Economic Feasibility of Conventional and Building-Integrated Photovoltaics Implementation in Brazil

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Abstract: Economic feasibility analysis is essential in the decision-making process regarding investment in photovoltaic projects. Project profitability must be measured based not only on the costs and revenues, but also on the climatic particularities of the different locations. Therefore, performing simulations of technical and economic performance of photovoltaic models is fundamental. Thus, the objective of this study was to analyze deterministic and stochastic models of investments in two types of photovoltaic systems, one incorporated into the enterprise’s architecture (a BIPV system) and the other, a conventional one, in different Brazilian locations, covering the predominant climatic factors in the country. The methodological proposal consisted of choosing a city in Brazil with each predominant climate type and compiling its data on irradiation, monthly sunshine hours, and tariffs of the electric power concessionaire, to simulate the electrical generation performance of the proposed photovoltaic systems and their profitability. For the economic analysis, the cumulative probability of positive Net Present Value (NPV) returns was obtained through deterministic simulations in all municipalities. Only the municipality of Pau dos Ferros-RN was chosen to perform 10,000 stochastic simulations, and its cumulative probabilities of positive NPV returns were obtained. In both models of photovoltaic technology analyzed and simulation logics, 100% of the NPVs were positive, indicating profitable cash flows in all scenarios. However, some municipalities obtained better results than others when the climate types favored sunny weather. Moreover, although all cases returned positive NPVs, the conventional model proved to be more economically attractive than BIPV system.

Keywords: NPV; Monte Carlo simulation; discounted cash flow; climate types; solar energy

1. Introduction

Society’s dependence on non-renewable resources is reflected in oil price fluctuation with companies considering any increase to be a threat to profitability. However, the effects of global warming have made society rethink and become aware of the impacts of prioritizing economic development and lifestyle witnessed in recent decades.

Theoretical frameworks and expert positions provide insights that improve the understanding of the need for sustainable development in the face of the exhaustion of natural resources [1].

Global energy availability will limit and shape the fate of future civilizations. Despite the serious environmental problems and the energy crisis faced, the world’s primary energy consumption of 5508.80 million tons of oil equivalent (Mtoe) in 1970 increased by 7676.68 Mtoe until 2018, when it reached 13,185.48 Mtoe, resulting mainly from fossil fuels and increased consumption [2]. With the trend of continuous increase in energy consumption, the use of fossil fuels is widely regarded as unsustainable due to the prospect.
of resource depletion and the increase in the concentration of greenhouse gases in the atmosphere [3].

The transition from the use of non-renewable resources to sustainable resources has technical constraints that prevent a gradual change [1]. One of the obstacles is the considerable cost increase of the energy supply to meet all economic processes. However, technological progress makes it feasible to implement other forms of energy, such as the use of increasingly cheaper solar cells [1]. The participation of renewable sources in energy matrices is favored by the increase in hydraulic, solar, and wind generation. In addition, due to an increase in the supply of black liquor and biodiesel, there will be a reduction in the supply of oil and derivatives and a reduction in the supply of natural gas, according to the Energy Research Company [4].

Renewable energy sources play a dual role: to mitigate global warming and to ensure energy security over the years [5]. Solar energy is widespread, is considered an important source of renewable energy, and, in the long term, will bring major contributions to society, such as security of energy supply and protection of the environment. Distributed generation of photovoltaic (PV) solar energy and solar water heating are benefits from the point of view of energy security [5].

The technological potential of PV energy integrates the solution of energy problems with social interests, environmental interests, and economic principles. Brazil is considered an ideal country for solar energy production due to various factors, including a large number of sunny days, ideal intensities of solar irradiation, and a large geographic area with these conditions. In addition to these factors, the costs of installing the equipment have been decreasing rapidly, which encourages and provides better energy use [6]. Brazilian solar electricity generation in 2018 was 3461 GWh, representing an increase of 316.1% compared to the previous year. The installed capacity in 2017 was 935 MW, while in 2018 there was an increase of 92.2%, reaching 1798 MW [4].

