# Integration of Photovoltaic Systems in University Buildings: A Retrofit Project at The Technology Center of the Federal University of Rio De Janeiro

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**Abstract**

This study examines the technical, economic, and environmental feasibility of installing photovoltaic systems integrated into Block I of the Federal University of Rio de Janeiro (UFRJ) Technology Center (TC), considering rooftop, façade, and carport walkway. The systems are dimensioned using SolarEdge software, considering area, modules, peak power, and orientation. Annual energy is projected at 1,811 MWh for the roof, 67 MWh for the façade, and 414 MWh for the carport, totaling 2,292 MWh and reducing 363 tons of $CO_2$ annually, equivalent to 16,685 trees. Financial indicators, including acquisition, operation, maintenance, inverter replacement, and a 30-year lifespan, show an LCOE of USD 0.0452/kWh, IRR of 23.1%, Payback of 5.4 years, NPC of USD 1.49 million, and annual revenue of USD 232,227.24, proving economic viability. TC's energy use varies from 821 to 1,089 MWh/month, with the system saving about 20% annually. The carport with a permanent educational exhibition fosters environmental awareness, renewable energy education, and engagement within the academic community, while providing additional power generation and vehicle protection. The façade integration serves as a model for sustainable retrofitting, reconciling heritage preservation with energy modernization. In summary, the study demonstrates that BIPV implementation at UFRJ TC is technically feasible, economically attractive, and environmentally beneficial, serving as a reference for future sustainability initiatives in universities and public institutions.

*Keywords: Photovoltaic, Sustainability, Retrofit, Efficiency, Architecture, BIPV.*

## 1. Introduction

Public universities play a key role in society beyond academic training (Perry, 2006). As research and innovation centers, they must lead initiatives addressing contemporary challenges like climate change and energy transition. Projects focused on sustainability, such as photovoltaic installations and structural retrofits, provide opportunities to align theory with practice, making the campus a living laboratory (Franz, 2015). Implementing clean technologies not only reduces environmental impact and saves energy, but also offers students crucial interdisciplinary experiences (Voytenko et al., 2016). Furthermore, these initiatives produce valuable data for academic research and inform public policy, strengthening the university's role in innovative social impact. By adopting sustainable practices, institutions exemplify coherence between discourse and action, inspiring both the academic community and society (Fleith de Medeiros et al., 2022). Therefore, engaging in such projects is essential for universities to fulfill their mission of promoting knowledge, development, and social transformation(Selvakkumaran & Ahlgren, 2021).

This research project aims to retrofit the "Block I" building in the Technology Center of the Federal University of Rio de Janeiro (TC/UFRJ), in Brazil, focusing on sustainability and renewable energy sources. The proposal encompasses three photovoltaic installations. The first will be located on the building's rooftop, spanning the entire roof. The second will be integrated into the façade using Building Integrated Photovoltaics (BIPV) technology. This technology allows the modules to generate electricity while simultaneously functioning as building materials, thus replacing traditional cladding (Broers et al., 2023). Architectural integration provides aesthetic and functional improvements. These attributes make BIPV a promising approach for modernizing public buildings in densely


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populated urban environments, where vertical surfaces are critical for energy efficiency (Fath et al., 2015; Thebault et al., 2022). Finally, the third installation will be built on a sidewalk within the parking lot, serving as a community space and a promotional platform for the project at the university, featuring a permanent exhibition on solar energy and sustainability for students and other interested parties (Ertmer & Ottenbreit-Leftwich, 2010).

The application of photovoltaic technology meets the growing demand for sustainable solutions in university buildings, aligning with UFRJ's guidelines for innovation, energy efficiency, and greenhouse gas reduction. Besides contributing to the campus' electricity grid, the system serves as an experimental platform, providing real-time data for academic research, energy performance studies, and interdisciplinary teaching. Block I was selected as the pilot unit due to its significance within the TC and its focus on experimental projects, housing courses and laboratories related to engineering, particularly alternative energy, civil construction, and urban planning. Thus, the retrofit has both technical and educational dimensions, fostering a learning environment that supports the training of professionals committed to sustainability and energy transition.

