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Economic Feasibility of On-Grid Photovoltaic Systems in a Single-Family House in Rio De Janeiro City

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Abstract: Brazil is a tropical country with favorable conditions for the generation and utilization of solar energy. This energy source becomes even more attractive when considering the dry periods that impact hydroelectric power generation in the country, resulting in an increase in energy costs reflected monthly in consumers' bills through tariff flags. In order to enhance residential architectural designs and promote energy efficiency, a feasibility study of photovoltaic systems was conducted, considering key economic indicators and the current tariff flags. To accomplish this, research was conducted in collaboration with Mounting Companies for a case study located in the city of Rio de Janeiro, adopting technical assumptions commonly used for residential photovoltaic system sizing. For the graphical sizing of the case study, factors such as the environment and summer and winter solstices were taken into account, and a shadow study was conducted to assess the potential loss of power generation by the photovoltaic system throughout the year. The shadow study revealed that, during both solstices, the optimal time for power generation by photovoltaic systems is between 9 a.m. and 6 p.m. Essentially, the calculated values of NPV (Net Present Value) and IRR (Internal Rate of Return) indicate that the project is economically viable and particularly advantageous during the yellow and red tariff flags, situations in which energy costs tend to be higher for consumers.

Keywords: Economic indicators, Energy efficiency, Energy saving, Residential project, Tariff flags.

Viabilidade Econômica de Sistemas Fotovoltaicos On-Grid em uma Residência Unifamiliar na Cidade do Rio de Janeiro

Resumo: O Brasil é um país tropical com condições favoráveis para a geração e aproveitamento de energia proveniente do sol. Essa fonte energética é ainda mais atrativa quando consideramos os períodos de estiagem que afetam a geração de energia hidrelétrica no país, resultando em um aumento do custo de energia que incide mensalmente na conta do consumidor através das bandeiras tarifárias. Com o objetivo de aprimorar projetos arquitetônicos residenciais e promover a eficiência energética, foi conduzida uma pesquisa de viabilidade econômica de sistemas fotovoltaicos, considerando os principais indicadores econômicos e as bandeiras tarifárias vigentes. Com esse propósito, realizou-se uma pesquisa com Empresas Integradoras para um estudo de caso localizado na cidade do Rio de Janeiro, adotando premissas técnicas de dimensionamento de sistemas fotovoltaicos comumente utilizados em projetos residenciais. Para o dimensionamento gráfico do estudo de caso, foram considerados o entorno, os solstícios de verão e de inverno, e também foi realizado um estudo de sombras para avaliação da possibilidade de perda de geração de energia pelo sistema fotovoltaico ao longo do ano. O estudo de sombras mostrou que, em ambos os solstícios, o horário ideal para geração de energia pelos sistemas fotovoltaicos é entre 09 a.m. e 06 p.m. Essencialmente, os valores encontrados de VPL (Valor Presente Líquido) e TIR (Taxa Interna de Retorno) indicam que o projeto é economicamente viável e especialmente vantajoso durante as bandeiras tarifárias amarelas e vermelhas, situações nas quais o custo de energia tende a ser mais elevado para o consumidor.

Palavras-chave: Bandeiras tarifárias, Eficiência energética, Economia de energia, Indicadores econômicos, Projeto residencial.

Viabilidad Económica de Sistemas Fotovoltaicos conectados a la Red en una Residencia Unifamiliar en la Ciudad de Río de Janeiro

Resumen: Brasil es un país tropical con condiciones propicias para la generación y aprovechamiento de la energía solar. Esta fuente de energía se vuelve aún más atractiva cuando consideramos los períodos de sequía que afectan la generación de energía hidroeléctrica en el país, lo que resulta en un aumento en costo de la energía que se refleja mensualmente en la factura del consumidor a través de las bandas tarifarias. Con el objetivo de mejorarlos proyectos arquitectónicos residenciales y promover la eficiencia energética, se llevó a cabo un estudio de viabilidad económica de sistemas fotovoltaicos, considerándolos principales indicadores económicos y las bandas tarifarias vigentes. Con este propósito, se realizó una investigación con Empresas Integradoras para un estudio de caso localizado en la ciudad de Río de Janeiro, adoptando premisas técnicas comúnmente utilizadas el dimensionamiento de sistemas fotovoltaicos residenciales. Para el dimensionamiento gráfico del estudio de caso, se tuvieron en cuenta factores como el entorno, los solsticios de verano e invierno, y también se llevó a cabo un estudio de sombras para evaluar la posibilidad de pérdida de generación de energía por parte del sistema fotovoltaico a lo largo del año. El estudio de sombras reveló que, durante ambos solsticios, el horario óptimo para la generación de energía por parte de los sistemas fotovoltaicos es de 9 a.m. a 6 p.m. En esencia, los valores calculados de VPN (Valor Presente Neto) y TIR (Tasa Interna de Retorno) indican que el proyecto es económicamente viable y especialmente ventajoso durante las banderas tarifarias amarilla y roja, situaciones en las que el costo de la energía tiende a ser más alto para el consumidor.
Palabras Clave: Energías Renovables, Eficiencia Energética, Proyecto residencial, Ahorro Energético.

