improve energy production and efficiency. Transparent PV panels, especially beneficial in winter due to favorable solar angles, enhance the overall power output of the BIPV/T system. Additionally, the BIPV/T system acts as a heat source for the air-source heat pump (ASHP) during winter, improving the system's performance and reducing energy consumption. The final configuration demonstrated superior renewable energy generation and a substantial reduction in grid reliance, resulting in an annual CO_2 emission decrease of 3757 kg through 8521 kWh of energy savings. This study highlights the potential to generate significant electrical power while maintaining the building's aesthetic appeal.

Cite this article: Abdali, S., Yaghoubi, S. (2025). Enhancing Solar Energy Utilization in Buildings: Integrating Transparent Solar Panels and BIPV/T Systems for Optimal Energy Efficiency in Tabriz, Iran. DOI: 10.22104/hfe.2024.7025.1309

 Publisher: Iranian Research Organization for Science and Technology (IROST)
DOI: 10.22104/hfe.2024.7025.1309

1 Introduction

The world is shifting away from its dependence on polluting fossil fuels towards sustainable and renewable energy sources. This transition brings both challenges and opportunities, requiring innovation and foresight to successfully navigate. A Sustainable energy supply, a fundamental pillar of sustainable development, has seen remarkable progress in recent decades, particularly in renewable energy systems such as solar cells, wind turbines, and batteries. These technologies have been a lifeline for many remote areas, providing essential electricity [1]. With the global population and energy demands on the rise, the search for clean sustainable energy sources has become more urgent than ever.

Traditional power plants, which rely heavily on fossil fuels, have made the building sector a significant contributor to global greenhouse gas emissions. Buildings are responsible for a large share of the problem, accounting for 30% of final energy consumption and 26% of energy-related emissions worldwide. This includes 8% from direct building operations and 18% from indirect emissions related to electricity and heating generation. Energy consumption in this sector grew by 1% in 2022. Despite the increasing adoption of renewable and energy-efficient technologies in buildings, the next decade is crucial. By 2030, all new buildings must be constructed, and 20% of existing buildings renovated, to be net-zero ready by 2030 [2]. Existing technologies could potentially reduce building-related greenhouse gas emissions by 30-50% [3].

Given its non-polluting characteristics, abundance, and potential to support ecosystem balance, solar energy offers the most versatile and promising applications among renewable energy sources, its applications span a wide range of sectors, including buildings, agriculture, and industry [4–6]. The photovoltaic technology market has been rapidly evolving, with a compound annual growth rate of 34% between 2010 and 2020 [7]. Despite advancements in solar cell technology, the peak power conversion efficiency of commercially available silicon modules remains limited to approximately 23% [8], meaning that approximately 77% of the incident solar energy is converted to heat. This excess heat significantly reduces cell efficiency. A promising solution to this challenge is cooling PV modules using fluids such as air or water. This method not only enhances power generation efficiency but also enables the captured heat to be used for space heating or domestic hot water [9].

Solar energy technologies have been criticized for their lack of visual appeal. As the electrical energy generated by solar panels is directly proportional to their surface area, leading to increased visual obstruction, aesthetics will be a key factor in the future success of these technologies in urban settings [10]. Transparent and semi-transparent solar panels have emerged as innovative alternatives to conventional photovoltaic panels. These panels have demonstrated particular utility in high-rise buildings where space constraints limit the installation of traditional photovoltaic systems. A primary obstacle to the widespread adoption of solar energy is the scarcity of suitable installation areas, especially in urban environments with limited land and rooftop space. Although transparent panels can be integrated into building windows, their efficiency is often lower than that of conventional panels due to less favorable solar angles and the inherent tradeoff between transparency and energy generation [11]. These panels can be broadly classified as transparent or semi-transparent [12]. The inverse relationship between power generation and light transmittance in semi-transparent devices has limited their widespread adoption. However, Michigan State University's 2014 breakthrough in fully transparent photovoltaics has challenged this paradigm. hese panels, which remain invisible to the human eye, allow for the seamless integration of solar energy into transparent surfaces such as windows and electronic displays [13]. The commercialization of transparent photovoltaics (TPVs) is now an emerging and growing trend.

Extensive research has focused on improving solar panel efficiency. Zhang et al. [14] enhanced perovskite solar cells by incorporating core-shell metal nanoparticles, which reduced exciton binding energy and increased charge carrier generation. Maleki et al. [15] optimized antisolvent dropping delay time to improve the morphology and performance of hole transport material-free perovskite solar cells. Sowmehesaraee et al. [16] used metal-organic frameworks as additives, enhancing the morphology, absorption, and overall performance of perovskite solar cells. Sardarabadi et al. [17] investigated the use of metallic nanofluids like ZnO and TiO_2, demonstrating significant improvements in energy and exergy efficiency in photovoltaic thermal (PVT) systems.

