Assessing the Passive Tracking Potential of PV-Integrated Building Façades in a Low-latitude Site

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Abstract

In dense urban areas, where roof space is limited and shading is common, façade-integrated photovoltaic (PV) systems offer an effective alternative to expand solar generation. When distributed across multiple orientations, façades can act as passive trackers, capturing sunlight throughout the day. This study compares the performance of building-integrated PV (BIPV) façades with a horizontal single-axis tracker (SAT) bifacial PV plant at a low-latitude site in Florianópolis, Brazil (27°S). Using measured and simulated data from clear-sky days and annual analyses, façades achieved up to 74% and 77% of the tracker's energy output in fall and winter, respectively, with an annual average tracking potential of 42%. The integration of rooftop and façade systems improved total generation and aligned production with residential, commercial and industrial building demand peaks. These results highlight the potential of BIPV façades to enhance self-consumption, reduce grid dependency, and support the development of nearly zero-energy buildings.

Keywords: BIPV potential, PV-integrated building façades, tracking potential, low-latitude sites, passive solar tracking, self-consumption.

1. Introduction

The global agenda on Zero Energy Buildings (ZEBs) and energy transition underscores the importance of integrating energy generation systems into urban architecture. This is further justified by the fact that building operations account for 40% of global final energy use and more than half of final electricity demand (IEA, 2024). Solar photovoltaic (PV) systems can be effectively integrated into buildings (BIPV – Building-integrated photovoltaics) when aligned with the original architecture or planned from early design stages. The integration of PV modules in buildings has advanced as a solution to both energy production and architectural envelope design (IEA SHC, 2012). By generating electricity at the point of consumption, PV integration optimizes energy use, reduces grid dependency, and eliminates the need for additional land. Using photovoltaics in buildings represents an efficient and refined approach to solar energy generation. In this configuration, the building envelope serves as both the structural support for the PV modules and the electrical interface connecting the solar system to the public grid (Rüther, 2004). Their primary impact is limited to the visual presence within built environments and landscapes, making them a low-impact solution for renewable energy generation in architectural applications (Torres-Sibille et al., 2009).

A major challenge on BIPV is balancing consumption demand and energy performance, particularly in dense urban areas where roof space is limited and shading from nearby structures is common. One solution is to extend PV systems to façades, increasing generation area – even if these surfaces are partially shaded. The use of vertical façades for PV integration remains a topic of debate, especially in low-latitude sites, as these surfaces generally receive lower solar irradiance compared to optimally tilted rooftops (Portolan dos Santos and Rüther, 2014). Nevertheless, façade-integrated PV systems are well established as technically and economically viable (Sorgato et al., 2018), particularly when modules replace conventional construction materials, reduce the building's thermal load, and enhance natural lighting. Therefore, in dense urban environments, where roof space is limited, façades become essential productive surfaces, enabling nearly zero-energy building (nZEB) performance even in areas with restricted solar access.

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Additionally, the PV modules can be installed on all façades, allowing energy generation throughout the day as sunlight strikes different orientations. This configuration can be conceptually compared to tracking systems in large-scale PV plants – where, instead of modules following the sun, the sun "follows" the façades. Thus, façades act as passive solar trackers embedded in architecture. Although building-integrated single-axis trackers (SATs) have been studied (Carbone and Borrello, 2023), using vertical façades as passive solar trackers is a novel and still underexplored approach.

Façades oriented to the east, west, and north in the southern hemisphere receive sunlight at different times, resulting in a smoother and more evenly distributed generation profile (Brito et al., 2017; Thebault and Gaillard, 2021). Unlike rooftop systems oriented in a single direction, typically north, which concentrate generation around midday, façades extend energy production into the morning and afternoon hours. This continuous production offers several benefits. It reduces the simultaneity of generation, that is, the concentration of solar production within a short period, and enhances local self-consumption, increasing the building's energy autonomy without requiring large storage systems (Schram and Shirazi, 2025). It also mitigates peak-time injection into the electrical grid, contributing to system stability, and complements rooftop generation by using diverse orientations to smooth the overall production curve (Thebault and Gaillard, 2021).

Such characteristics are particularly useful for buildings with daytime or continuous energy demand. In commercial and institutional buildings, façade generation aligns with operating hours, matching air-conditioning, lighting, and equipment loads. In residential multifamily buildings, façades oriented in different directions help supply energy during morning and evening peaks, such as cooking or shower times. For mixed-use or 24-hour buildings, such as hospitals, hotels, universities, or data centers, the continuous output helps reduce grid dependence throughout the day (Pessanha et al., 2014; Schram and Shirazi, 2025).

Given this context, the present study aims to analyze and compare a single-axis tracker bifacial PV plant and vertically integrated, fixed PV façades implemented on a building at the same low-latitude site. The objective is to evaluate the tracking potential of façades and their complementary role in supplying electricity to buildings, considering their contribution relative to typical residential, commercial, and industrial load curves. Ultimately, these analyses aim to provide insights into the potential of façade-integrated PV systems as viable contributors to urban energy generation and to support their inclusion in building design and energy planning strategies.

2. Case studies

This study investigates two solar energy systems located at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27°S latitude): a single-axis tracker bifacial PV plant with a horizontal configuration and a building with PV integration on the rooftop and all four façades (Figure 1).