INTRODUÇÃO

Energy consumption increases as the population grows. In Brazil, residential use accounts to around 10% of total energy consumption (EPE, 2020). Due to its significance, residential energy efficiency is an important topic, specially to municipalities' development.

According to Sarkar and Singh (2010), energy efficiency is the set of technologies and practices adopted to reduce the energy required to provide the same output or service level. This subject is so important that it is one of the 17 sustainable development goals (SDG) defined by the United Nations. One of the targets of “SDG 7: Affordable and clean energy” is to double the global rate of improvement in energy efficiency by 2030.

Considering energy efficiency in the analysis of urban sustainability, a city is sustainable insofar as it increases the efficiency of its processes, services and consumption of natural resources. Consequently, sustainability results from the adequate spatial distribution of people over the physical environment, in which environmental resources are embedded (MACÊDO and MARTINS, 2015).

Popescu *et al.* (2012) explain that the construction techniques widely used in buildings represent the largest sector of primary energy consumption. Besides, it is the biggest contributor to global greenhouse gas emissions (GHG). The authors also point out that investments in energy performance projects have added value in buildings because they reduce operating costs, increase commercial profitability and appreciation of the property as well as promote intelligent use of natural resources.

Solutions for obtaining energy from renewable sources are the best options available to meet the population's demand (MEKHILEF *et al.*, 2011; SOLANGI *et al.*, 2011; KAPOOR *et al.*, 2014; GUPTA *et al.*, 2016). According to Parida *et al.* (2011), solar energy is the most abundant, inexhaustible, and clean of all the renewable energy resources. Likewise, it is one of the main renewable sources for generating electricity (SOLANGI *et al.*, 2011; GUPTA *et al.*, 2016; RAM *et al.*, 2017; AL-ROUSAN *et al.*, 2018). It is also the one with less negative impacts on the environment (SADINENI *et al.*, 2011; SOLANGI *et al.*, 2011; POPESCU *et al.*, 2012).

Parida *et al.* (2011), state that photovoltaic technology is one of the best options to harness the solar power. Cai *et al.* (2015) point out that the interest in the development and application of photovoltaic power systems increased due to environmental concerns. It is because photovoltaic power systems reduce the consumption of fossil fuels and greenhouse gas emissions (GHG). However, photovoltaic systems do not have a linear behavior since they depend on photons provided by sunlight (BANDARA *et al.*,2012) and some efficiency losses in energy conversion (SOLANGI *et al.*, 2011; GUPTA *et al.*, 2016; GUPTA *et al.*, 2017). The intermittency of electricity generation under cloudy weather conditions or by partial shading is due to the unpredictability of climatic conditions throughout the year, such as solar radiation and temperature (GUPTA *et al.*, 2016; GUPTA *et al.*, 2017; RAM *et al.*, 2017; AL-ROUSAN *et al.*, 2018; PILLAI and RAJASEKAR, 2018).

One should highlight that photovoltaic systems are more efficient in areas where there is a greater incidence of sunlight, mild temperature, absence of shaded areas, latitude, and favorable inclination of the modules for capturing solar power (*e.g*: BIALASIEWICZ, 2008; SADINENI *et al.*, 2011; GOMES and CAMIOTO, 2018; AL-ADDOUS *et al.*, 2017; PEREIRA *et al.*, 2017; SYAFIQ *et al.,* 2018; CARVALHO and LAGE, 2019). The power generated can be consumed in any type of building and installed on the roofs of houses, buildings or remotely from the point of consumption.

According to Jackson (2010), changes or adaptations in buildings for the implementation of energy efficiency measures can occur at any time. Yao *et al.* (2012) consider that it is important to have an evaluation of the energy performance measures to be adopted before the construction or adaptation so it can be compared with the performance after implementing them.

The aim of this study is to evaluate the economic feasibility of installing photovoltaic systems in a single-family house located in Rio de Janeiro, Brazil. To do so, we assessed the economic profitability (save power) and energy efficiency of the solution, considering different tariff flags. Thus, the purpose is to demonstrate that the installation of photovoltaic systems in single-family houses can be a feasible investment that of firs power generation and reduces monthly electricity costs (which is also influenced by the fluctuation of prevailing tariff flags).

MATERIAL AND METHODS

Study area

The study was conducted in a single-family three levels penthouse (two floors and roof) (figure 1), with a built area of 200 m^2 and roof area of 31.92 m^2, in a residential building located in Recreio dos Bandeirantes, which is a neighborhood in the West Zone of Rio de Janeiro city, Brazil (see table 1 for details).