## 2. Methodology

The methodology employed in this study encompasses the technical sizing of three photovoltaic installations situated in various locations within the TC. One on the roof of the Block I building, another on the façade of the same building, and a third on a walkway within the parking lot. For each configuration, the annual electricity generation is estimated and compared to the building's consumption profile, enabling an assessment of the efficiency of the proposed system and its contribution to reducing the TC electricity costs. The plants are being sized using the free-to-use SolarEdge software, which permits system performance simulations that consider the orientation, inclination, and type of photovoltaic module employed in each scenario. In the case of the façade plant, the study encompasses the proposed retrofit of the building, integrating engineering and architectural strategies. Concurrently, the architectural design is developed within the BIM environment utilizing Revit software, which facilitates detailed modeling of the building and its interaction with photovoltaic systems. Finally, a survey of implementation costs is conducted, followed by an economic-financial analysis based on the initial investment, the savings provided by energy generation, and the estimated return on investment time.

### 2.1. Characterization of the UFRJ Technology Center

The TC/UFRJ is recognized as one of the foremost institutions in Brazil dedicated to education, research, and technological innovation. It is located within the University Campus on Ilha do Fundão, in Rio de Janeiro, Brazil, and is composed of the majority of the faculties and departments focused on engineering, architecture, and urban planning, including undergraduate and postgraduate programs that are nationally and internationally acknowledged. The facilities are organized into multiple interconnected blocks, specialized laboratories, auditoriums, administrative offices, and communal areas, all distributed across an extensive architectural complex that is explicitly designed to promote the integration of teaching, research, and community engagement. In addition to its academic significance, the TC/UFRJ is regarded as a strategic institution in the promotion of technological innovation and sustainability initiatives. The campus is frequently employed as a testing ground for applied research in areas such as energy efficiency, renewable energy integration, building retrofitting, and energy systems modeling. The architectural complex of the TC is composed of nine principal blocks, designated by the letters A through I. In this study, the rooftop and façade photovoltaic systems are designed for Block I, which is selected due to its strategic position within the campus, its large roof area, and the favorable orientation of its façade for solar radiation capture, making it particularly suitable for the installation of building-integrated photovoltaic systems. The third photovoltaic installation is located in a parking area adjacent to Block I, an area characterized by high pedestrian circulation and proximity to the Student Union, which increases the project's visibility and strengthens its educational and demonstrative role.

### 2.2. Simulation and Design of Photovoltaic Systems Using SolarEdge

The SolarEdge Designer software is an online simulation and design tool developed by SolarEdge Technologies to support the planning and optimization of photovoltaic (PV) systems. It permits users to model and simulate solar installations with a high level of accuracy, incorporating technical parameters such as geographic location, solar irradiation, shading effects, module orientation and tilt, and inverter configuration. The software automatically conducts energy generation estimates based on local meteorological data, facilitating precise predictions of the system's annual energy output. The sizing and generation forecasting of the three PV plants are conducted utilizing SolarEdge software.

## 2.3. BIM Revit for Building Design and Integration of Photovoltaic Systems

The BIM Revit software, developed by Autodesk, is a building information modeling (BIM) platform extensively utilized in architectural, engineering, and construction projects. It facilitates the creation of a highly detailed and parametric 3D model of a building, integrating architectural, structural, and MEP (mechanical, electrical, and plumbing) elements into a unified virtual environment. Revit enables precise spatial planning, visualization, and coordination among various disciplines, ensuring that modifications in one system are automatically reflected throughout the model. This study utilizes Revit to model the Block I building of the TC/UFRJ, thereby providing an accurate representation of its geometry, façade, and roof surfaces. The software facilitates the integration of the proposed photovoltaic systems, enabling the assessment of their spatial compatibility and interaction with the existing building structure. This methodology allows for a comprehensive evaluation of architectural and engineering considerations, thereby contributing to the optimization of the retrofit design and the facilitation of future construction or installation procedures. In addition, the adoption of the BIM methodology aligns with the implementation of Brazilian law nº. 14.133/21, the new Public Procurement and Contracting Law, which establishes guidelines for innovation, efficiency, and digital transformation in public works management. This legislation encourages the progressive use of BIM as a mandatory tool in public projects, promoting transparency, integration, and optimization of resources throughout the design, execution, and maintenance phases. Consequently, the use of Revit in this study not only supports technical precision and interdisciplinary coordination but also responds to the contemporary regulatory framework that guides public sector projects in Brazil.