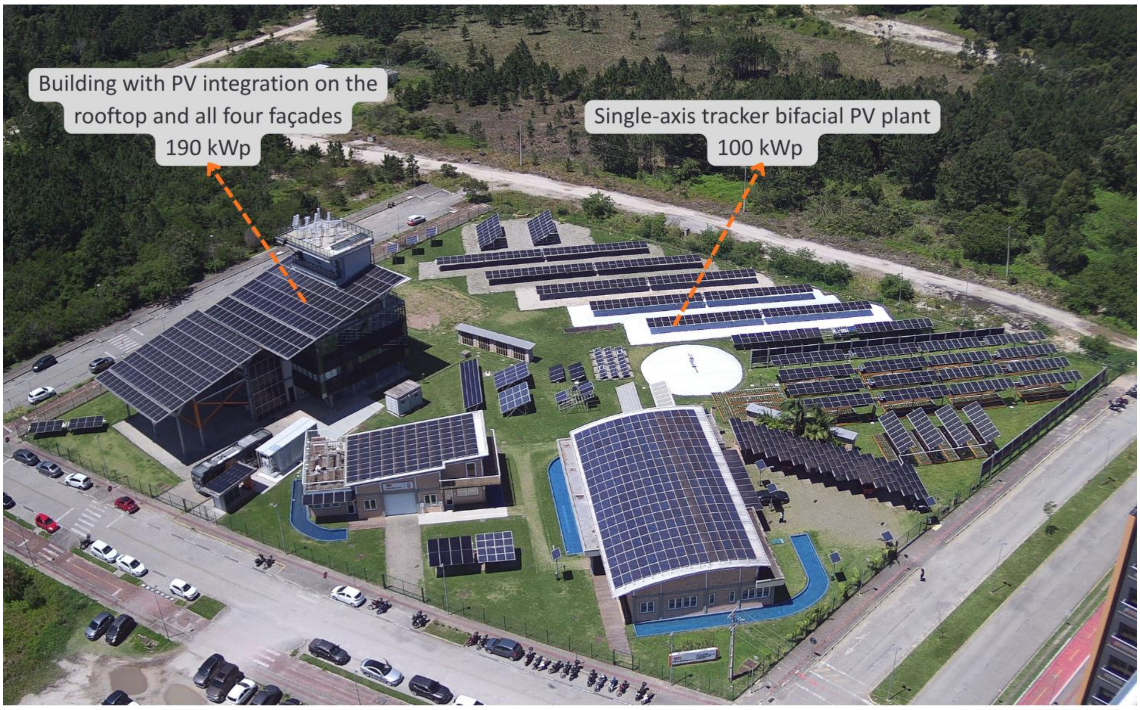

Figure 1: Solar tracking PV plant and building with PV integration on the rooftop and all four façades located at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27°S latitude).

The single-axis tracker bifacial PV plant (horizontal SAT) has an installed capacity of approximately 100 kWp, divided into six distinct subsystems employing bifacial monocrystalline silicon (m-Si) modules, being five trackers and one fixed subsystem. The subsystems were strategically installed over different ground surface types (compacted gravel, sand, and white geomembranes) to assess the energy gains provided by varying ground albedos. For the purposes of this study, one of the tracking subsystems with white geomembrane ground surface was assessed (Figure 2), as it presents shading conditions closest to those of a typical large-scale PV plant – essentially unshaded throughout the day. The subsystem consists of 30 N-type bifacial modules of 575 Wp each, equally distributed across two strings of 15 modules, totaling 17 kWp, connected to a 20 kW multi-string inverter. It is an independently driven system with a 1P configuration (one module in portrait orientation) and mounted at a height of 1.5 m.

Figure 2: Case study - 17 kWp bifacial solar tracking PV subsystem with white geomembrane ground surface.

The building presents PV systems employing bifacial monocrystalline silicon (m-Si) modules on all four façades and rooftops, totaling 190 kWp (Figure 3). It features vertical façades with two configurations: PV modules installed as exterior walls (22 kWp) and as ventilated double-skin shading devices (35 kWp) which, besides generating energy, contribute to the building's thermal comfort and improve the use of daylighting. Systems oriented 130° west consist of 20 exterior wall modules (9 kWp) and two shading subsystems with 24 modules (13 kWp), totaling 22 kWp, connected to three 6 kW multi-string inverters. Systems oriented 50° east include 28 exterior wall modules (13 kWp) and two shading subsystems with 24 modules (13 kWp), totaling

26 kWp, connected to three 6 kW multi-string inverters. A 140° east oriented shading subsystem includes 9 modules (4.8 kWp) with a 3 kW single-string inverter, while a 40° west oriented subsystem includes 8 modules (4.2 kWp) with a 3 kW single-string inverter. Complementing the façades, the building includes two PV rooftops which, together, comprise 255 modules totaling 134 kWp, both installed at a 10° tilt, oriented 40° west, and connected to two 75 kW multi-string inverters.