Figure 1. Graphical representation of the case study residential building (in grayscale) and volumetric representation of the surrounding buildings (in white). Exploded-view drawing of the apartment levels is also presented (indicated in the red rectangle).
Source: Self elaboration using Autodesk Revit and Autocad modeling software's, 2023.

Table 1. Location and general characteristics of the case study area.

Location and General Characteristics	
Case study location	Recreio dos Bandeirantes, Rio de Janeiro, RJ, Brazil.
Latitude[1]	23.012° S
Longitude[1]	43.449° W

Consumer unit class	B[2]
Number of floors in the apartment	2 + roof area
Solar potential – average daily solar radiation[1]	4.62 kWh/m² per day (annual average)

[1] CRESESB (2019). [2] According to the definition of ResoluçãoNormativa ANEEL nº 414/2010.
Source: Self elaboration, 2023.

Photovoltaic array should be installed on the roof (figure 2), with 31.92 m² area available for construction on the third level (figure 1; table 2), where there is a partially sunny area facing the north facade (see table 2 for details).

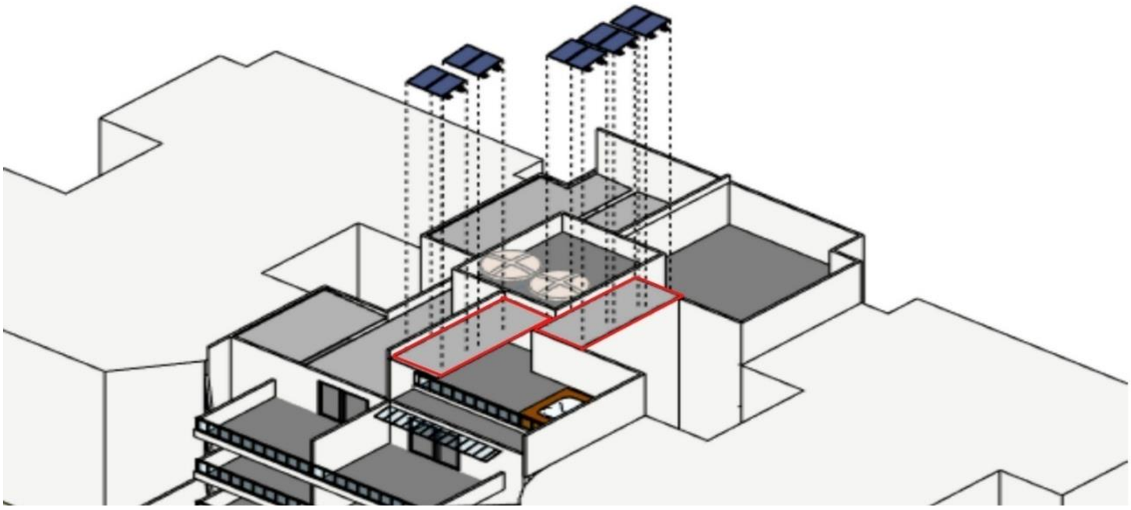

Figure 2. Exploded-view technical drawing of the photovoltaic array. Roof area intended for the installation of the photovoltaic array is highlighted in red and belongs to the apartment owner.
Source: Self elaboration using Autodesk Revit modeling software, 2023.

Table 2. Designing details and parameters used as premises for the case study.

Technical Specifications	
Photovoltaic modules orientation	North Facade
Direct sunlight on the roof area	Yes
Shading	Yes
Area available for the installation of photovoltaic modules[1]	31.92 m²
Approximate system weight[2]	20 kg/m²
Type of cover or roof	Fiber cement slab
Estimated monthly average power consumption[3]	200 – 500 kWh
Voltage class	Three-phase

[1] Belongs to the individual-unit (apartment) owner. [2] Provided by the Mounting Companies. [3] Based on average monthly electricity bills, for the year 2019, of the studied apartment.
Source: Self elaboration, 2023.

Solar study and qualitative analysis of shadow

A solar study was carried using Autodesk Revit modeling software to assess sun path during the year and, consequently, the incident solar irradiation at the studied site. In the

Autodesk Revit modeling software setup it is possible to assess the solar path of different predetermined locations, dates and hours, for summer and winter solstices.

Therefore, based on the solar study it is possible to carry out a qualitative analysis of shadow, which allows to understand how power generation can be affected by the presence of shadow on the roof area intended for the installation of the photovoltaic array. So, Autodesk Revit modeling software was used to generate images for the qualitative analysis of the shadows projected on the studied roof area at different hours of the day (06 a.m., 09 a.m., 12 p.m., 03 p.m., and 06 p.m.) (see LIMA and KRENZINGER, 2020), at summer and winter solstices, for the year of 2019. It is important to highlight that all elements that could generate shadow on the photovoltaic array were considered for this analysis, such as: surrounding buildings, large trees, electric power poles, cell towers, high-voltage power lines and chimneys.