## 2.4. Financial Performance Assessment of Photovoltaic Systems

The financial viability of the proposed photovoltaic systems is assessed through the computation of essential financial metrics. These metrics include the Levelized Cost of Energy (LCOE), which signifies the average cost per unit of electricity produced over the system's lifespan; the Internal Rate of Return (IRR), representing the anticipated rate of return on the investment; the Discounted Payback Period, which indicates the duration required to recoup the initial investment accounting for the time value of money; the Net Present Value (NPV), quantifying the total expenditure of the project in current monetary terms; and the Annualized Cost and Revenue, which offer insights into the annual financial performance of the system. By analyzing these indicators, it is possible to quantify the economic feasibility of the photovoltaic installations, assess the potential savings on electricity expenses, and determine the payback period for the investment. The methodology ensures a comprehensive understanding of both the technical and financial performance of the systems, supporting informed decision-making for the deployment of renewable energy solutions.

## 2.5. Methodological Assumptions

The following assumptions are utilized for the computation of financial indicators. The exchange rate applied is R$5.22 per USD, and the discount rate employed is 8% annually, as specified by the EPE (2024). The installation costs of photovoltaic plants vary depending on their specific characteristics. For the rooftop plant and the carport walkway plant, the assumed cost is USD 0.49/Wp, according to GREENER (2024). For the façade plant, the value is USD 4.83/Wp, due to the use of lightweight transparent glass modules, custom-made for architectural integration and installation on a ventilated façade. The calculations presuppose that Operation and Maintenance (O&M) costs amount to 1.0% annually of the acquisition value (EPE, 2024), whereas the inverter replacement cost is estimated at 12% of the acquisition value in the fifteenth year (Greener, 2024). The PV modules are presumed to have a useful lifespan of thirty years, as indicated by the manufacturer, which also aligns with the overall duration of the project. An annual degradation rate of 0.4% per year is assumed for PV modules. The electricity bill for TC/UFRJ is classified under Group A4 Green, public sector tariff, with a seasonal time-of-use tariff, wherein peak and off-peak rates fluctuate based on consumption timing. In Rio de Janeiro, the applicable utility provider is Light, which establishes a three-hour peak period on weekdays, from 5:30 PM to 8:30 PM (Brasília time). All other periods are classified as off-peak. In order to determine the revenue generated by the photovoltaic system, the off-peak active energy tariff is employed, as this period corresponds to when the PV plant produces electricity and the building's consumption is supplied by the PV system rather than the grid. The tariff applied is USD 0.11 per kWh.

## 2.6. Characteristics of the Photovoltaic System Locations

The three photovoltaic plants examined in this study possess distinct characteristics, contingent upon their geographic locations and the available space for installation. The rooftop plant is the largest among the three, situated on the building's rooftop, with an available area of 6,492 m², facilitating the installation of a considerable number of PV modules and thereby promoting greater electricity generation. The façade plant is the smallest, with an available area of 249 m². Its installation is integrated into the building's retrofit, designed to optimize the orientation and slope of the façade facing the sun, while also taking into account the architectural and aesthetic considerations of the building. Lastly, the carport walkway plant, positioned along a sidewalk within the university parking lot, encompasses an available area of 1,200 m² and is located in a highly trafficked area, in proximity to the Student Union, which enhances the project's visibility and educational potential. All plants are situated at Av. Athos da Silveira Ramos – Cidade Universitária, Rio de Janeiro – RJ, 21941-611. Their respective geographic coordinates vary slightly based on the location of each installation: the rooftop plant is positioned at 22°51'41.4"S 43°13'49.9"W, the façade plant at 22°51'44.3"S 43°13'46.4"W, and the carport walkway plant at 22°51'43.9"S 43°13'43.0"W. The total area designated for the installation of these three plants is 7,941 m², which represents the combined set considered for the photovoltaic sizing in this study. Figure 1 presents the geographic location of the site where the case study is conducted, while Figure 2 shows the building's appearance before the implementation of the façade retrofit project.


**Figure 1: Geographic location of the Technology Center of the Federal University of Rio de Janeiro (TC/UFRJ) in Brazil. Source: Google Maps.**

**Figure 2: Current state of Block I façade at TC/UFRJ before retrofit.**

## 3. Results and Discussion

This section presents and discusses the results derived from the technical and financial analyses of the three proposed photovoltaic systems, namely, rooftop, carport walkway, and façade. The evaluation criteria encompass energy generation potential, financial performance metrics, and their roles in reducing electricity consumption from the grid. The discussion aims to elucidate how the assumptions adopted and the specific characteristics of each system impact their economic viability, thereby offering valuable insights into the effectiveness of photovoltaic integration within various architectural contexts.