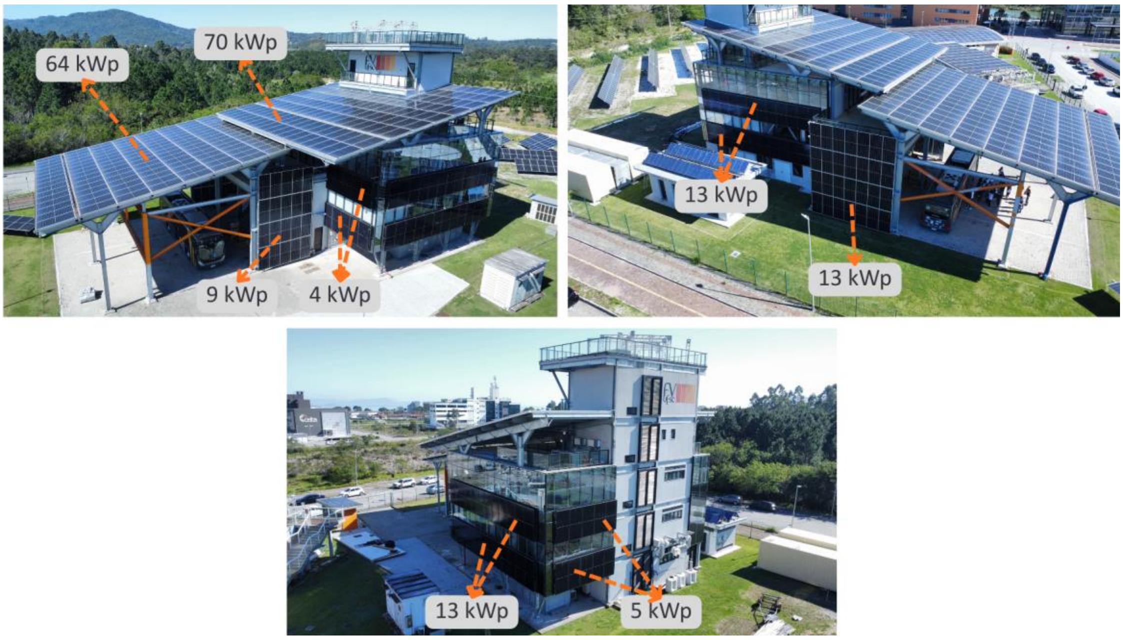

Figure 3: Case study - 190 kWp building featuring bifacial PV systems on the rooftops and all four façades.

Figure 4 presents an abacus illustrating the availability of the solar irradiation resource in Florianópolis, Brazil (Portolan dos Santos and Rüther, 2014). The abacus assumes a fixed PV plane tilted at 27° and oriented toward the north, which represents the optimal configuration for energy generation at the site. This reference plane receives 1741 kWh/m²/year, corresponding to 100% of the available irradiation. Simulations performed in PVsyst® indicate that the single-axis tracker receives approximately 2000 kWh/m²/year on the plane of the modules. According to the abacus on Figure 4, the rooftops receive around 1670 kWh/m²/year (~95 % of the available irradiation), while the façades receive between 680 and 920 kWh/m²/year (~39–53 % of the available irradiation). Although façades receive a smaller share of the solar resource, they still exhibit significant potential for energy generation, particularly given their continuous daytime exposure and architectural integration. Beyond serving as energy-producing surfaces, the façades also function as constructive envelope and cladding elements, as well as architectural devices that enhance thermal and visual comfort, contributing to the reduction of artificial lighting and air-conditioning use.

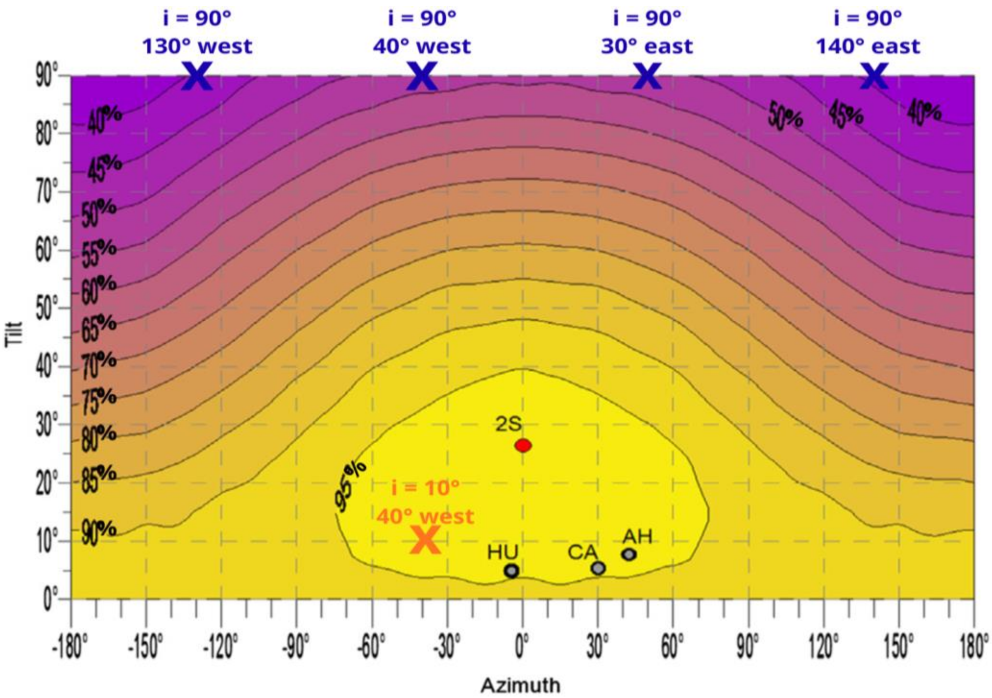

Figure 4: Solar irradiation resource availability in Florianópolis – Brazil (100% radiation = 1741 kWh/m²/year), located at 27.5° S, 48.5° W. The blue "X' marks indicate irradiation resource availability for the façades of the building and the orange "X" mark for the rooftops of the building. Adapted from (Portolan dos Santos and Rüther, 2014).