Mounting Companies survey

Given that there is continuous and regular electricity supply provided by the local utility company in the case study region, on-grid photovoltaic system is the proposed available alternative. So, to compare technical and commercial proposals, photovoltaic system Mounting Companies located close to the case study area were surveyed. The survey was conducted using the "*Portal Solar*" website, a relevant national platform in the solar photovoltaic system field (PORTALSOLAR, 2019). To do so, verified Mounting Companies located in the city of Rio de Janeiro were searched and the number of companies operating close to the case study area was obtained (figure 3). Searching was limited by the neighborhood and surroundings. Due to the scope of this research, the commercial names of the Mounting Companies are not disclosed, being therefore represented by letters (A to Q).

Figure 3. Location of the Mounting Companies operating close to the residential building used for the case study in the city of Rio de Janeiro, Brazil.
Sources: Self elaboration using Google Earth satellite image and data from PORTALSOLAR (2021).

For the designing of the on-grid photovoltaic system by the Mounting Companies, a maximum average monthly consumption of 500 kWh was considered (table 2), given the monthly average power consumption of the studied individual-unit (apartment).

Economic feasibility

Power generation, consumption, cost of electricity, energy savings and cash flow

Power generation and consumption data were collected from each company individually, measured in kilowatt-hours (kWh). Using the tariff flags from December 2019, we calculated the cost of electricity for each company by multiplying the individual consumption values with the tariff flags (green: R$ 0,69/kWh; yellow: R$ 0,70/kWh; red 1: R$ 0,73/kWh; and red 2: R$ 0,75/kWh), and then multiplying by 12 to obtain annual cost (since the data provided by the companies was monthly). The Tariff Flag System is a mechanism that passes on the real costs of power generation to the final consumer, depending on the conditions of electricity generation (MME; ANEEL, 2021).

The new cost of electricity considered the average monthly consumption, average monthly power generation, the tariff flags and cost of availability, following the formula:

I. new_cons_x = max(100*12;cons_x – ges_x*tariff_z*12)

where,

ges_x = system power generation given by the Mounting Company "x"

The useful life of a photovoltaic system is about 25 years (SADINENI *et al.*, 2011). Therefore, the cash flow generated from year 01 (where the system's efficiency is 100%) up to year 25 was calculated taking into account the average annual efficiency loss of 0.8% (CARVALHO and LAGE, 2019).The loss is represented by the percentage reduction in power generation in kWh and follows the formula:

II. ges_n_x = (1 - 0.008*(n-1))*ges_x

where,

ges_n_x - system power generation in year "n" for company "x"

ges_x - system power generation of the system for company "x"

n – year

Note that we used (n-1) since we assumed that the generation was 100% efficient in year 01, and the efficiency loss begins from the following year.

To calculate the savings generated by the installation of the photovoltaic system (in kWh), we considered that when the difference between consumption and power generated is less than 100 kWh, the minimum amount charged will be 100 kWh for the three-phase system. Consequently, the system annual savings in kWh is given by:

III. saving_n_x = cons_x – max (100; cons_x - ges_n_x)

where,

cons_x - consumption of company "x"

Note that if the difference between cons_x and ges_n_x is greater than 100, then the savings will be equal to the power generated by the photovoltaic system, i.e., cons_x - (cons_x - ges_n_x) = ges_n_x.

Moreover, it is also important to mention that the company considered monthly consumption and generation values, and thus, to adjust the calculations to annual values, we multiplied them by 12.

Net Present Value and Internal Rate of Return

According to GOMES and CAMIOTO (2018), the net present value (NPV) is measured by the present value generated by the project throughout its useful life. Therefore, in order to calculate NPV and internal rate of return (IRR), it is necessary to analyze the cash flow of an investment considering the useful life of the photovoltaic system from year 01 to year 25. For the calculation of Net Present Value (NPV), we used the standard formula:

IV. $NPV = \sum_{i=1}^{n} \frac{R_i}{(1+r)^i}$ – Initial Investment

where,

R_i is the estimated net cash flow for i^{th} period,

r is the required rate of return per period, and

n is the life of the project in months, years etc.

The "r" value used in the formula was the cost of capital, which was 7.39% per annum (BRASIL, 2020). This value was provided by the regulatory agency Aneel in 2019 as the regulatory rate of return on capital for energy generators.

For the calculation of Internal Rate of Return (IRR), we used the equation NPV (r) = 0, which means that the present value of the cash flow is equal to zero for the required rate of return. Lastly, we as summed that the in flat ion rate would be zero, considering that the tariff flags would be adjusted ccc by the in flat ion rate.