### 3.1. Rooftop PV plant

The design of the photovoltaic plant installed on the building's roof was based on an analysis of the available area, the structural conditions of the slab, and the predominant roof orientation. The total area designated for installation is 6,401 m², on which 1,708 photovoltaic modules were positioned. Each module has a nominal power of 700 Wp, resulting in a total peak power of 1,196 kW. The module arrangement was optimized to maximize the use of incident solar radiation, considering adequate spacing between rows and maintenance zones. The system was configured to meet operating and electrical safety conditions, with balanced strings and inverters sized according to the installed capacity. The estimated annual generation for this plant is 1,811 MWh, which represents an average annual reduction of 287 tons of $CO_2$, equivalent to planting approximately 13,173 trees. Figure 3 presents the visualization of the rooftop photovoltaic system, created using SolarEdge software, depicting the configuration of the modules on the building's roof.

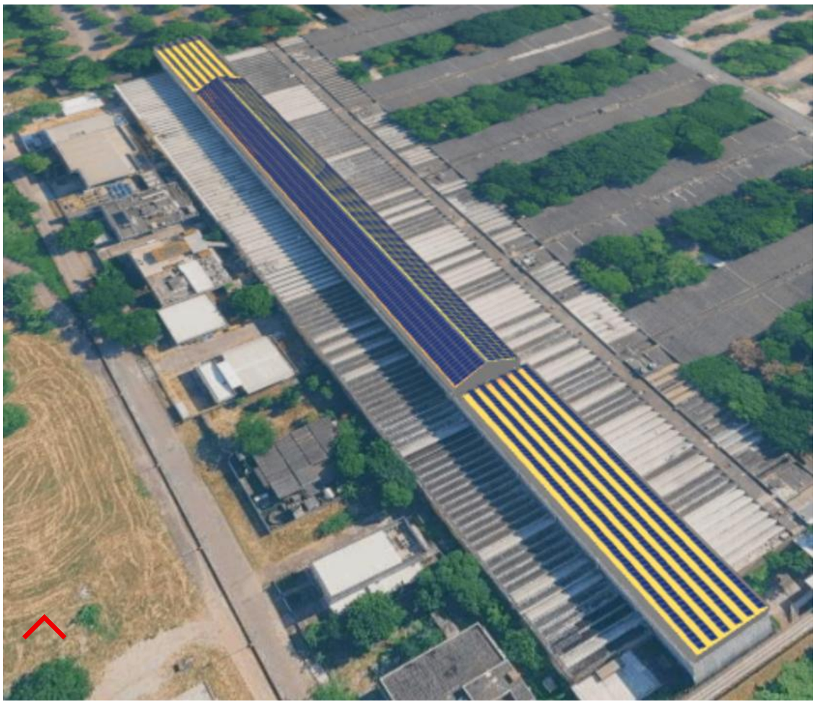

**Figure 3: Simulation of the rooftop photovoltaic plant in SolarEdge software illustrates module arrangement on the building's roof.**

### 3.2. Façade PV plant

The façade-integrated power plant was designed with a focus on architectural integration and compatibility with the building's retrofit project. 200 photovoltaic modules specifically designed for architectural integration were used, made of lightweight transparent glass and custom-made to create a ventilated façade. Each module has a power output of 266 Wp, totaling a peak installed power of 53 kW, distributed over an area of 249 m². The system was developed to meet both aesthetic and functional criteria, ensuring adequate airtightness, ventilation, and thermal performance. The plant's projected annual electricity generation is 67 MWh, providing an average reduction of 11 tons of $CO_2$ per year, which is equivalent to planting approximately 491 trees. In addition to its energy role, this plant also fulfills a demonstrative and educational function, serving as a showcase for architecturally integrated photovoltaic technologies. The renderings below illustrate the application of the photovoltaic system integrated into the ventilated façade, using lightweight transparent glass modules, custom-designed to simultaneously meet the building's aesthetic and functional requirements. The simulations highlight the arrangement of the panels on the building's vertical surface and the visual harmony achieved between the construction and technological elements. Figure 4 shows the front view of the façade of Block I, highlighting the uniformity of the set of photovoltaic modules and their integration into the architectural design. Figure 5 shows the side view of the building, allowing us to observe the depth and distribution of the modules along the façade, as well as how the PV system adapts to the building's geometry, reinforcing the sustainable retrofit concept adopted in the project.


**Figure 4: Front view of the façade of Block I with the integration of photovoltaic modules, showing the uniformity of the arrangement and the aesthetic compatibility with the architectural retrofit.**


**Figure 5: Side view of the façade of Block I, highlighting the distribution of photovoltaic modules along the vertical surface and their adaptation to the geometry of the building.**

As shown in Figure 6, a square with a common area will be created next to the building, providing a space for social integration and leisure for students and employees, in addition to enhancing the landscape and strengthening the educational and sustainable character of the campus.