Distributed generation is any small-scale electrical generation technology that generates electricity in a location that is closer to customers than the central station generation. In addition, it is usually interconnected to the distribution system or directly connected to the customer’s installations [7]. Therefore, in this scenario of evolution, the National Electric Energy Agency created Normative Resolution 482/2012 [8], which regulates the criteria for the application of distributed generation, through micro- and mini-generation, as a way to introduce renewable energy source mechanisms in the Brazilian energy matrix.

This Resolution operates in Brazil through the consumed energy compensation system, called net metering, which consists of measuring the energy flow of the small generation consumer unit through bi-directional meters. Besides being a safety requirement of the system, this standardization encourages the incorporation of renewable energy sources into the Brazilian energy matrix [9].

Economically, PV technology has its insertion compromised due to the initial high investment. However, in the first decade of the 21st century the price dropped to between 3 and 5 USD/Wp for small buyers and between 2 and 4 USD/Wp for large buyers [5]. The costs for financing and the tax burden on micro-generation investments are directly related to the specific economic conditions of consumers in each Federative Unit. Sensitive analyses indicate that financial risk is still impacted by the incorporation of taxes such as the ICMS (Tax on Circulation of Goods and Services) and the PIS/Cofins (Social Integration Program and the Contribution to Social Security), in the case of Brazil [9].

In view of this, small-scale green electricity generation has become the focus of study of some researchers. The analysis of its economic feasibility supports the decision-making by investors, because the objective of any electric generation system is to achieve a positive cash flow [10]. Developing simulations of performance rate of PV models and tools is critical to economic decision-making.

In the Brazilian scenario, feasibility studies have been proposed, evaluating different perspectives and aspects, such as regulatory, tax exemptions and incentives, social and political issues, and isolated communities, and more recently, the use of energy storage
systems (ESS) has aroused interest. Distributed generation systems (DGs) were evaluated from an economic perspective considering tax exemptions [10]. In addition, economic analysis of the impact of regulatory changes to DGs, recently proposed by ANEEL, were carried out [9,11,12]. The viability of the PV generation considering social programs has also been evaluated [13,14] by programs such as “Light for everyone” (from Portuguese, Luz para todos) and “My house, my life” (from Portuguese, Minha casa, minha vida).

There is no regulation for ESS in Brazil so far, but studies on the use of technology have already been presented. The economic viability of PV systems with fuel cells and battery energy storage systems (BESS) in an isolated community in the Amazon region has already been evaluated, using the HOMER software [15,16]. A model for dimensioning an isolated PV system with BESS in a small rural property has already been presented [17]. Regarding the utility-scale, more recently, studies that evaluate the implementation of the use of storage in the Brazilian energy market have been carried out [18,19]. However, none of the studies presented above assess the economic feasibility of using BIPV technology.

Based on the studies presented, it is noted that the connection between performance and profitability of the PV system is influenced by the initial investment, maintenance processes, and several other factors [20]. Its profitability is assessed based not only on costs and revenues, but also on climatic particularities [21]. The analysis of the initial investment cost is the most recurrent factor in economic studies of photovoltaic energy, and is often considered the main parameter for determining financial viability [22]. In the specific case of building-integrated photovoltaic (BIPV) technologies, the development of research has made the useful life of these systems longer, with shorter payback time. This makes investing in the sector more profitable, especially in tropical regions, such as Brazil [23]. In addition, relevant research on the deployment of BIPV technologies in regions with high solar irradiance is scarce [24].

Thus, the objective of this study was to analyze deterministic and stochastic models of investments in two types of photovoltaic systems, one incorporated into the enterprise’s architecture (BIPV), and the other, the conventional one, in different Brazilian locations, covering the predominant climate types in the country.

This study can be seen as a successful case of the application of these methodologies in the evaluation of investments in BIPV technologies, and will contribute to the literature with regard to the development of future studies on the feasibility of applying this technology. Finally, the comparison between conventional and BIPV technologies, helps to demonstrate the current level of maturity of BIPV technology when compared to conventional technology, which is already consolidated in the market. Finally, in our literature review, no studies were identified that stochastically, through Monte Carlo simulation, assessed the economic feasibility of implementing BIPV technologies in Brazil.