RESULTS AND DISCUSSION

Solar study and qualitative analysis of shadow

The analysis of the shadow projection on the building's roof was performed at different times of the day during the summer and winter solstices. The images presented in Figures 4 and 5 show the shadow projection at 06 a.m., 09 a.m., 12 p.m., 03 p.m., and 06 p.m. in both seasons, allowing for a comprehensive visualization of the building's solar exposure throughout the day.

During the summer solstice, the shadow projection is partial in the first row at 06 a.m., as shown in Figure 4(a), while the second row receives total solar exposure. This partial solar exposure enables power generation during the early hours of the day, while the other hours of the day have total solar exposure, as shown in Figures 4(b) to 4(e). The optimal time for power generation using photovoltaic panels in summer solstice is between 09 a.m. and 06 p.m.

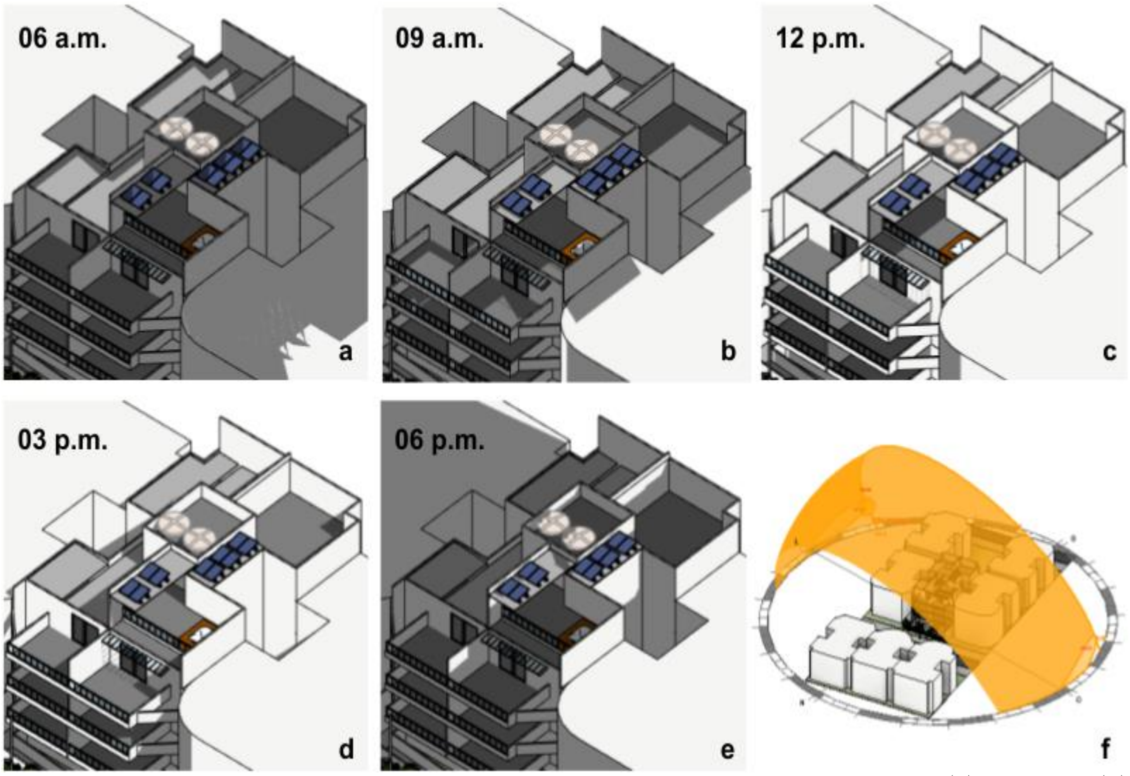

Figure 4. Shadow projection on the roof during summer solstice at: 06 a.m. (a); 09 a.m. (b); 12 p.m. (c); 03 p.m. (d); 06 p.m. (e). The sun's trajectory over the course of a year is represented in "f".
Source: Self elaboration using Autodesk Revit modeling software, 2023.

In the case of the winter solstice - when the sun is lowest in the sky, and shadows are largest (BARKER *et al.*, 2013) - as shown in Figure 5, the shadow projection directly affects the building's roof at 06 a.m., and partial solar exposure is observed at 09 a.m. and 06 p.m. In contrast, the solar exposure is total at 12 p.m. and 03 p.m., which are the optimal times for power generation using photovoltaic panels. Thus, power generation by photovoltaic panels is between 09 a.m. and 06 p.m. Therefore suggesting that the photovoltaic panels should be positioned to receive maximum solar exposure during the optimal time of the day for power generation.