By integrating solar panels and thermal systems into building envelopes, BIPV/T systems offer a promising solution for sustainable energy generation in buildings. These systems, often replacing traditional building materials on roofs or facades, can simultaneously produce electricity and heat, thereby reducing reliance on fossil fuels [18]. Consequently, in addition to providing the necessary electrical power for the building, the generated heat can be effectively utilized for a variety of applications, including domestic hot water production, space heating, and industrial processes [19]. The generated heat may not be directly applicable to space heating. Alternatively, it can serve as a heat source for heat pumps during winter. In other words, the solar collector system provides heat at a temperature higher than the ambient level, thereby improving the coefficient of performance (COP) of the heat pump [20]. Kumar, Sudhakar [21] compared the performance of 32.7 kWp BIPV and BAPV systems using three distinct solar cell technologies (crystalline, CIS, CdTe). While BAPV yielded higher energy generation, the relative variations in annual energy yield, performance ratio, and capacity factor were negligible across the different solar cell technologies and installation configurations. Consequently, the aesthetic appeal of BIPV-integrated buildings should not be overlooked.

Salman et al. [22] developed a multigeneration system aimed at harnessing energy from Parabolic Trough Collectors and Photovoltaic Thermal solar collectors. This system is capable of generating electricity, cooling, hot water, freshwater, and hydrogen. Detailed energy, exergy, and thermoeconomic analyses revealed that, among various working fluids considered for the Organic Rankine Cycle, R141b demonstrated superior performance in hydrogen and freshwater production. The overall energy and exergy efficiencies of the system were found to be 33.49% and 13.31%, respectively.

Dupeyrat, Ménézo [23] employed TRNSYS to assess the thermal and electrical performance of a photovoltaic/thermal (PV/T) hybrid solar collector. The results indicated that PV/T collectors provide a more optimized solution for energy generation and efficiency compared to conventional PV collectors, especially in regions with limited installation space. Aste, Del Pero [24] evaluated the performance of a BIPV system after 13 years of continuous operation. The study aimed to assess the system's technical and economic performance and predict its lifespan. Findings revealed a minimal annual degradation rate of just 0.37% over the 13 years. Moreover, visual and infrared spectroscopy inspections indicated no damage to the BIPV modules. These results highlight the durability and longevity of BIPV systems, supporting their potential for widespread adoption in the building industry.

Chae et al. [25] investigated the impact of electrical and optical parameters of semi-transparent BIPV windows on the overall energy performance of a mid-scale commercial building under varying climatic conditions. The results highlighted the importance of tailoring BIPV window characteristics to real optical data via the solar spectral distribution, which is significantly influenced by cell fabrication conditions. This approach is crucial for optimizing building energy performance across different climatic regions. Refat and Sajjad [26] explored the feasibility of employing semi-transparent photovoltaic panels in residential buildings. Findings indicated that, with 50% visible light transmittance, semi-transparent photovoltaic on clear glass reduced energy demand by approximately 50% and 30% in tropical and hot desert regions, respectively, and 20-25% in Scandinavian and cold continental regions. When coupled with low-emissivity glass, net savings reached 90% in tropical regions, 60% in hot desert regions, and 45-70% in other regions.

Previous studies have often overlooked the significance of preserving the aesthetic appeal of buildings incorporating solar energy systems. While earlier research has emphasized the importance of renewable energy production in buildings [27–31], there has been limited emphasis on integrating energy efficiency with architectural design. The integration of BIPV/T and TPV technologies can enhance electrical power generation while preserving the building's facade. However, there is a gap in the literature concerning the potential of highly transparent solar cells as an effective mechanism for electricity production in net-zero energy buildings.

This research aims to assess the feasibility of integrating multiple solar energy technologies within the Iranian climatic context. The specific objectives of this study are as follows:

1. Modeling a building according to Iranian building codes
2. Calculating power consumption and generation
3. Simulating renewable energy systems
4. Evaluating the performance of transparent solar panels
5. Optimizing BIPV/T system size and angle
6. Calculating TPV power output and efficiency in each season
7. Assessing CO_2 emissions and energy savings

2 Climate, System Description and Simulation

This section elaborates on the research methodology. Initially, the climatic data of the target city is examined, followed by an introduction to the proposed residential building. Subsequently, the operational principles and components of the system are investigated. Furthermore, the assumptions underlying the study and the building simulation process are outlined.

2.1 Climate

Iran's climate is predominantly arid and semi-arid, with the exception of the western and northern coastal areas. The extent of arid areas in the country continues to expand. Additionally, the northwestern and western regions experience harsh, cold winters and mild, temperate summers [32,33]. This study focuses on the city of Tabriz, located in northwestern Iran. Geographically, Tabriz is located at 38°5′ North latitude and 46°16′ East longitude, at an elevation of 1361 meters above sea level [34]. The average monthly temperature of 11.6 °C indicates a cold climate. Tabriz has a potential of 4369 sunshine hours; however, 30% of this is lost due to foggy, cloudy, and misty days, resulting in only 3147 effective sunshine hours. Additionally, the primary building orientation is towards the south, leading to increased solar energy absorption on this facade. The total solar radiation on the building reaches a peak of 28,838 kWh/m^2 on June 21st, while the minimum radiation is recorded on December 21st at 5,511 kWh/m^2 [35].