2. Material and Methods

2.1. Locations and Object of Study

For the selection of locations to be compared, the criterion used was the Köppen–Geiger climatic classification [25], which is based on the distinction between climate types considering the characteristic vegetation of the locations, in addition to temperature and rainfall data [26]. In Brazil, it is possible to find three major climate types according to the Köppen–Geiger climate classification: tropical (A) in 81.4% of the territory, dry (B) in 4.9%, and temperate (C) in 13.7%. For better specificity, the symbols of the specific climate types are followed by two or three characters, which represent the distribution of rainfall and seasonal variation of temperature, respectively [27].

For the present study, one city was chosen for each specific climate type in Brazil, considering the average solar irradiation levels and the average monthly values of insolation. Information about the chosen locations is presented in Tables 1–3 and represented in Figure 1.
Table 1. Climate types of the analyzed cities according to the Köppen–Geiger climate classification.

<table>
<thead>
<tr>
<th>City</th>
<th>Climate Type</th>
<th>Denomination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manaus-AM</td>
<td>Af</td>
<td>Equatorial climate</td>
</tr>
<tr>
<td>Aracaju-SE</td>
<td>Am</td>
<td>Monsoon climate</td>
</tr>
<tr>
<td>Pau dos Ferros-RN</td>
<td>As</td>
<td>Tropical climate with dry season</td>
</tr>
<tr>
<td>Ouricuri-PE</td>
<td>BSh</td>
<td>Semi-arid climate</td>
</tr>
<tr>
<td>Bagé-RS</td>
<td>Cfa</td>
<td>Humid subtropical climate</td>
</tr>
<tr>
<td>Itaí-PR</td>
<td>Cfb</td>
<td>Temperate oceanic climate</td>
</tr>
<tr>
<td>São Simão-SP</td>
<td>Cwa</td>
<td>Humid subtropical climate with dry winter</td>
</tr>
<tr>
<td>São Thomé das Letras-MG</td>
<td>Cwb</td>
<td>Subtropical highland oceanic climate</td>
</tr>
</tbody>
</table>

Source: Adapted from IBGE [28] and Alvares et al. [27].

Table 2. Values of monthly mean solar irradiation (kWh/m²·day) in the analyzed cities.

<table>
<thead>
<tr>
<th>City</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manaus-AM</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.8</td>
<td>3.9</td>
<td>4.4</td>
<td>4.4</td>
<td>4.9</td>
<td>4.9</td>
<td>4.6</td>
<td>4.6</td>
<td>4.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Aracaju-SE</td>
<td>6.3</td>
<td>6.4</td>
<td>6.1</td>
<td>5.1</td>
<td>4.4</td>
<td>4.1</td>
<td>4.2</td>
<td>4.8</td>
<td>5.6</td>
<td>6.1</td>
<td>6.4</td>
<td>6.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Pau dos Ferros-RN</td>
<td>5.9</td>
<td>6.0</td>
<td>6.0</td>
<td>5.7</td>
<td>5.3</td>
<td>5.0</td>
<td>5.4</td>
<td>5.1</td>
<td>6.4</td>
<td>6.6</td>
<td>6.6</td>
<td>6.1</td>
<td>5.8</td>
</tr>
<tr>
<td>Ouricuri-PE</td>
<td>5.9</td>
<td>5.6</td>
<td>5.8</td>
<td>5.2</td>
<td>4.7</td>
<td>4.4</td>
<td>4.6</td>
<td>5.6</td>
<td>6.3</td>
<td>6.4</td>
<td>6.4</td>
<td>6.2</td>
<td>5.6</td>
</tr>
<tr>
<td>Bagé-RS</td>
<td>6.5</td>
<td>5.9</td>
<td>5.0</td>
<td>3.8</td>
<td>2.7</td>
<td>2.3</td>
<td>2.6</td>
<td>3.2</td>
<td>3.8</td>
<td>5.2</td>
<td>6.4</td>
<td>7.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Itaí-PR</td>
<td>5.5</td>
<td>5.3</td>
<td>4.6</td>
<td>3.8</td>
<td>3.1</td>
<td>2.7</td>
<td>2.9</td>
<td>4.0</td>
<td>4.1</td>
<td>4.6</td>
<td>5.6</td>
<td>5.7</td>
<td>4.3</td>
</tr>
<tr>
<td>São Simão-SP</td>
<td>5.6</td>
<td>5.9</td>
<td>5.1</td>
<td>4.8</td>
<td>4.1</td>
<td>3.8</td>
<td>4.0</td>
<td>4.9</td>
<td>5.0</td>
<td>5.5</td>
<td>5.6</td>
<td>6.0</td>
<td>5.0</td>
</tr>
<tr>
<td>São Thomé das Letras-MG</td>
<td>5.4</td>
<td>5.6</td>
<td>4.9</td>
<td>4.5</td>
<td>3.9</td>
<td>3.7</td>
<td>3.9</td>
<td>4.8</td>
<td>5.0</td>
<td>5.4</td>
<td>5.2</td>
<td>5.6</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Source: Adapted from Chigueru et al. [29] and Pereira et al. [30].