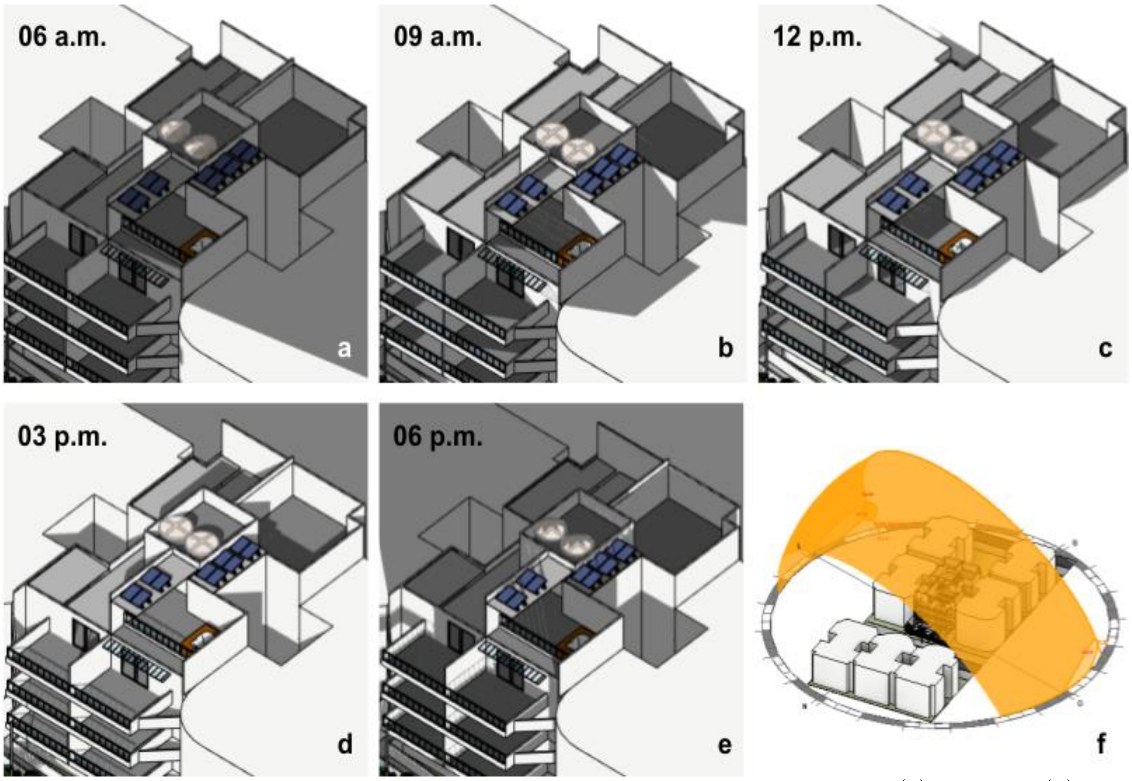

Figure 5. Shadow projection on the roof during winter solstice at: 06 a.m. (a); 09 a.m. (b); 12 p.m. (c); 03 p.m. (d); 06 p.m. (e). The sun's trajectory over the course of a year is represented in "f".
Source: Self elaboration using Autodesk Revit modeling software, 2023.

In a study conducted by OBANE *et al.* (2012) in Japan, a peak in solar irradiation was observed on the unshaded panel around 09 a.m. during the summer solstice, decreasing gradually thereafter. This is similar to the findings of the present study for the summer solstice. On the other hand, contrary to the findings of the present study, the authors observed that solar irradiation on shaded panels were too low to generate sufficient power during the winter solstice. Probably because of the harsh climatic conditions in Japan.

When designing a photovoltaic system, besides considering the orientation, inclination of panels, and analysis of the best hours of the day in order to obtain the highest power generation, several other factors that affect solar energy absorption should be taken into account, especially non-uniform lighting on photovoltaic panels, such as shading from neighboring buildings, trees, clouds, and dust (*e.g.* Obane *et al.*, 2012; Al-Rousan *et al.*, 2018). Pillai and Rajasekar (2018) further add that there may be permanent partial shading due to the accumulation of dust and bird droppings, which can result in declining power generation by the photovoltaic system.

Economic feasibility

Power generation, consumption, cost of electricity, energy savings and cash flow

The present study aimed to demonstrate the economic feasibility of installing residential photovoltaic systems, considering the calculations of the values of the current tariff flags with data provided by Mounting Companies and economic indicators. To achieve this, we arbitrarily considered three companies (A, C and F) according to the values of average monthly generation and consumption, from the lowest to the highest, analyzing the data provided by Mounting Companies. These values guide us on the efficiency of the photovoltaic system sizing and can serve as a basis for analyzing the final monetary results.

The results of the comparative analysis of the annual energy costs without the installation of the photovoltaic system showed that, for the Mounting Companies A, C and F, the energy costs varied depending on the tariff flag. Specifically, for the green flag, the costs were R$ 3,331.20, R$ 4,164.00, and R$ 4,588.73 for Companies A, C, and F, respectively. For the yellow flag, the costs were R$ 3,395.66, R$ 4,244.58, and R$ 4,677.53, respectively, while for the red 1 flag, the costs were R$ 3,531.31, R$ 4,414.14, and R$ 4,864.38, respectively. Finally, for the red 2 flag, the costs were R$ 3,630.86, R$ 4,538.58, and R$ 5,001.52, respectively (table 3).