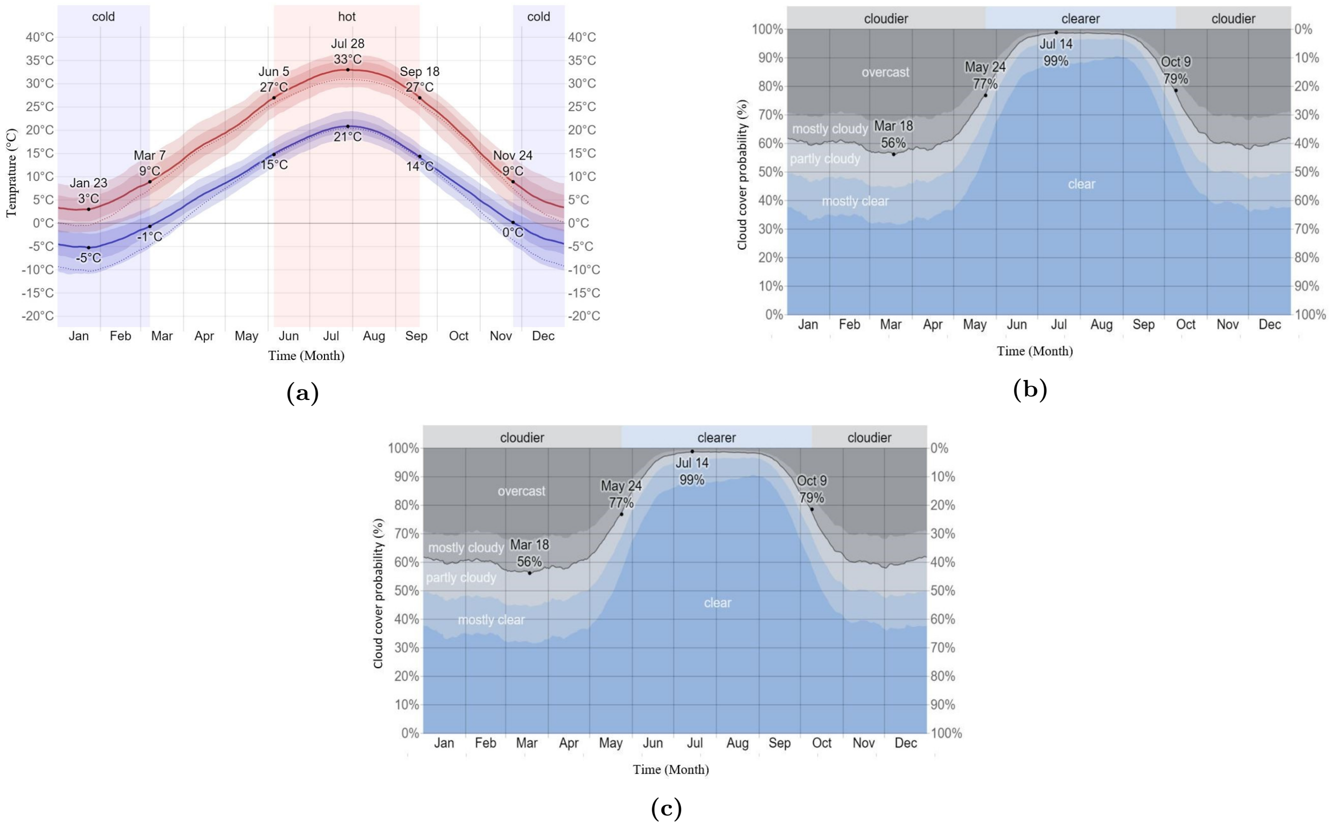

Fig. 1. (a) The daily average high and low air temperature at 2 meters above the ground. The thin dotted lines are the corresponding perceived temperatures. (b) Cloud cover distribution. (c) The average daily shortwave solar energy reaching the ground per square meter [36].

Figure 1 illustrates the annual temperature profile, cloud cover distribution, and incoming solar radiation per square meter in Tabriz throughout the year. The cloudiest period spans from November to March, characterized by frequent overcast and cloudy conditions. Between April and May,cloud cover gradually diminishes, with partly cloudy days becoming more common. July is the clearest month, exhibiting minimal cloud cover and over 98% clear sky days.

Given its latitude and the resulting constraints on solar radiation angles, Tabriz, Iran, was selected as a case study to simulate challenging conditions for a TPV and BIPV/T system. This city experiences harsh winters with minimal solar radiation, making it one of the most challenging climates in Iran for solar energy applications.