**Figure 6: Proposal to create a square with a communal area next to Block I for socializing, recreation, and campus landscaping.**

### 3.3. Carport walkway PV plant

The photovoltaic installation situated within the garage walkway, adjacent to the parking area of the building, was engineered to generate energy, provide shade for parking spaces, and serve as a permanent educational exhibit on solar energy and sustainability. The metal framework was designed to hold 380 photovoltaic modules, each with a capacity of 700 Wp, resulting in a peak capacity of 266 kW over an area of 1,200 m². The configuration of the modules was strategically optimized to maximize solar energy collection throughout the day, while ensuring safe circulation for pedestrians and vehicles. The electrical system was carefully designed to minimize losses caused by localized shading and to facilitate maintenance activities. The estimated annual energy production of this installation is 414 MWh, which corresponds to an average reduction of 66 tons of $CO_2$ emissions annually, approximately equivalent to 3,021 tree-planting efforts. Due to its strategic location in a traffic zone near the Student Union, this installation also enhances the educational value and visibility of the project. Figure 7 illustrates the layout of the carport walkway photovoltaic system generated using SolarEdge software, emphasizing the configuration of the modules on the shading structure within the parking area.

**Figure 7: Simulation of the carport walkway photovoltaic plant generated in the SolarEdge software, illustrating the arrangement of the modules installed on the shading structure in the parking lot.**

The PV plant installed on the carport walkway is regarded as highly significant, functioning as an exhibition and educational resource for students. The production of electrical energy is demonstrated in a conspicuous and enduring manner, enabling the academic community to observe the operation of the system and comprehend the principles of solar energy and sustainability. This installation additionally serves to promote the initiatives conducted on campus, thereby reinforcing environmental awareness, encouraging student engagement with renewable technologies, and fostering the integration of theoretical knowledge with practical application. The following figures depict various views of the photovoltaic plant installed along the carport walkway, emphasizing its educational role and function as a permanent exhibition. Figure 8 illustrates a daytime rendering of the promenade, highlighting the configuration of the photovoltaic modules and the educational purpose of the system, which enables students and visitors to visually observe energy production and comprehend the underlying sustainability principles.


**Figure 8: Rendering of walkway with photovoltaic plant during the day, showing the educational exhibit and solar modules.**

Figure 9 illustrates the perspective of the carport walkway from the entrance of the parking lot, emphasizing the integration of the plant with its environment and its accessibility for campus visitors. This reinforces its function as an element of environmental awareness and educational engagement.


**Figure 9: View of the walkway from the parking lot entrance, showcasing how the photovoltaic plant integrates with the surroundings and serves an educational purpose for the academic community.**

Figure 10 depicts the carport walkway at night, a time during which the system does not produce electricity but remains operational as a permanent educational exhibit. This ensures continued visibility and fosters the dissemination of the campus's sustainability initiatives to all passersby, irrespective of the time of day.


**Figure 10: Nighttime walkway shows the plant as a permanent educational exhibit.**

## 3.4. Summary of three PV plants results

Collectively, the three installations achieve a peak installed capacity of 1,515 kW, with an estimated annual energy production of 2,292 MWh. These facilities contribute to an average annual reduction of 363 tons of $CO_2$ emissions, which is comparable to the carbon sequestration of 16,685 trees. Beyond the environmental benefits, the integration of the three types of systems, namely, rooftop, façade, and carport walkway, illustrates the technical viability of combining diverse photovoltaic applications within a single university complex. This approach optimizes spatial utilization and underscores the institution's dedication to sustainability and technological advancement. Figure 11 illustrates the projected electricity generation of the three photovoltaic installations over the first year's months, calculated utilizing SolarEdge software. The figures are expressed in megawatt-hours (MWh) and represent the anticipated output based on the orientation, tilt, and characteristics of the installed modules. Generation is affected by fluctuations in solar radiation throughout the year, with higher levels observed in months with increased solar incidence and lower levels during periods of reduced radiation. This underscores the seasonality inherent in electricity generation, enabling the identification of peak production months and periods when energy generated by the plants partially substitutes grid consumption, thereby contributing to energy planning and system efficiency assessments.