3. Methodology

The analysis was conducted using both measured and simulated data. Energy generation values were obtained for the façades and for the single-axis tracker PV system on two specific clear-sky days in 2025 – one in fall (April 17) and another in winter (July 16) – to evaluate the short-term tracking potential of the façades, calculated from the ratio between the yield of the façades and that of the tracker. In addition, measured energy generation data for the façades and simulated data for the rooftops were used to assess how vertical surfaces can contribute to meeting the demand of representative residential, commercial, and industrial load profiles. The annual tracking potential of the façades was then evaluated through full-year simulations, also based on the yield ratio between façades and tracker.

Temporal energy output (kWh) simulations were conducted using PVsyst® software version 8.0.9 for both the horizontal SAT and the BIPV façades and rooftops. Yearly simulations were performed using Global Horizontal Irradiance (GHI) data sourced from the Atlas Brasileiro de Energia Solar (Pereira et al., 2017), and ambient temperature data obtained from the *Instituto Nacional de Meteorologia* (INMET, 2025). Simulations of specific days were performed using environmental data obtained from the site's solar energy measurement station (Mantelli et al., 2020), which is equipped with a large number of sensors to monitor Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), spectral irradiance, cloud movement (sky cameras), air temperature, wind speed, humidity, rainfall, and pressure.

In the PV plant simulation, partial self-shading was considered in the central rear portion of the modules, caused by the torque tube of the horizontal SAT. No additional external shading elements were included. An albedo value of 0.72 was applied (white geomembrane). The albedo value of 0.72 was determined from measurements taken by a pyranometer installed at the site's dedicated albedo monitoring station. Bifaciality was accounted for in the simulation.

For the BIPV façades and rooftops, shading elements specific to the building's geometry were incorporated to ensure a more realistic estimation of energy output. The bifaciality of the BIPV systems could not be simulated in PVsyst® because the software's bifacial model is based on a simplified two-dimensional representation intended for regular ground-mounted or tracking arrays, and it requires uniform and consistent pitch between rows. It does not account for complex 3D geometries, multiple orientations, or surrounding architectural elements typical of building-integrated configurations (PVsyst® SA, 2024). Nevertheless, the influence of bifaciality on temporal energy output was assessed through analysis of the measured performance data. An albedo value of 0.2 (grass) was used for the BIPV simulations.

Operational AC power data (in kW for the SAT PV plant and in W for the building systems) were collected from the PV inverters using the manufacturer's datalogger (Huawei) for the SAT PV plant and through the manufacturer's cloud monitoring platform (Solis, 2025) for the building systems.

For the SAT PV plant, 1-minute interval data were obtained by requesting the datalogger via HTTP, stored locally on the laboratory server, and then integrated into energy values and aggregated into hourly totals (Wh).

For the building PV systems, data were accessed through the official Application Programming Interface (API) of the manufacturer's platform, which provides time-series active power measurements pre-aggregated into 5-minute intervals based on raw inverter telemetry. The retrieved data were automatically collected via API requests, stored locally, and processed in the same manner to obtain hourly energy totals (Wh).

4. Results

Figure 5 and Figure 6 present the energy output profiles (kWh) for the two analyzed clear-sky days – April 17, 2025 (fall season) and July 16, 2025 (winter season) – for both the horizontal SAT PV plant and the BIPV façades. In fall, the façades achieved up to 74% of the tracker's energy output, while in winter this contribution increased to 77%. The energy profiles exhibit typical BIPV façade behavior for the Southern Hemisphere: the northeast and southeast façades generate mainly in the morning, whereas the southwest and northwest façades produce in the afternoon. Despite this complementary pattern, a generation gap occurs between 09:00 and 16:00, reaching a minimum around 14:00 on both days. On April 17, the generation peaks for the northeast, southeast, southwest, and northwest façades occur at 09:00, 08:00, 16:00, and 16:00, respectively, while on July 16, they occur at 09:00, 08:00, 16:00, and 15:00. In fall, the output profiles generally resemble that of the tracker, with more evenly distributed generation throughout the day, although at lower absolute energy values. In winter, the northeast façade produces higher energy than in fall and extends its generation slightly later in the day due to the lower solar elevation angle. However, afternoon generation is limited, contributing less to the overall tracking potential than in fall. These results emphasize the capability of BIPV façades to emulate directional daily solar tracking behavior in low-latitude conditions.