After the installation of the photovoltaic system, the annual energy costs for Companies A, C, and F were reduced to R$ 832.80, R$ 848.92, R$ 882.83, and R$ 907.72, respectively, depending on the tariff flag. The results for the three Mounting Companies exemplified here had equal values, as they had the same difference of 100 kWh between monthly average consumption and monthly average generation (table 3).

The savings obtained with the installation of the photovoltaic system were R$ 2,498.40, R$ 3,331.20, and R$ 3,755.93 for Companies A, C, and F, respectively, for the green flag. For the yellow flag, the savings were R$ 2,546.75, R$ 3,395.66, and R$ 3,828.61, respectively, while for the red 1 flag, the savings were R$ 2,648.48, R$ 3,531.31, and R$ 3,981.55, respectively. Finally, for the red 2 flag, the savings were R$ 2,723.15, R$ 3,630.86, and R$ 4,093.80, respectively (table 3).

The savings obtained with the installation of the photovoltaic system are higher for companies that generate more power. This is because the savings are directly related to the amount of power generated by the system. For example, Company A, which generates 300 kWh, obtained a savings of R$ 2,546.75 for the yellow flag, while Company F, which generates 452 kWh, obtained a savings of R$ 3,828.61 for the same flag (table 3).

It is important to note that the increase in the tariff flags may vary and fluctuate throughout the year. For instance, when there is a low water index in the hydroelectric reservoirs, thermal power plants are activated (CARVALHO AND LAGE, 2019; MORALES AND GIACOMELLI, 2019). In these cases, the National Electric Energy Agency (ANEEL) passes on the costs of the activation of these plants to the consumer (MORALES AND GIACOMELLI, 2019).

In addition, the analysis is of the cash flow of each company for 25 years showed a fluctuation of values due to the loss of energy efficiency of 0.8% per year and the cost of availability of 100 kWh for the three-phase system. These changes directly impact there venue of the cash flow.

Table 3. Comparison of the data provided by the Mounting Companies with the data on Energy Generation Potential, Energy Cost, New Energy Cost, and Energy Savings for each tariff flag (green, yellow, red 1 and red 2).

Mounting Company	Average Monthly Generation (kWh)	Average Monthly Consumption (kWh)	Energy Cost (R$)				New Energy Cost (R$)				Savings (R$)			
			Green	Yellow	Red 1	Red 2	Green	Yellow	Red 1	Red 2	Green	Yellow	Red 1	Red 2
A	300	400	3,331.2	3,395.7	3,531.3	3,630.9	832.8	848.9	882.8	907.7	2,498.4	2,546.7	2,648.5	2,723.1
B	457	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9
C	400	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9
D	400	494	4,114.0	4,193.6	4,361.2	4,484.1	832.8	848.9	882.8	907.7	3,281.2	3,344.7	3,478.3	3,576.4
E	412	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9
F	452	551	4,588.7	4,677.5	4,864.4	5,001.5	832.8	848.9	882.8	907.7	3,755.9	3,828.6	3,981.5	4,093.8
G	434	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9
H	402	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9
I	393	500	4,164.0	4,244.6	4,414.1	4,538.6	891.1	908.3	944.6	971.3	3,272.9	3,336.2	3,469.5	3,567.3
J	380	500	4,164.0	4,244.6	4,414.1	4,538.6	999.4	1,018.7	1,059.4	1,089.3	3,164.6	3,225.9	3,354.7	3,449.3
K	389	495	4,122.4	4,202.1	4,370.0	4,493.2	882.8	899.8	935.8	962.2	3,239.6	3,302.3	3,434.2	3,531.0
L	400	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9

Mounting Company	Average Monthly Generation (kWh)	Average Monthly Consumption (kWh)	Energy Cost (R$)				New Energy Cost (R$)				Savings (R$)			
			Green	Yellow	Red 1	Red 2	Green	Yellow	Red 1	Red 2	Green	Yellow	Red 1	Red 2
M	412	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9
N	383	483	4,022.4	4,100.3	4,264.1	4,384.3	832.8	848.9	882.8	907.7	3,189.6	3,251.3	3,381.2	3,476.5
O	437	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9
P	305	400	3,331.2	3,395.7	3,531.3	3,630.9	832.8	848.9	882.8	907.7	2,498.4	2,546.7	2,648.5	2,723.1
Q	435.75	500	4,164.0	4,244.6	4,414.1	4,538.6	832.8	848.9	882.8	907.7	3,331.2	3,395.7	3,531.3	3,630.9

Source: Self elaboration, 2023.