Table 3. Hours of average monthly insolation in the analyzed cities.

<table>
<thead>
<tr>
<th>City</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manaus-AM</td>
<td>124.7</td>
<td>79.7</td>
<td>135.4</td>
<td>113.2</td>
<td>126.9</td>
<td>181.8</td>
<td>224.1</td>
<td>228.2</td>
<td>197.9</td>
<td>162.3</td>
<td>119.2</td>
<td>114.7</td>
<td>150.7</td>
</tr>
<tr>
<td>Aracaju-SE</td>
<td>285.6</td>
<td>250.3</td>
<td>224.1</td>
<td>220.5</td>
<td>232.2</td>
<td>136.7</td>
<td>155.5</td>
<td>234.6</td>
<td>244.3</td>
<td>270.3</td>
<td>298.9</td>
<td>316.5</td>
<td>237.5</td>
</tr>
<tr>
<td>Pau dos Ferros-RN</td>
<td>292.9</td>
<td>199.3</td>
<td>206.9</td>
<td>237.0</td>
<td>275.3</td>
<td>240.7</td>
<td>215.8</td>
<td>275.2</td>
<td>316.0</td>
<td>307.7</td>
<td>316.3</td>
<td>294.3</td>
<td>264.8</td>
</tr>
<tr>
<td>Ouricuri-PE</td>
<td>255.0</td>
<td>192.2</td>
<td>220.3</td>
<td>225.8</td>
<td>240.8</td>
<td>166.3</td>
<td>151.6</td>
<td>260.6</td>
<td>276.3</td>
<td>309.2</td>
<td>281.8</td>
<td>285.7</td>
<td>239.6</td>
</tr>
<tr>
<td>Bagé-RS</td>
<td>176.0</td>
<td>226.7</td>
<td>215.9</td>
<td>171.2</td>
<td>107.2</td>
<td>152.6</td>
<td>165.2</td>
<td>189.8</td>
<td>232.3</td>
<td>264.2</td>
<td>241.8</td>
<td>258.5</td>
<td>193.4</td>
</tr>
<tr>
<td>Itaí-PR</td>
<td>172.0</td>
<td>122.7</td>
<td>139.0</td>
<td>109.3</td>
<td>83.3</td>
<td>168.2</td>
<td>187.7</td>
<td>177.8</td>
<td>146.5</td>
<td>171.6</td>
<td>162.4</td>
<td>177.7</td>
<td>151.5</td>
</tr>
<tr>
<td>São Simão-SP</td>
<td>227.1</td>
<td>151.4</td>
<td>204.7</td>
<td>221.2</td>
<td>208.4</td>
<td>244.5</td>
<td>240.3</td>
<td>216.0</td>
<td>221.9</td>
<td>244.3</td>
<td>187.2</td>
<td>158.9</td>
<td>210.5</td>
</tr>
<tr>
<td>São Thomé das Letras-MG</td>
<td>198.4</td>
<td>169.7</td>
<td>186.6</td>
<td>228.3</td>
<td>198.1</td>
<td>237.7</td>
<td>268.7</td>
<td>225.4</td>
<td>245.8</td>
<td>246.8</td>
<td>149.3</td>
<td>149.0</td>
<td>208.7</td>
</tr>
</tbody>
</table>

Source: Adapted from INMET [31].

The cities studied cover the predominant climate types in Brazil, as described in Table 1. The information in Tables 2 and 3 is the result of the compilation of data from the National Institute of Meteorology [31], the Brazilian Solar Resources Atlas [29], and the Brazilian Atlas of Solar Energy [30].