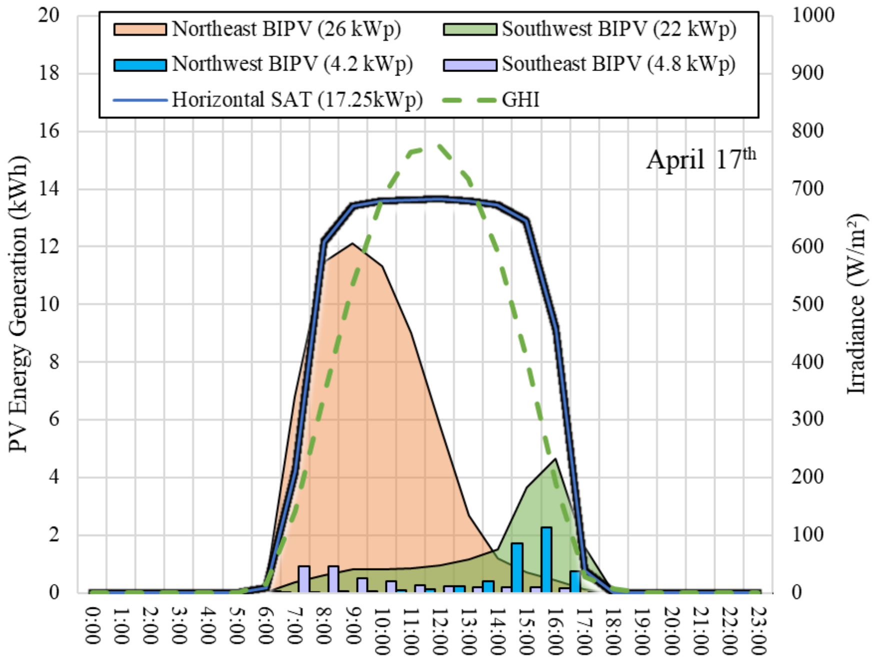

Figure 5: Temporal energy output (kWh) of both the solar tracking PV plant and the building-integrated façades at a clear-sky day during fall (April 17, 2025).

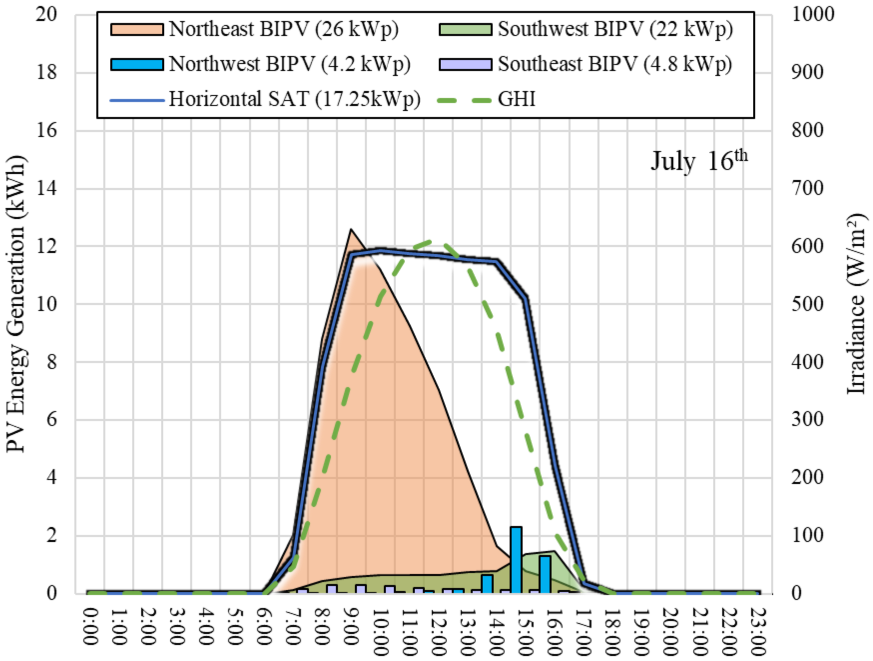

Figure 6: Temporal energy output (kWh) of both the solar tracking PV plant and the building-integrated façades at a clear-sky day during winter (July 16, 2025).

Figure 8 and Figure 8 show the tracking potential of the BIPV façades for the two analyzed clear-sky days – April 17, 2025 (fall season) and July 16, 2025 (winter season). The tracking potential of the façades in the fall day is 18%, while on the winter day it is 12%. The difference between the two periods is mainly attributed to the higher irradiance levels and longer daylight duration in April, which accounts for the greater overall tracking potential observed in fall. Although the lower solar elevation angle in winter causes sunlight to strike the PV module surfaces more directly, the reduced irradiance and shorter solar window limit the façades' energy contribution during this season. The tracking potential lines show peaks corresponding to periods when one or more façades align with the solar position. On April 17, the peak observed around 17:00 results from the solar position, when sunlight directly strikes the vertical façades, causing their energy generation to momentarily exceed that of the tracker. These results reinforce the seasonal dependence of façade-based tracking.

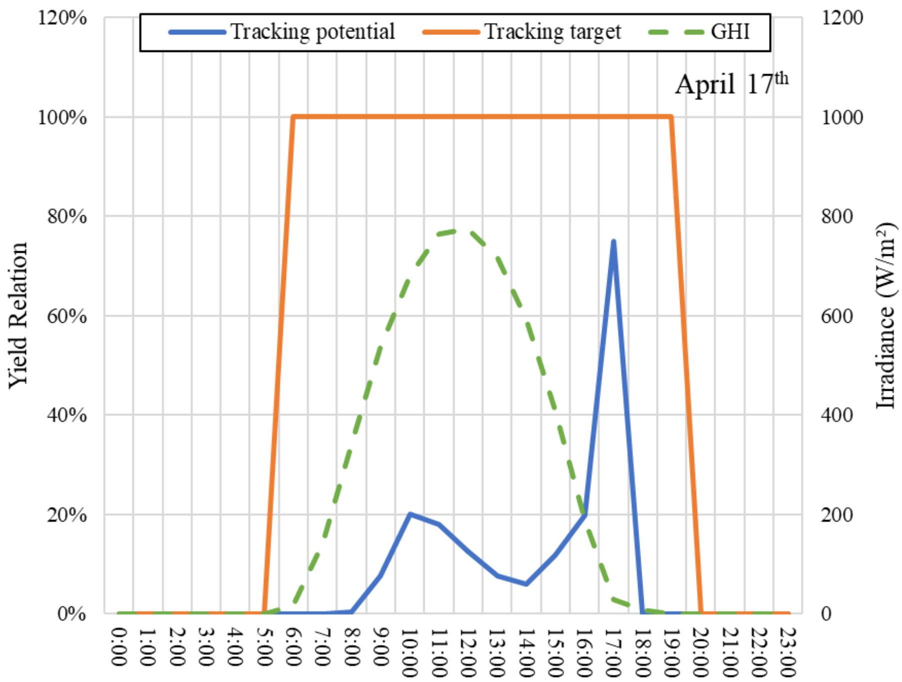

Figure 7: Tracking potential of the building-integrated façades at a clear-sky day during fall (April 17, 2025) – 18%.