Net Present Value and Internal Rate of Return

For companies A, C, and F, considering the minimum attractive rate of return (MARR) of 7.39%, we have the following NPVs: R$ 3,336.70, R$ 9,219.65, and R$ 16,127.38, respectively (green flag), R$ 3,843.97, R$ 9,896.01, and R$ 16,891.52, respectively (yellow flag), R$ 4,911.41, R$ 11,319.26, and R$ 18,499.48, respectively (red flag 1), and R$ 5,694.80, R$ 12,363.78, and R$ 19,679.55, respectively (red flag 2) (table 4).

Additionally, the IRR for companies A, C, and F were 9.07%, 11.40%, and 14.87%, respectively (green flag), 9.32%, 11.68%, and 15.20%, respectively (yellow flag), 9.84%, 12.27%, and 15.90%, respectively (red flag 1), and 10.22%, 12.70%, and 16.41%, respectively (red flag 2) (Table 4).

Based on the results presented here, in all tariff bands, we have positive NPVs. Moreover, as explained by GOMES and CAMIOTO (2018), if NPV results are positive, the project is economically viable. Additionally, if the IRR is greater than the MARR, the project is also economically viable (JACKSON, 2010). Thus, in our study, the value of MARR is 7.39%, and we had IRR results higher than MARR in all tariff bands for companies A, C, and F. Therefore, the photovoltaic system investment is economically feasible for all companies analyzed in this study.

Table 4. Net Present Value (NPV) and Internal Rate of Return (IRR) data for each Mounting Company, considering tariff flags.

Mounting Company	NPV (R$)				IRR (%)			
	Green	Yellow	Red 1	Red 2	Green	Yellow	Red 1	Red 2
A	3,336.70	3,843.97	4,911.41	5,694.80	9.07	9.32	9.84	10.22
B	17,469.89	18,190.70	19,707.47	20,820.63	16.43	16.78	17.51	18.04
C	9,219.65	9,896.01	11,319.26	12,363.78	11.40	11.68	12.27	12.70
D	9,474.85	10,149.92	11,570.45	12,612.97	11.55	11.83	12.42	12.85
E	17,252.80	17,945.48	19,403.06	20,472.77	17.22	17.59	18.36	18.93
F	16,127.38	16,891.52	18,499.48	19,679.55	14.87	15.20	15.90	16.41
G	14,428.40	15,139.58	16,636.07	17,734.35	14.24	14.56	15.22	15.71
H	18,406.21	19,085.66	20,515.39	21,564.67	18.98	19.38	20.23	20.84
I	13,450.71	14,115.24	15,513.58	16,539.82	14.39	14.72	15.40	15.90
J	9,404.02	10,046.57	11,398.65	12,390.94	11.80	12.08	12.68	13.12
K	11,961.43	12,619.20	14,003.30	15,019.10	13.35	13.66	14.31	14.78
L	15,446.01	16,122.37	17,545.62	18,590.14	15.90	16.25	16.98	17.52

M	10,669.46	11,362.14	12,819.72	13,889.43	12.08	12.37	12.98	13.42
N	10,566.15	11,213.78	12,576.53	13,576.66	12.50	12.79	13.41	13.87
O	17,437.82	18,150.70	19,650.75	20,751.64	16.70	17.05	17.79	18.34
P	3,592.52	4,107.13	5,189.99	5,984.70	9.18	9.43	9.95	10.33
Q	14,602.54	15,314.73	16,813.34	17,913.18	14.35	14.67	15.33	15.81
Average	12,520.38	13,187.92	14,592.59	15,623.48	13.58	13.89	14.54	15.01

Source: Self elaboration, 2023.

FINAL CONSIDERATIONS

Overall, the analysis of the shadow projection on the building's roof shows the importance of considering the optimal time of the day for energy generation using photovoltaic panels. The results also suggest that the positioning of the panels should be carefully planned to receive maximum solar exposure during the optimal time of the day, considering the solar exposure conditions during the winter and summer solstices. This information can be used to optimize the design and positioning of photovoltaic panels, resulting in increased energy efficiency and cost savings.

In summary, the results of this case study have demonstrated that the installation of a photovoltaic systems can be highly viable and advantageous for electricity consumers, especially during periods of yellow or red tariff flags. During them, the cost of energy is higher, as well as the "opportunity cost", resulting in a higher NPV and IRR, mainly in the red flags. With the installation of the photovoltaic system, consumers stop paying this additional value on their energy bill, resulting in significant savings.

The Brazilian economic scenario and positive economic indicators are fundamental factors to make the photovoltaic system viable and advantageous for consumers. Therefore, it can be concluded that the economic feasibility of a photovoltaic system is directly influenced by the country's economic context, tariff flag levels, efficiency in energy generation and correct technical details of system sizing.

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