2.2 Building

The case study building, modeled in SketchUp (Figure 2), is a two-story, 52.5 m^2 residence with a single room, measuring 7.5 m in length, 7 m in width, and 3 m in height. Located in Tabriz, Iran, the building has two interior walls and is designed to accommodate two occupants. The upper floor contains an air-conditioned unit, with heating and cooling set points maintained at

22 °C and 26 °C, respectively, and an interior lighting level of 300 lux. An ASHP was employed for heating and cooling in the primary residential unit. Design standards, including insulation U-values, ventilation parameters, and air infiltration rates, followed the Iranian National Building Regulations [27]. Occupants were assumed to be away from home for work between 8 AM and 4 PM on weekdays. On weekends, residents were expected to spend most of their time indoors, following a predominantly sedentary lifestyle (ASHRAE activity level III – sitting, very light work). Table 1 presents the thermal transmittance values of the building envelope, and Figure 3 illustrates the layers of the external wall.

(a)

(b)

Fig. 2. (a) Building elevation designed using SketchUp. (b) Sectional view.

Table 1. Thermal properties of walls.

Parameter	Value
External wall U-value	$0.56\,W/m^2k$
Internal wall U-value	$2.3\,W/m^2k$
Flat Roof U-value	$0.3\,W/m^2k$
Ground floor U-value	$0.55\,W/m^2k$
Double glass Window U-value	$1.1\,W/m^2k$
Window R-value	0.62%
Heating set point	22 °C
Cooling set point	26 °C
Ventilation rate	7 l/s/person
Infiltration	0.52/h

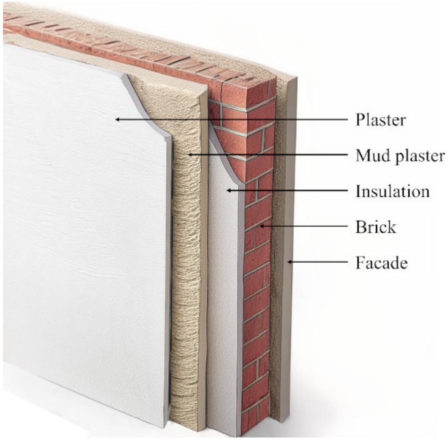

Fig. 3. Material composition of the external wall.

2.3 System components

2.3.1 Transparent solar panels

To simultaneously utilize solar radiation for indoor illumination and electricity generation, the integration of transparent solar cells is proposed. These cells allow visible light to pass through while generating electricity. However, a key challenge with conventional transparent solar cells is their low efficiency and limited transparency. Traditional panels not only transmit less light compared to conventional glass but also generate less electrical power than standard solar panels. Ubiquitous Energy claims to have developed solar cells that selectively transmit visible light while absorbing and converting invisible ultraviolet and infrared radiation into electricity. This innovation positions them as the first company to introduce truly transparent solar technology. Table 2 provides detailed specifications of the solar cell designed by Ubiquitous Energy. In its Redwood City, California headquarters, Ubiquitous Energy installed the world's first real transparent solar window façade, spanning approximately 100 square feet (Figure 4). The company has also deployed additional installations in Boulder, Colorado; Michigan State University, Ohio; and Chiba, Japan [37].

Table 2. Specifications of the ubiquitous energy solar cell.

Efficiency	≈ 10%
Wavelengths	380-700 nm
Photovoltaic Material	a combination of inorganic (metal and metallic oxides) and organic materials (small molecule materials like dyes used in clothing).
Dimensions	14×20 inches per unit
Transparency	80 to 90%.

In this study, the south-, east-, and west-facing window areas were simulated as photovoltaic windows. The southern window area was set to 7.25 m^2, while the western and eastern windows were each 9.5 m^2. These dimensions were modeled using the TRNSYS simulation software. Each window was composed of smaller units measuring 35 cm × 50 cm, configured in accordance with data provided by Ubiquitous Energy. A total of 150 smaller units were designed for all three windows.

Fig. 4. A ubiquitous energy transparent photovoltaic window was installed in Redwood, California, as a field demonstration [37].

2.3.2 BIPV/T panels

BIPV/T is a widely used method for converting solar energy into electricity in buildings. PV technologies convert incident solar energy directly into electrical energy through the photovoltaic effect. A significant portion of the solar radiation impinging on a PV panel is converted into thermal energy, resulting in a decrease in conversion efficiency as the operating temperature of PV cells increases [38]. Integrating electricity generation with thermal collection offers a promising solution to this technical challenge. As illustrated in Figure 5, BIPV/T panels can capture absorbed heat for direct space heating or heat pump systems,while simultaneously reducing the temperature of the solar panel. Utilizing the waste heat from these panels enhances the thermal efficiency of heat pumps during winter, leading to decreased greenhouse gas emissions and reduced electricity costs [39].