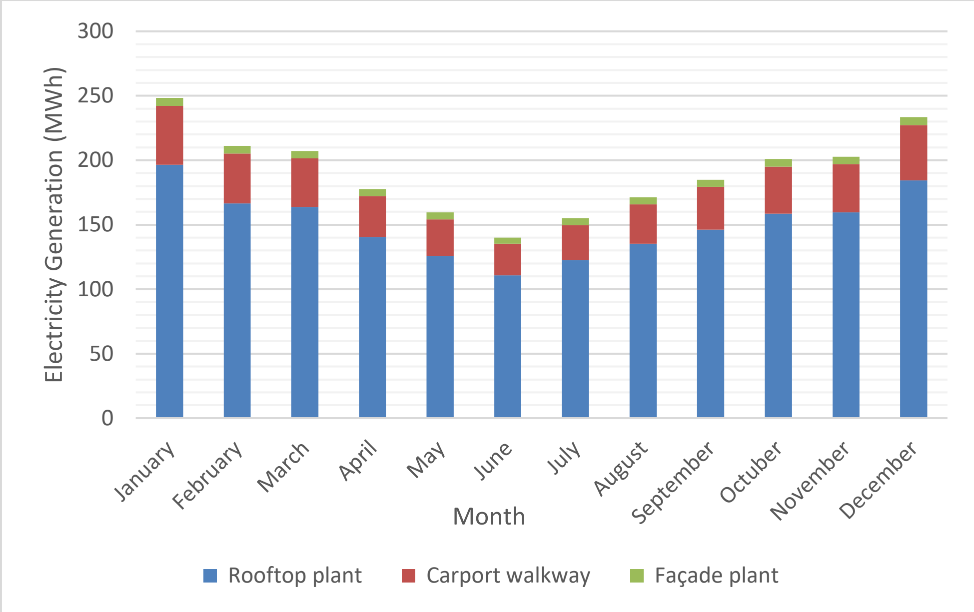


**Figure 11: Forecast of Solar Photovoltaic Power Plants Generation for the First Year (MWh).**

Table 1 provides a comprehensive summary of the primary technical and performance characteristics of the three photovoltaic plants examined. It includes parameters such as the area occupied by the modules, the number of installed panels, the nominal power of each module, the peak power of each plant, the estimated annual energy production, the average annual reduction in $CO_2$ emissions, and the equivalent number of trees planted. This table facilitates a comparative analysis of each system's performance, emphasizing both the individual contributions and the overall environmental benefits of the project.

**Table 1: Summary of Characteristics and Performance of Photovoltaic Power Plants.**

| PV Power Plant configuration | Rooftop plant | Façade plant | Carport walkway | Total |
|---|---|---|---|---|
| Project address | Athos da Silveira Ramos Avenue – University City, Rio de Janeiro – RJ, Brazil | | | |
| Geographic Coordinates | 22°51'41.4"S 43°13'49.9"W | 22°51'44.3"S 43°13'46.4"W | 22°51'43.9"S 43°13'43.0"W | - |
| Area of building (m2) | 6,492 | 249 | 1,200 | 7,941 |
| Area of PV panels laid (m2) | 6,401 | 249 | 1,200 | 7,850 |
| Quantities of solar PV panels (units) | 1,708 | 200 | 380 | 2,288 |
| Peak power of solar PV panels (Wp) | 700 | 266 | 700 | 1,666 |
| Total peak power (kW) | 1,196 | 53 | 266 | 1,515 |
| Annual electricity generation (MWh) | 1,811 | 67 | 414 | 2,292 |
| Average annual $CO_2$ emission reduction (t) | 287 | 11 | 66 | 363 |

## 3.5. Energy Consumption and Savings

The results obtained for electricity consumption and savings at the TC/UFRJ permit an assessment of the impact of PV generation on the overall demand of the complex's buildings. The analyzed consumption pertains to Blocks A through I, which accommodate air-conditioned classrooms, research laboratories, and high-energy-consuming equipment. Consequently, the total consumption of the TC is substantial, mirroring the typical profile of an energy-intensive university infrastructure. Throughout the year, monthly energy consumption fluctuates between 821 MWh, recorded in July, and 1,089 MWh, recorded in March. This demonstrates a significant variation between the months of lowest and highest demand. The average monthly consumption is approximately 960 MWh, culminating in an estimated total annual consumption of approximately 11,920 MWh for all TC buildings. These figures affirm the substantial electrical load involved, primarily attributable to the continuous operation of air conditioning systems and medium- to large-scale laboratory equipment. Monthly photovoltaic generation demonstrates characteristic seasonal patterns, with increased production observed in January (248 MWh) and decreased output in June (140 MWh), thereby reflecting fluctuations in solar incidence across the year. When assessing the total annual energy output, it is estimated that the installed photovoltaic system facilitates an average reduction of approximately 20% in monthly grid consumption. Although the percentage reduction fluctuates across different months, attaining 27% in January and 26% in December during periods of peak solar radiation, and decreasing to 15% in May and 16% in June during months of minimal solar radiation, the overall impact remains substantial. While a 20% reduction may appear modest relative to the CT's high total consumption, it signifies considerable savings given the scale of the complex, amounting to an approximate annual reduction of 2,290 MWh from the grid. These savings contribute to reducing contracted demand with the utility company, diminish the environmental impact associated with the consumption of non-renewable energy, and reinforce UFRJ's institutional commitment to sustainability and energy efficiency. The detailed monthly values for generation, consumption, and reduction percentages are presented in Figure 12.