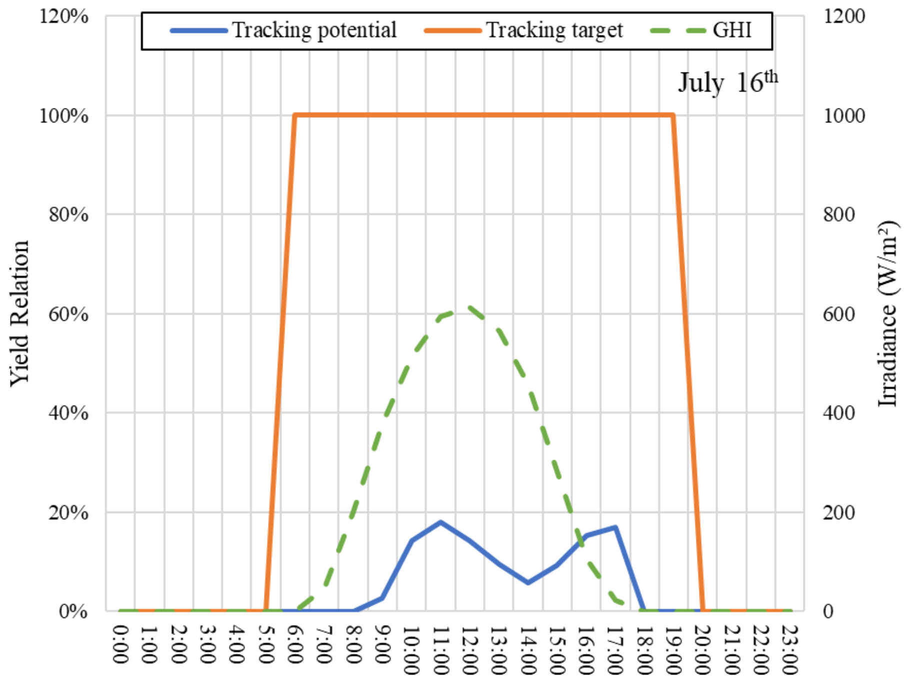

Figure 8: Tracking potential of the building-integrated façades at a clear-sky day during winter (July 16) – 12%.

Figure 9 shows the daily tracking potential of the BIPV façades, with an annual average of 42%. Days such as July 22, September 17, and November 2, 5, 6, 9, 10, and 19 particularly increased this average, exhibiting tracking potentials between 72% and 98%. These high values occur mainly due to enhanced façade generation at the end of clear-sky days, when the sun's position favors direct irradiation on the vertical surfaces, allowing their output to surpass that of the tracker. The lowest tracking potentials of the year, around 29%, were recorded on January 17, July 10 and December 12, while the highest, 98%, occurred on July 22. These variations highlight the strong seasonal influence of solar geometry and atmospheric conditions on the tracking potential of BIPV façades throughout the year.

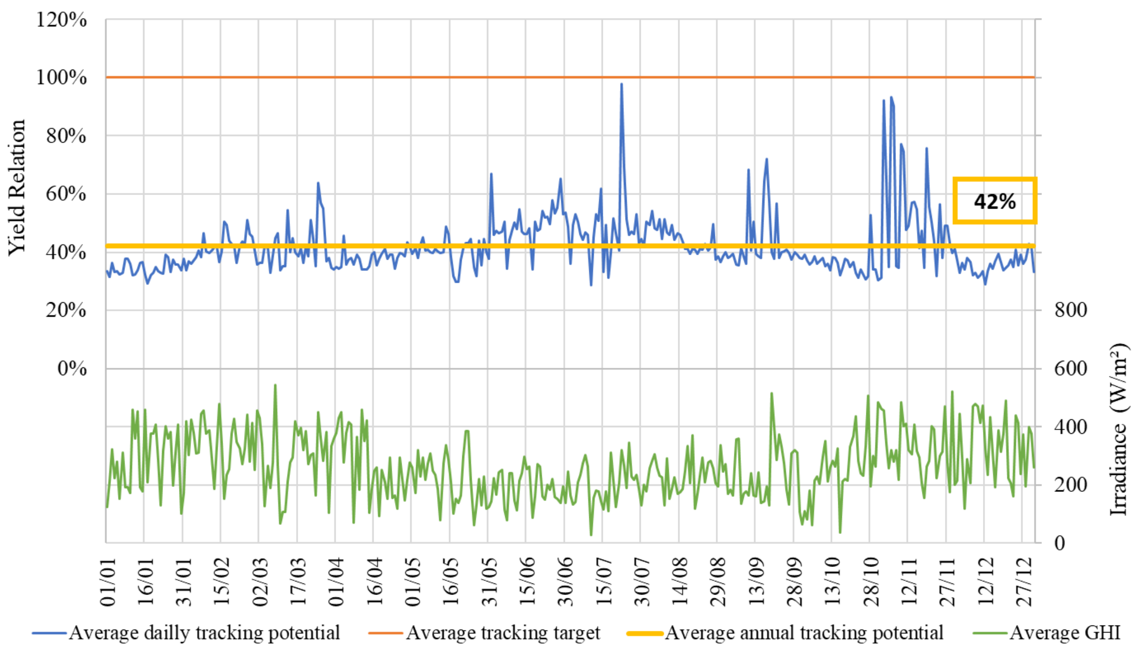

Figure 9: Annual tracking potential of the building-integrated façades – 42%.