Given the structural constraints and geographic latitude of Iranian cities, a roof pitch of 25 degrees facing south was adopted. The photovoltaic field had a nominal power of approximately 15.8 kW, covering a total panel area of 50.7 m^2.This enabled the installation of 39 PV/T panels, each measuring 1.30 m × 1.00 m, arranged in 3 rows of 13 panels. The collector's width was equivalent to the length of a PV/T panel, while the collector's length coincided with the airflow direction through the channel. The lower channel also served as the building's ceiling. Consequently, in simulations, the building model (i.e., the house envelope) utilized the surface temperature of the lower air channel as an external boundary in the calculations. The electrical efficiency of the BIPV/T system was assumed to be 12%. During winter, the heat pump utilized the warm air produced by the BIPV/T collector as a heat source. This integration of the BIPV/T system with the ASHP resulted in a highly efficient heating solution for the winter season. In the simulations, each PV/T panel was considered as a singular integrated thermal air node on the roof. The output from each PV/T panel was calculated individually and then used as the input for the next panel. The final panel was connected to the heat pump.

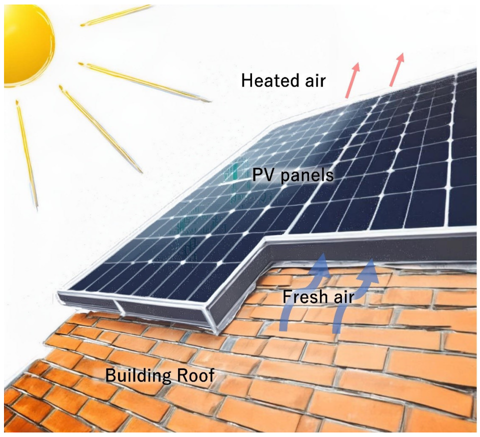

Fig. 5. Schematic of a BIPV/T system.

2.3.3 Heat pump

Heat pumps have emerged as an attractive alternative for consumers seeking to replace fossil fuel-based heating systems. Recognized for their low maintenance requirements, reduced operational costs, and contributions to carbon reduction while improving indoor air quality, heat pumps offer a compelling solution [40]. Transitioning residential heating systems to heat pumps diminishes the demand for non-renewable energy sources and enables the utilization of renewable energy, thereby enhancing energy security [41]. Typically exhibiting a COP ranging from 3 to 5, heat pumps present a highly efficient heating solution. To further optimize energy performance, ASHPs can be integrated with solar collectors, allowing for increased capacity and higher COP values by supplying heat to the evaporator at temperatures exceeding ambient conditions [42].

2.4 Simulation

2.4.1 Building model development

The initial step in this study involved the creation of a detailed three-dimensional (3D) model of the building using SketchUp, a widely adopted computer-aided design (CAD) software. SketchUp is renowned for its versatility in architectural design, enabling the precise modeling and modification of complex structures, including both interior and exterior elements. The software's intuitive interface and extensive library of prebuilt components make it an invaluable tool for professionals in architecture and interior design, facilitating the accurate representation of real-world scenarios [43]. In this study, the building model was meticulously developed to reflect the physical characteristics essential for subsequent energy simulations, ensuring that all architectural details were accurately captured.

2.4.2 Transient simulation of the thermodynamic system

The core of this research revolves around the transient simulation of the building's thermodynamic system. Transient simulations are a sophisticated form of thermodynamic modeling that capture the dynamic behavior of systems over time. Unlike steady-state analysis, which provides only snapshots of a system's performance under fixed conditions, transient simulations offer a more comprehensive understanding by modeling the continuous evolution of the system in response to varying inputs. This approach is particularly valuable in fields such as engineering, meteorology, and environmental science, where understanding temporal changes is critical.

In this study, transient simulations were crucial for analyzing the building's energy performance under fluctuating environmental conditions. This method allows for the assessment of how the building's systems respond to daily and seasonal variations in temperature, solar radiation, and other climatic factors. By modeling the time-dependent behavior of the system, the transient approach provides insights into the real-world performance of the building, capturing the effects of thermal inertia, system lag, and other dynamic phenomena that steady-state models would overlook.

2.4.3 Simulation environment and methodology

The simulations were carried out using TRNSYS (Transient System Simulation Tool), a highly versatile and powerful simulation environment developed by the University of Wisconsin. TRNSYS is specifically designed to model the transient behavior of energy systems, making it an ideal choice for this study. The software's architecture is built around a robust solver for algebraic and differential equations, enabling it to handle complex, time-dependent simulations with a high degree of accuracy. The model is composed of distinct components, each representing a specific part of the overall system. Every component, referred to as a "TYPE", has an associated FORTRAN subroutine program, which is compiled into a Windows Dynamic Link Library (DLL) file. This DLL-based architecture enables users to modify existing types and create new custom component models [44].

TRNSYS offers an extensive library of preconfigured components, ranging from simple elements like pumps and valves to intricate multi-zone building models. This modular approach allows for the flexible assembly of simulation systems, tailored to specific research needs. Additionally, TRNSYS features a graphical user interface (GUI) that streamlines the process of connecting these components, facilitating the creation of detailed and accurate simulations. The building model, developed in SketchUp, was imported into the TRNSYS environment, where it was integrated with various energy systems and subjected to a series of transient simulations to evaluate its performance under different climatic scenarios [45].