The practical focus of this study was related to the Serrote do Jatobá Tourist Complex (Complexo Turístico Serrote do Jatobá—CTSJ), a work of the city hall located in the rural area of Pau dos Ferros, state of Rio Grande do Norte, Brazil, with a total area of 247,987 m² and built area of 78,024 m². The location of the CTSJ is shown in Figure 2.
Figure 1. Location map of the analyzed cities in Brazil, within the corresponding climate types; Source: Adapted from IBGE [28] and Alvares et al. [27].

Figure 2. Location map of Pau dos Ferros-RN and the Serrode Jatobá Tourist Complex (CTSJ).
The proposed BIPV systems will be installed on the CTSJ parking cover and both were designed to meet the energy demand of 386 kWh/day. The BIPV system is used as a building element, replacing the structure’s roof with semi-transparent and frameless photovoltaic panels. The present study does not consider the saving with the construction material in the case of BIPV systems.

2.2. PV System Design

The performance parameters of a PV system are mainly influenced by the level of light intensity in the environment and the air temperature [32]. Thus, technical and economic planning is essential to evaluate the resulting energy, and one should be aware of the variation of inputs that affect energy production. The electricity produced is evaluated using Equation (1).

\[ P = \eta \times I_m \times A \]  

where \( P \) represents the generation capacity in kW; \( \eta \) is the efficiency of the PV module determined; \( I_m \) represents average daily local horizontal irradiance (kW/m\(^2\)), calculated based on local solar irradiance and daily insolation; and \( A \) is the module area (m\(^2\)).

To quantify the energy produced by the PV system, it is necessary to calculate the product of the power to be generated in Equation (1) by the amount of hours of insolation in a period of time, taking into account the losses that occurred, such as: accumulation of dust and dirt on the surface of the modules, shading, losses in inverters and cabling, and reduced efficiency by exposure to high temperatures [33]. A performance rate (\( \rho \)) of 81% was considered, similar to that defined by Elibol et al. [34]. Equation (2) defines this quantification.

\[ E = P \times h \times \rho \]  

where \( E \) is the amount of electricity produced (kWh); \( P \) is the electricity generation capacity (kW) defined by Equation (1), and \( h \) is the time of insolation (hours of full sun).

The \( E \) values obtained in Equation (2) were adjusted (\( E_{adj} \)) in Equation (3) [19], at a degradation rate (\( \varphi \)) of 1% [22], considering the service life of the equipment (\( n \)).

\[ E_{adj} = E(1 - \varphi)^n \text{(kWh)} \]

In this study, the economic feasibility analysis was performed considering probabilities related to PV production, expecting the conditions of irradiance levels, annual daily insolation, electricity tariffs, and equipment characteristics to play a prominent role in energy production.

2.3. Economic Analysis

Economic feasibility analysis serves as an aid in making decisions regarding the feasibility of an investment. Among the most common methods for analyzing financial statements is the net present value (NPV), which is based on forecasts of cash flows in base cases [35].

NPV is calculated by subtracting the cash outflows from the inflows, when all the flow is brought to the value of the currency at the present time, by applying the fixed discount rate. Negative NPV return demonstrates the inability to recover the cost of acquisition, while positive NPV indicates the feasibility of the investment [36,37]. NPV can be obtained from Equation (4) [38,39].

\[ \text{NPV} = \sum_{t=0}^{n} \frac{FV_t}{(1 + r)^t} - \text{investment} \]

where \( FV \) represents net cash flow in year \( t \); \( t \) means time in years; and \( r \) is discount rate.

However, the presence of uncertainties in cash flow represents risk factors to the result of NPV and is worrisome from the point of view of the consumer, who is usually not prepared to face the economic effect. Many variables involved in the process, including
values related to the production system, interest rates, project cost after incentives, and electricity tariffs, which are often used in projects assuming constant values, actually represent estimates that, depending on their accuracy, can quantify the NPV with a limited degree of certainty [40].