Figure 10 and Figure 11 present the load curves of residential, commercial, and industrial buildings (Pessanha et al., 2014), alongside the measured energy output from the BIPV façades and the simulated generation from the BIPV rooftop system, for the two analyzed clear-sky days - April 17, 2025 (fall season) and July 16, 2025 (winter season). The inclusion of the rooftop BIPV system enhances the overall daily tracking profile by filling the midday generation gap observed in both days, thereby increasing the total energy production. Meanwhile, the peak output from the façades coincides with the typical peak demand periods of residential, commercial, and industrial consumers. This alignment between façade generation and building demand profiles is particularly important, as it enables BIPV systems to directly support peak load periods, reducing dependency on the electrical grid and enhancing on-site energy self-sufficiency.

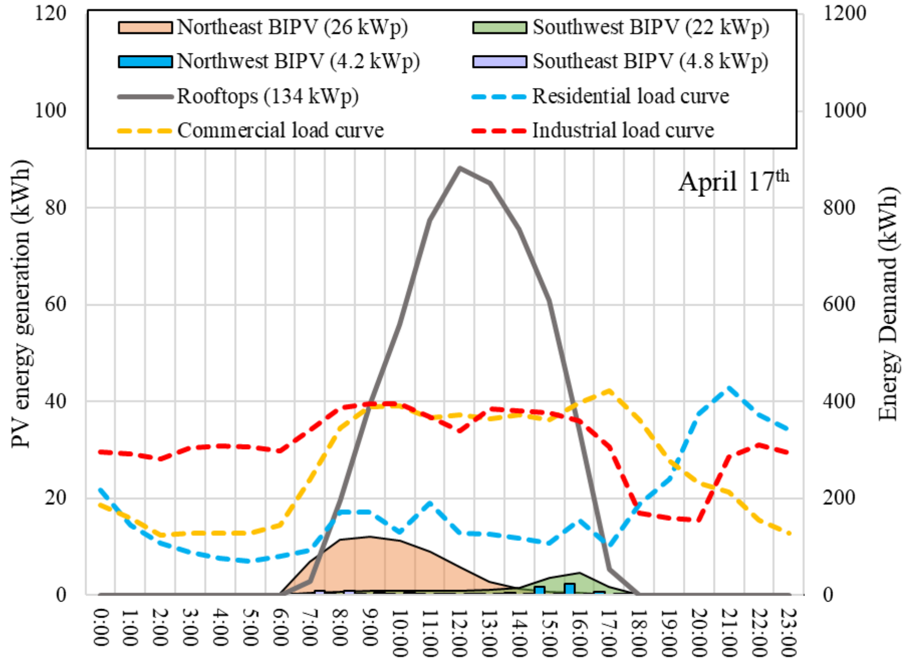

Figure 10: Load curves of residential, commercial, and industrial buildings (Pessanha et al., 2014) alongside the measured energy output from the BIPV façades and the simulated generation from the BIPV rooftops for April 17, 2025 (fall season).

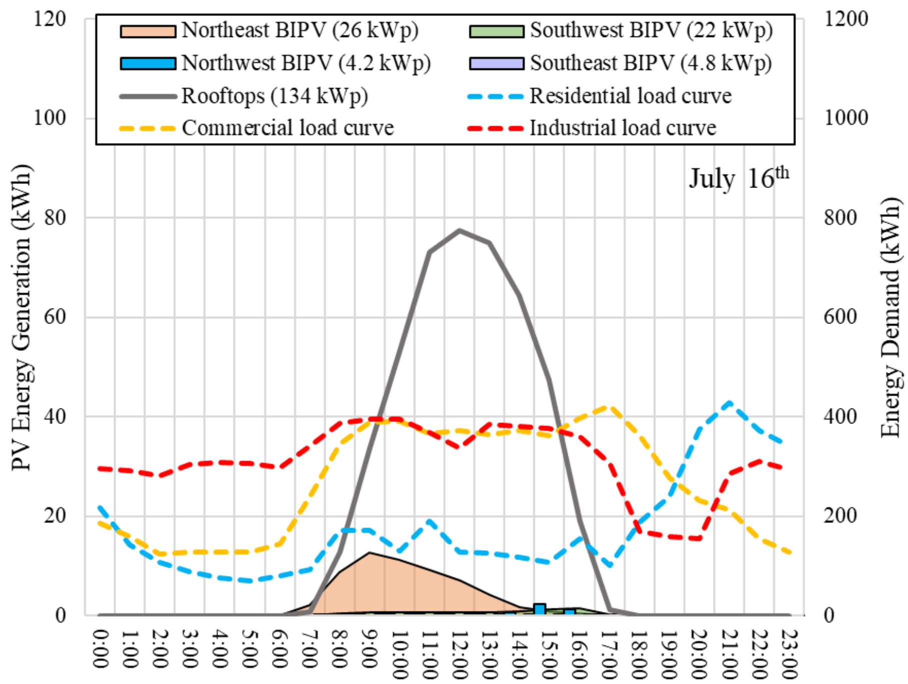

Figure 11: Load curves of residential, commercial, and industrial buildings (Pessanha et al., 2014) **alongside the measured energy output from the BIPV façades and the simulated generation from the BIPV rooftops for July 16, 2025 (winter season).**