By employing TRNSYS, this study leverages the software's advanced modeling capabilities to ensure that the results are both reliable and applicable to real-world conditions. Opting for transient simulation rather than steady-state analysis underscores the study's commitment to capturing the full complexity of the building's thermodynamic behavior, thereby providing a more accurate assessment of its energy efficiency and sustainability potential.

2.4.4 Algorithmic implementation of the simulation process

The simulation process was organized into a structured algorithm to ensure systematic execution and clarity. The flowchart (as illustrated in Figure 6) outlines the steps involved, starting from the input of building parameters and weather data, followed by the analysis of power generation and consumption, and concluding with the evaluation of results.

1. **Input parameters:** The process begins with the collection of building parameters, including geometry, materials, and insulation characteristics. Weather data, such as temperature, solar radiation, and humidity, are fed into the model to simulate real-world conditions.
2. **3D modeling and data integration:** The building is first modeled in SketchUp to ensure accurate representation of all physical attributes. The model is then imported into the TRNBuild module within TRNSYS, where it is integrated with the relevant system components.

3. **Power generation and consumption simulation:** The simulation evaluates both power generation- using technologies such as BIPV/T systems and TPV systems- and power consumption for cooling, heating, water, and electrical loads. This step assesses the balance between energy supply and demand.
4. **Transient evaluation:** TRNSYS runs transient simulations to evaluate the building's performance under various configurations and time-dependent conditions, capturing the dynamic interactions between the building systems and the environment.
5. **Optimization and result analysis:** The results are analyzed to determine the optimal efficiency of each configuration. This analysis includes calculating carbon emissions and energy generation/consumption for each configuration, providing a comprehensive evaluation of the building's energy performance.
6. **Final output:** The simulation culminates in the selection of the most efficient configuration, offering insights into the building's energy performance and its potential for sustainability.

This algorithmic approach ensures that the simulation process is methodically organized, promoting accurate modeling and reliable results. By adhering to this structured methodology, the study captures the full complexity of the building's thermodynamic behavior, thereby providing a comprehensive assessment of its energy efficiency and sustainability potential.

3 Results and Discussion

Meteorological data was obtained from Meteonorm. The building, designed in SketchUp, along with structural information, was defined in TRNBuild and then input into TRNSYS 18. The energy generated by the BIPV/T panel and TPV systems was modeled on the supply side, while domestic consumption- including heating, cooling, electronics, and lighting- was represented on the demand side.

3.1 Power generation

The simulated system meets its energy demands through TPV and BIPV/T technologies. The power output of each system fluctuates throughout the day and across different seasons. Figure 7 illustrates the monthly power generation of each source. As expected, power generation diminishes during nighttime due to the absence of solar radiation. Owing to the sun's zenith angle in winter, TPV panels produce more power compared to warmer seasons, making this transparent solar system particularly advantageous. In summer, excessive midday heat and increased cooling loads impose significant demands on the HVAC system. Conversely, power generation exceeds consumption during periods of reduced HVAC operation. Hence, energy storage and strategic consumption can alleviate power imbalances during periods of low generation.

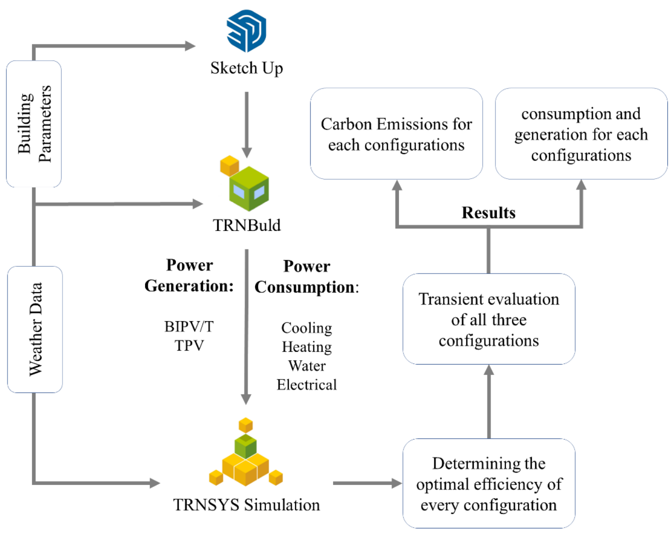

Fig. 6. Simulation process flowchart integrating 3D modeling with TRNSYS for transient analysis of building energy efficiency.