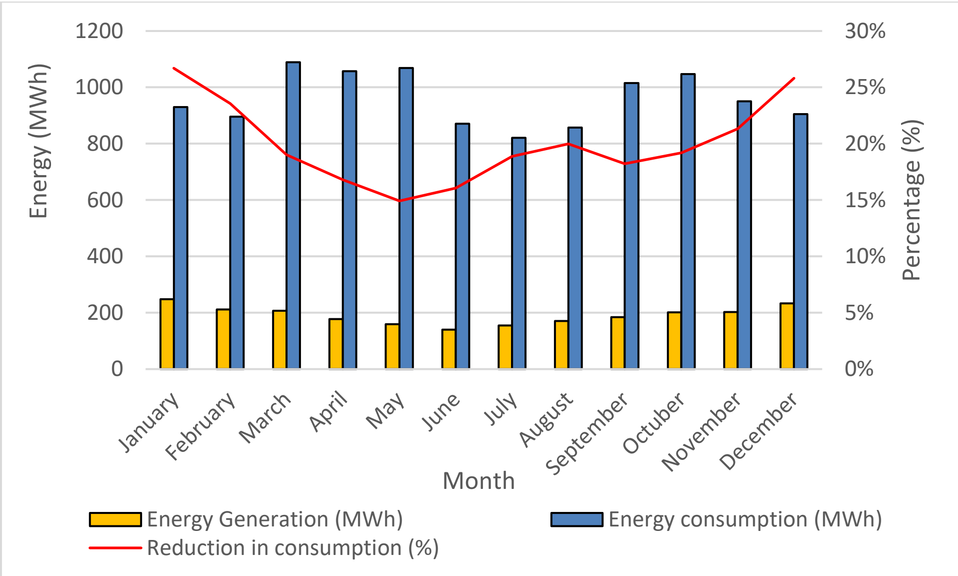


**Figure 12: Monthly energy generation, consumption, and reduction percentage for the TC buildings throughout the first year of photovoltaic system operation.**

## 3.6. Financial Performance Results

Based on the sizing of each plant and the investment value adopted in USD/Wp under the assumptions described in the methodology, the total acquisition cost of the project is estimated at USD 976,588.68, distributed among the three plants: the rooftop plant at USD 588,638.31, the façade plant at USD 256,988.68, and the carport walkway plant at USD 130,961.69. The annual O&M cost is assumed to be USD 9,765.89, and the inverter replacement is expected in the 15th year, with a value equivalent to 12% of the initial investment, totaling USD 117,190.64. Considering these assumptions, the financial indicators of the project are derived. The LCOE is calculated at USD 0.0452/kWh, a competitive figure for photovoltaic systems integrated into public buildings. The IRR stands at 23.1%, reflecting strong economic viability. The discounted payback period is 5.4 years, indicating that the investment is recovered within a relatively brief timeframe over the 30-year project duration. The NPV of the system is estimated at USD 1,490,889.64. The annualized cost amounts to USD 99,795.34, while the annualized revenue derived from electricity generation and energy bill savings is USD 232,227.24. These findings underscore the financial viability and economic attractiveness of the photovoltaic project proposed for the UFRJ Technology Center. The progression of accumulated cash flow over the years is depicted in Figure 13.