Beyond their strategic energy contribution and tracking potential, façade-integrated PV systems offer notable multifunctionality by replacing conventional construction materials. These findings support the adoption of BIPV façades even in low-latitude sites, underscoring their relevance in the global expansion of urban solar energy solutions.

5. Conclusions

This study demonstrated that BIPV façades can effectively complement conventional rooftop and tracking PV systems by extending energy generation beyond the midday period and better aligning production with building demand profiles. Despite receiving lower solar irradiance compared to optimally oriented surfaces, façades achieved an annual average tracking potential of 42%, with peaks reaching up to 98% under favorable solar positions. These results confirm that façade-integrated PV systems in low-latitude regions can act as passive solar trackers, enhancing energy generation during morning and afternoon hours and contributing directly to self-consumption during peak demand periods. In addition to their energy performance, BIPV façades provide architectural, thermal, and aesthetic benefits, supporting sustainable building design. Therefore, the integration of PV systems into façades represents a technically viable and architecturally meaningful strategy to advance nearly zero-energy buildings (nZEBs) and to promote a more resilient and distributed urban energy landscape.

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7. References

Brito, M.C., Freitas, S., Guimarães, S., Catita, C., Redweik, P., 2017. The importance of facades for the solar PV potential of a Mediterranean city using LiDAR data. Renew Energy 111, 85–94. https://doi.org/10.1016/j.renene.2017.03.085

Carbone, R., Borrello, C., 2023. A Building-Integrated Bifacial and Transparent PV Generator Operated by an "Under-Glass" Single Axis Solar Tracker. Energies (Basel) 16. https://doi.org/10.3390/en16176350

IEA, 2024. More efficient and flexible buildings are key to clean energy transitions. Available at: https://www.iea.org/commentaries/more-efficient-and-flexible-buildings-are-key-to-clean-energy-transitions.

IEA SHC, 2012. Task 41 A.2 - Solar Energy Systems in Architecture: integration criteria and guidelines. Available at: https://task41.iea-shc.org/publications.

INMET, 2025. Históricos de dados meteorológicos. Instituto Nacional de Meteorologia.

Mantelli, S.L.N., Martins, G.L., Rüther, R., 2020. Uncertainty analysis of solar monitoring station: A case study, in: Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019. International Solar Energy Society, pp. 2135–2140. https://doi.org/10.18086/swc.2019.44.03

Pereira, E., Martins, F., Gonçalves, A., Costa, R., Lima, F., Rüther, R., Abreu, S., Tiepolo, G., Pereira, S., Souza, J., 2017. Atlas brasileiro de energia solar. Universidade Federal de São Paulo. https://doi.org/10.34024/978851700089

Pessanha, J.F.M., Xavier, V.L., Amaral, M.R. dos S. do, Laurencel, L. da C., 2014. Construindo tipologias de curvas de carga com o programa R. Pesquisa Operacional Para O Desenvolvimento 7. Available at: https://www.podesenvolvimento.org.br/podesenvolvimento/article/view/310.

Portolan dos Santos, Í., Rüther, R., 2014. Limitations in solar module azimuth and tilt angles in building integrated photovoltaics at low latitude tropical sites in Brazil. Renew Energy 63, 116–124. https://doi.org/10.1016/j.renene.2013.09.008

PVsyst® SA, 2024. PVsyst®.

Rüther, R., 2004. Edifícios solares fotovoltaicos: o potencial da geração solar fotovoltaica integrada a edificações urbanas e interligada à rede elétrica pública no Brasil, 1st ed, UFSC/LABSOLAR. Florianópolis. ISBN 85-87583-04-2. Available at: https://fotovoltaica.ufsc.br/sistemas/livros/livro-edificios-solares-fotovoltaicos.pdf.

Schram, W.L., Shirazi, E., 2025. PV on façades: A financial, technical and environmental assessment. Energy Build 328, 115010. https://doi.org/10.1016/j.enbuild.2024.115010

Solis, 2025. SolisCloud [WWW Document]. URL www.soliscloud.com

Sorgato, M.J., Schneider, K., Rüther, R., 2018. Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate. Renew Energy 118, 84–98. https://doi.org/10.1016/j.renene.2017.10.091

Thebault, M., Gaillard, L., 2021. Optimization of the integration of photovoltaic systems on buildings for self-consumption – Case study in France. City and Environment Interactions 10, 100057. https://doi.org/10.1016/j.cacint.2021.100057

Torres-Sibille, A. del C., Cloquell-Ballester, Vicente Agustín, Cloquell-Ballester, Víctor Andrés, Artacho Ramírez, M.Á., 2009. Aesthetic impact assessment of solar power plants: An objective and a subjective approach. Renewable and Sustainable Energy Reviews 13, 986–999. https://doi.org/10.1016/j.rser.2008.03.012