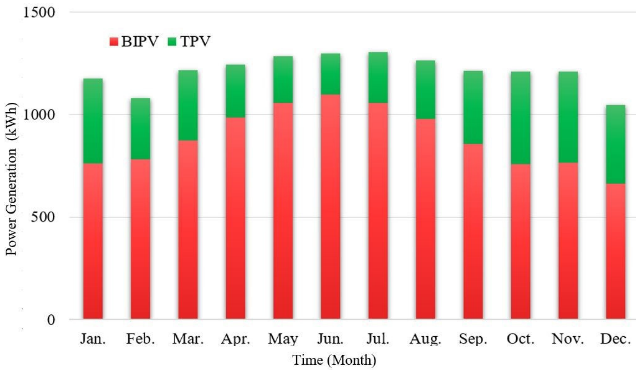

Fig. 7. Monthly power generation per producer.

3.2 Power balance

The annual heating and cooling loads for the 52.5 m^2 building were simulated to be 11537 kWh and 1675 kWh, respectively. Additionally, the annual domestic hot water demand was calculated as 1135 kWh, and the electrical demand for appliances and lighting was found to be 5396 kWh. The total annual electricity demand to meet all building requirements was estimated at 18608 kWh. The peak heating load occurred on January 7th, while the peak cooling load was observed on July 12th. The power generation and consumption profile is illustrated in Figure 8.

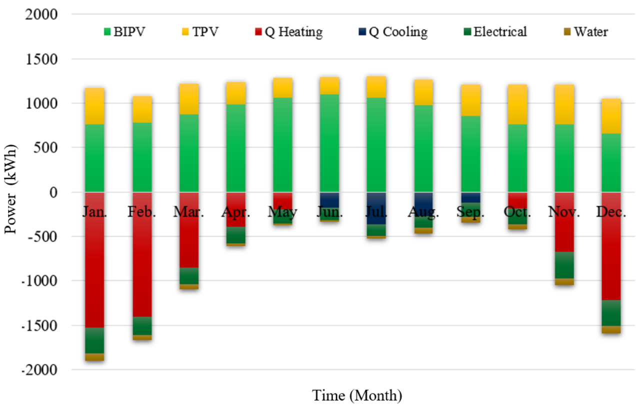

Fig. 8. Power generation and consumption.

The heating period spanned six months, while the cooling period extended for three months and nine days. Maximum monthly electricity consumption peaked in January at 1898 kWh, contrasting with the annual minimum of 378 kWh in April. Summer's highest monthly energy consumption occurred in August, reaching 525 kWh, primarily attributed to cooling equipment. Of this, 368 kWh was supplied by the photovoltaic system. Notably, 78% of the solar energy generated was provided by BIPV/T due to the sun's more perpendicular angle to the roof. However, in January, the lower solar angle and the photovoltaic system's inability to meet the building's energy demand resulted in a monthly energy deficit of 1225 kWh, sourced from the grid. The total solar energy produced in January was 1881 kWh, with BIPV/T contributing 67% and thin-film photovoltaics providing the remaining 33%. The increased contribution from TPV was due to the southward shift in solar radiation. It's worth noting that although a significant portion of the solar energy was generated during daylight hours, much of it went unused because of the lack of a storage system.

Three distinct simulation configurations were evaluated. In the first configuration, a conventional building equipped with an ASHP was simulated, drawing all its energy from the grid. The second configuration incorporated only the power generated by BIPV/T into the calculations and simulations. In the third configuration, TPV panels were added to the renewable energy system, and their effects were observed.

BIPV/T panels can not only generate electricity but also serve as an air supply for the ASHP. As discussed in subsection 2.3.3, introducing warmer air into the ASHP significantly enhances its efficiency. Therefore, utilizing BIPV/T panels and their warm air channel is expected to further improve the efficiency of the ASHP.This is reflected in Table 3 and the corresponding reduction in power consumption. In the second configuration, the integration of BIPV/T and ASHP reduced the energy demand from the grid, with the ASHP's annual energy consumption decreasing by 3,242 kWh. Adding transparent solar panels in the third configuration further augmented the system's power output, especially during winter. Consequently, reliance on the grid was reduced by 8,521 kWh per year compared to the first configuration.

The findings indicate that high-peak power devices are not suitable for off-grid residential applications. Although the electricity demand from such devices may overlap with peak solar power generation during midday, it primarily occurs in the morning, evening, and night. To sustain an off-grid energy system, appliance usage should be aligned with solar power generation whenever possible, and high-power demands during periods of low solar generation should be minimized. This requires a shift towards designing household electronic appliances with smarter, more controllable loads.

3.3 Carbon emissions

Among renewable energy technologies, solar energy systems are among the most promising for energy savings and carbon emission reduction. To calculate the CO_2 emissions of the building, it is assumed that each kilowatt-hour of electricity consumed in Iran results in the production of 549 grams of CO_2 [46]. The seasonal reduction in CO_2 emissions by the building is presented in Table 3. The utilization of solar energy and advanced control strategies in buildings significantly reduces greenhouse gas emissions. This reduction is particularly notable in the cold climate of Tabriz, especially during the winter when energy demand peaks. Conversely, during the summer, when energy demand is at its lowest, CO_2 emissions also decrease to their minimum levels.