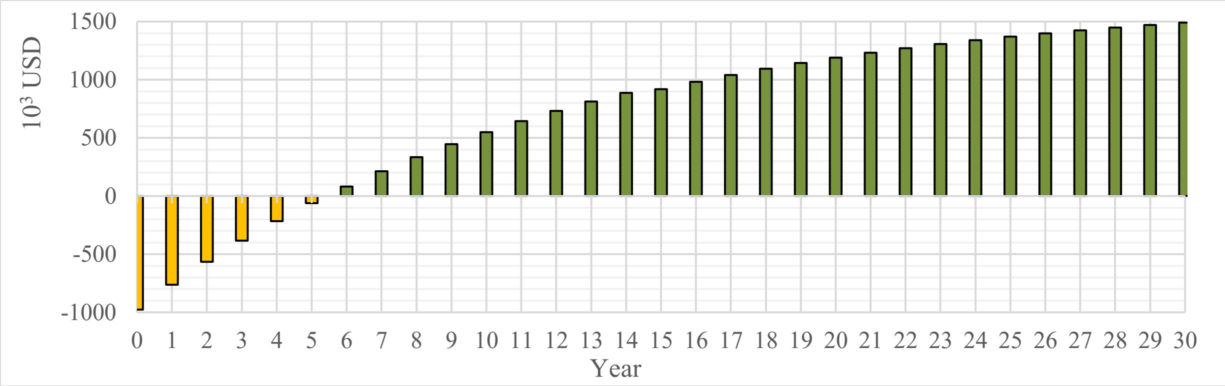


**Figure 13: Cumulative cash flow of the photovoltaic system project over a 30-year lifetime.**

The results obtained are deemed favorable and suggest that the proposed investment is both technically and financially feasible. The LCOE of USD 0.0452 per kWh is regarded as competitive relative to the average electricity cost from the grid, demonstrating that self-generation via the photovoltaic system is economically advantageous throughout the project's lifespan. The IRR of 23.1% is considered significant, indicating that the project provides a commendable return on investment, particularly given that it involves a public building where environmental and educational benefits are also primary objectives. The discounted payback period of 5.4 years is viewed as quite satisfactory, as it signifies that the invested capital is recovered in less than one-fifth of the system's estimated 30-year lifespan. Consequently, post this period, the system continues to operate with diminished costs, producing savings and net revenue for more than two decades. The NPV and annualized revenues further corroborate the project's economic sustainability, illustrating that energy savings and decreased operating costs substantially outweigh the initial investment and maintenance expenses. Therefore, it can be concluded that the proposed system is economically attractive and environmentally advantageous, aiding in reducing electricity costs and enhancing sustainability within the university campus.

## 4. Conclusions

Based on the results obtained, numerous conclusions can be drawn from this study, emphasizing the technical, economic, environmental, and educational significance of the proposed project. The implementation of retrofit measures in UFRJ's Block I, which involves the installation of photovoltaic panels on the roof and façade, is deemed feasible and effective, thereby fostering renewable energy generation on campus. This initiative directly aids in decreasing electricity consumption from the grid and reducing the university's operational expenses. Sustainability principles are reinforced, as clean energy production reduces greenhouse gas emissions, aligning with the institution's environmental goals and promoting the responsible use of natural resources. The architectural integration of photovoltaic modules into the façade of Block I, combined with natural ventilation and lighting optimization, is presented as a viable retrofit model for both historic and modern buildings, demonstrating the possibility of reconciling architectural preservation with modernization and energy efficiency.

Furthermore, the installation of a carport walkway a permanent educational exhibition within the university's parking facility is regarded as a strategic instrument for education and awareness. It enables students, faculty, and visitors to comprehend the operation of photovoltaic systems, promotes sustainable practices, and reinforces the culture of innovation on campus. This structure additionally offers protection and convenience for vehicles, contributes to electricity generation, and functions as a demonstration of sustainability, rendering the practice visible and motivational to the academic community. Therefore, this study demonstrates that the combination of distributed generation, architectural integration, and educational initiatives can provide economic, environmental, and social benefits, reinforcing the importance of implementing integrated photovoltaic systems in universities. The project serves as a benchmark for future sustainability initiatives in higher education institutions, consolidating the viability of solutions that promote energy efficiency, cost reduction, heritage preservation, and environmental education in an integrated and practical manner.

For future studies, a comprehensive energy efficiency analysis of TC is advised, with the objective of identifying opportunities to decrease energy consumption across all campuses and to optimize the performance of equipment, lighting, and air conditioning systems. Additionally, it is deemed pertinent to investigate the integration of battery storage systems, which would facilitate the management of energy consumption in accordance with seasonal tariff variations and enhance campus self-sufficiency. Finally, the practical implementation of the project is recommended, as it will enable the validation of the actual performance of the photovoltaic systems, support architectural integration, and incorporate educational carports walkway, providing tangible data to inform potential future enhancements and to promote the expanded adoption of renewable energy sources in other TC facilities.

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