Through simulations it is possible to accommodate risks and uncertainties quantitatively in the evaluation of investment, and the Monte Carlo method is one of the most applicable. It is based on the repeated iteration of random numbers to obtain specific predictions of probabilistic models for problem solving, such as the case of the financial feasibility of the project considering the associated risks and uncertainties. In the simulation steps, a quantitative model is defined for the investment, considering all the relevant information of the variables through a statistical model. Next, the probability density functions (PDF) of each input variable are estimated and, from the results obtained, the simulation is analyzed and interpreted [41].

For the project’s investment to be considered feasible, the NPV must be greater than zero, so the probability of feasibility is characterized according to Equation (5).

\[ P_{NPV > 0}(x_1 \ldots x_n; r) = \int_{0}^{+\infty} PDF(\tilde{NPV}) d\tilde{NPV} \]  

(5)

where \( P_{NPV > 0} \) represents the cumulative probability of positive NPVs in the project; \( PDF(\tilde{NPV}) \) indicates the PDF of the NPVs in the project \( (\tilde{NPV}) \); and \( x_i \) represents the random variables of the project.

The rate of return on investment to consumers was estimated using the weighted average cost of capital (WACC), similar to that defined by EPE [42], of 8% p.a. The lower the WACC, the higher the value of the project, since the opportunity cost directly influences the discount rate, with respect to the investment risk [43,44].

2.4. Procedures Applied

The procedures carried out in this study comprise modeling and simulation methods for cash flow, considering the financial premises for a PV micro-generation project. First, the feasibility of the system was analyzed in eight Brazilian municipalities, according to the climate types in the Köppen–Geiger climate classification [25], with different levels of irradiation and hours of full sun, as observed in Figure 1 and Tables 1–3.

The methodology initially involved surveying the historical series of electricity tariff values charged by the concessionaires in each location. An increase of 1.05% p.a. of average readjustment was considered, consistent with the rate proposed by ANEEL, deflated. On the other hand, the monthly electricity produced was calculated based on Equations (1) and (2), using the values of solar irradiance levels and daily hours of insolation for each city, presented in Tables 2 and 3, respectively. The tariff values mentioned and the minimum power of the systems recorded for each municipality are shown in Table 4.

<table>
<thead>
<tr>
<th>City</th>
<th>Distributors</th>
<th>Tariff ( ^\dagger ) (R$/kWh)</th>
<th>Minimum Power of the System (kWp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manaus-AM</td>
<td>AmE</td>
<td>0.76</td>
<td>77.92</td>
</tr>
<tr>
<td>Aracaju-SE</td>
<td>Cercos</td>
<td>0.99</td>
<td>49.44</td>
</tr>
<tr>
<td>Pau dos Ferros-RN</td>
<td>Cosern</td>
<td>0.76</td>
<td>44.34</td>
</tr>
<tr>
<td>Ouricuri-PE</td>
<td>Celpe</td>
<td>0.82</td>
<td>48.99</td>
</tr>
<tr>
<td>Bagé-RS</td>
<td>CEEE-D</td>
<td>0.84</td>
<td>60.72</td>
</tr>
<tr>
<td>Irati-PR</td>
<td>Copel-DIS</td>
<td>0.82</td>
<td>77.49</td>
</tr>
<tr>
<td>São Simão-SP</td>
<td>CPFL, Paulista</td>
<td>0.75</td>
<td>55.78</td>
</tr>
<tr>
<td>São Thomé das Letras-MG</td>
<td>Cemig-D</td>
<td>0.94</td>
<td>55.27</td>
</tr>
</tbody>
</table>

\(^\dagger\) (Historical average of the last 10 years \(* ICMS\); Source: Adapted from ANEEL [45,46].

The investment quotations in the case studied were made by compiling quotes requested from specialized companies, referring to meeting the demand of 386 kWh/day.
This primary value accounts for all the costs that make up the photovoltaic equipment: solar panels, inverters, cables, protection systems, and fixing structure (in the conventional case). In the case of BIPV systems, the fixation system is not included since the existing parking structure will be used. After estimating the price of the system, it was multiplied by the factor of 0.5%, referring to Operation and Maintenance (O and M), as defined by the Brazilian Association of Electrical and Electronic Industry [47]. The average values obtained are shown in Table 5.

Table 5. Data used in the deterministic simulations of net present values (NPVs).