Table 3. Annual power balance evaluation results for all three proposed configurations.

	Configuration 1	Configuration 2	Configuration 3
Power consumption (kWh)	18608	15366	15366
Renewable Power Generation (kWh)	–	10638	14588
Power savings relative to Configuration 1 (kWh)	–	7042	8521
Power from GRID (kWh)	18608	8324	6845
CO_2 emissions (kg)	10215	4570	3757

4 Challenges and Limitations

Integrating TPV technology within BIPV/T systems introduces several maintenance challenges that can significantly impact their long-term performance. One major issue is thermal management. TPV modules, when incorporated into building envelopes as windows or skylights, require careful temperature control. Efficiency can decrease by approximately 5% for every 10 °C rise in temperature. Without proper management, this can lead to overheating, which reduces both the efficiency and lifespan of the modules [47–49]. Another concern is the durability of photovoltaic components compared to traditional building materials. While solar modules typically have a lifespan of around 25 years, buildings often last over 50 years, which raises issues related to premature replacement [50]. This mismatch in longevity could lead to increased maintenance costs and potential disruptions in the building's functionality. Additionally, any failure in the waterproofing of these components could result in water ingress, compromising both the structural integrity and internal operations of the building [51]. Furthermore, integrating transparent photovoltaic modules into building envelopes may pose aesthetic challenges. Maintaining architectural continuity and ensuring that the photovoltaic systems do not detract from the building's visual appeal could limit design options and increase costs, particularly if custom solutions are required [47]. The integration of solar technologies into building facades was carefully designed to maintain the aesthetic appeal of the buildings. By utilizing transparent solar panels that allow visible light to pass through while generating electricity, the study ensured that the architectural integrity and visual appeal of the building were preserved. The flexibility of these panels in terms of size and transparency allowed for seamless incorporation into windows and facades, enhancing the building's energy efficiency without compromising its design. This approach not only meets energy goals but also addresses the growing demand for aesthetically pleasing sustainable architecture.

This study on integrating transparent solar panels and BIPV/T systems in Tabriz, Iran, highlights challenges tied to the region's specific climate, which may limit the generalizability of the findings. While solar adoption is growing in Iran, technologies like BIPV/T and TPV are still uncommon, making maintenance difficult. High installation costs and varying cultural norms regarding building aesthetics also present barriers to commercialization. Future research should focus on optimizing these technologies for various climates and building types throughout Iran. Additionally, exploring advanced materials and energy storage solutions will be crucial to ensure broader applicability and consistent performance.

5 Conclusion

This study highlights the potential of integrating multiple solar energy technologies within the Iranian climatic to reduce reliance on fossil fuels and decrease greenhouse gas emissions. By modeling a 52.2 m^2 building in Tabriz, Iran, designed for two occupants and adhering to Iranian building regulations, this research demonstrates the feasibility and benefits of using BIPV/T systems and TPV panels, combined with an a ASHP system. The model was implemented and solved using TRNSYS software.

The results reveal that the combination of BIPV/T and TPV panels significantly enhances power generation and efficiency, particularly in urban settings with limited installation space. The innovative integration of transparent solar panels into building windows addresses aesthetic concerns while maximizing the use of available sunlight. A notable feature of this research was the utilization of a specialized TPV with exceptional transparency, enabling efficient solar energy absorption while maintaining a near-glass transparency. Key findings include:

- The renewable energy system independently supplied 36.7% of the building's annual energy demand.
- The combined use of BIPV/T and ASHP resulted in a 17% reduction in peak power demand.
- The synergistic effects led to a reduction of approximately 6458 kg of CO_2 emissions.
- Specifically, the third configuration, which includes both BIPV/T and TPV panels, demonstrated an 8521 kWh reduction in annual grid energy reliance and a significant decrease in CO_2 emissions compared to conventional setups.

This study focused on simulating the system's performance in Tabriz, a city with a challenging climate characterized by harsh winters and reduced solar radiation due to its latitude. While system performance may vary in regions with different solar irradiation patterns and climates, Tabriz was chosen to represent a worst-case scenario for solar energy in Iran.

Although solar energy adoption is growing in Iran, specialized technologies such as BIPV/T and TPV remain relatively uncommon, posing challenges in terms of maintenance and repair. Commercializing these technologies in Iran faces obstacles including high installation costs, regulatory hurdles, and the need for infrastructure development. Government support and incentives could accelerate their adoption. Given that the proposed systems do not significantly alter a building's appearance, they are unlikely to face significant cultural barriers.

Future research should deal with optimizing these systems for various climates and building types across Iran, improving material efficiency, and integrating energy storage solutions to ensure consistent performance. While BIPV/T systems offer substantial benefits, addressing challenges related to maintenance, cost, and cultural acceptance is crucial for their long-term success. The findings from Tabriz may not be directly applicable to all regions, highlighting the need for further research across diverse contexts.

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