<table>
<thead>
<tr>
<th>Demand</th>
<th>BIPV</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel area (m²)</td>
<td>1.88</td>
<td>2.12</td>
</tr>
<tr>
<td>Panel efficiency (%)</td>
<td>15.0</td>
<td>19.8</td>
</tr>
<tr>
<td>Panel maximum power (Wp)</td>
<td>218.7</td>
<td>222.3</td>
</tr>
<tr>
<td>Investment (R$/kWp)</td>
<td>11,391.20</td>
<td>3659.57</td>
</tr>
<tr>
<td>Panel service life (years)</td>
<td>25</td>
<td>0.5%</td>
</tr>
<tr>
<td>O&amp;M (%investment/year)</td>
<td>0.5%</td>
<td>8%</td>
</tr>
<tr>
<td>WACC</td>
<td>8%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Tariff increment</td>
<td>1.05% p.a.</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

The simulations related to cash flow and identification of the respective distributions of values to obtain the NPV for each scenario were performed in two moments. First, the values of NPVs of all cities defined were obtained deterministically based on the data presented in Tables 4 and 5. Then, the Monte Carlo method with 10,000 simulations was applied only for the municipality of Pau dos Ferros-RN, with the aid of Crystal Ball® software, to compare the return of positive NPV probability for the two PV models, under the influence of stochastic variables represented in Table 6.

Table 6. Input data used in stochastic simulations of NPVs (only Pau dos Ferros—RN).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution</th>
<th>BIPV</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel area (m²)</td>
<td>Uniform</td>
<td>1.69</td>
<td>1.98</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>Triangular</td>
<td>12.20</td>
<td>15.00</td>
</tr>
<tr>
<td>Panel power (Wp)</td>
<td>Triangular</td>
<td>205</td>
<td>218.7</td>
</tr>
<tr>
<td>Demand (kWh/day)</td>
<td>Fixed</td>
<td>386</td>
<td>386</td>
</tr>
<tr>
<td>Service life (year)</td>
<td>Fixed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tariff increment</td>
<td>Triangular</td>
<td>0.54</td>
<td>0.61</td>
</tr>
<tr>
<td>Tariff (R$/kW)</td>
<td>Triangular</td>
<td>5830.65</td>
<td>11,591.20</td>
</tr>
<tr>
<td>Investment (R$/kWp) O and M (%)</td>
<td>Fixed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICMS</td>
<td>Fixed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend: Min—minimum value, MP—most probable value, Max—maximum value.

A triangular distribution can be used to insert uncertainty into the input parameters, as they represent human expertise in correctly judging the behavior of common variables in various practical situations [48–50]. Similarly, Antweiler and Muesgens [50] claim that the triangular function is a good trade-off between realism and complexity. Furthermore, the authors say that a triangular distribution provides a reasonable approximation of the variables, in which the minimum and maximum values are less likely than values closer to the average.

Still, it is important to mention that data related to the values and characteristics of photovoltaic systems were collected through budgets from real companies. The max, min, and more probable efficiency, power panel, and investment values refer, respectively, to the highest, lowest, and average values found among the analyzed models (manufacturers’ data.
and budgets). Regarding the panel area, a uniform distribution was assumed considering the values of sizes available and offered by the suppliers.

For the analyzed region, the minimum and maximum electricity tariffs charged by the concessionaires were considered, and the average of these values was adopted as the most likely. Finally, for the discount rate, a triangular distribution was defined, with minimum and maximum values of 7% and 20% per year, respectively. These percentages corresponded to the minimum obtainable returns from savings accounts in Brazil and the potential maximum returns from high-risk investments, respectively [11]. As the more probable value, we used the one recommended by EPE [42] for individual investments in energy, which is 8% per year.

2.5. Statistical Hypothesis Test

The method for comparison between the samples of the stochastic simulations was the t-test for two independent samples. For its application, the test in question requires that the samples meet the conditions of normality, homogeneity of variances, and independence [51].

The Shapiro–Wilk test was used to test the normality of the samples [52]. It should be run for each sample separately, in cases where they are independent. The significance level for the test was $\alpha = 0.05$ and the hypotheses were: $H_0$: The data follow normal distribution $\Rightarrow p$-value $> 0.05$ and $H_1$: the data do not follow normal distribution $\Rightarrow p$-value $\leq 0.05$.

The Levene test was adopted to confirm the homogeneity of variances, considering the distances of the observations from the sample means. For $p$-value $< 0.05$, the null hypothesis is rejected, where: $H_0: \sigma^2_1 = \sigma^2_2$ and $H_1: \sigma^2_1 \neq \sigma^2_2$ [53].

Once the conditions were met, the final method was applied to compare the difference between the sample means. For this, the following hypotheses were considered: $H_0$—mean of the NPVs of the BIPV = mean of the NPVs of the conventional system and, $H_1$—mean of the NPVs of the BIPV $\neq$ mean of the NPVs of the conventional system, and the hypothesis $H_0$ was rejected when $p$-value $< 0.05$ [51]. The test was performed using Minitab® software.

3. Results and Discussion

After performing the deterministic simulation for all selected locations, the NPV values were obtained for each of them. The results are presented in Table 7.

Some initial physical aspects, according to Table 5, differentiate the two models and influence the values obtained through the simulations. The first point is the factory default settings of the equipment, because the BIVP semi-transparent photovoltaic panels have smaller dimensions and lower efficiency compared to the conventional one. However, both reach similar power, allowing the BIVP to meet the requested demand even with a smaller area. The second point is the value of the investment per kWp, because the cost of a BIPV system is more than three times that of the conventional one.

As observed in Table 7, all simulations returned an estimate of NPV $> 0$. Despite the variations among the locations and among the two proposed models, all applications are considered feasible, according to the economic criterion of the NPV. In any case, in a comparison between them, the conventional model proved to be more accessible from the point of view of investment values, and with better levels of return.

As illustrated in Figure 3, an inverse quasi-proportionality was identified between the investment value and the NPV obtained. The largest investments occurred in the municipalities of Manaus-AM, Irati-PR, and Bagé-RS, and the smallest investments were found in Pau dos Ferros-RN, Ouricuri-PE, and Aracaju-SE. Regarding the values of NPV, the situation was reversed, with the highest values in Aracaju-SE, Pau dos Ferros-RN, and Ouricuri-PE, and the lowest returns in Irati-PR, Bagé-RS, and Manaus-AM, in this order. According to Rocha et al. [36], the value of the investment directly impacts the NPV result.
Table 7. Results of the deterministic simulations of NPV for the defined cities.

<table>
<thead>
<tr>
<th>City</th>
<th>Area (m²)</th>
<th>Investment (R$)</th>
<th>O and M (R$/year)</th>
<th>NPV (R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B C B C</td>
<td>B C</td>
<td>B C</td>
<td>B C</td>
</tr>
<tr>
<td>Manaus-AM</td>
<td>677.87</td>
<td>751.56</td>
<td>894,246.51</td>
<td>282,336.10</td>
</tr>
<tr>
<td>Aracaju-SE</td>
<td>431.03</td>
<td>477.49</td>
<td>567,428.36</td>
<td>179,151.39</td>
</tr>
<tr>
<td>Ouricuri-PE</td>
<td>427.23</td>
<td>473.21</td>
<td>562,278.17</td>
<td>177,525.35</td>
</tr>
<tr>
<td>Bagé-RS</td>
<td>527.87</td>
<td>586.69</td>
<td>696,783.93</td>
<td>219,992.20</td>
</tr>
<tr>
<td>Irati-PR</td>
<td>674.07</td>
<td>747.28</td>
<td>889,279.02</td>
<td>280,767.74</td>
</tr>
<tr>
<td>São Simão-SP</td>
<td>486.09</td>
<td>537.44</td>
<td>640,123.17</td>
<td>202,102.97</td>
</tr>
<tr>
<td>São Thomé das Letras-MG</td>
<td>489.89</td>
<td>543.86</td>
<td>645,773.27</td>
<td>203,886.85</td>
</tr>
</tbody>
</table>

Legend: B—BIPV; C—conventional.

Figure 3. Representation of the results of the deterministic simulations of the studied locations.

This dissimilarity between the values of investment in different cities has a direct relationship with their climatic particularities. The load and production of photovoltaic energy are affected by the local climate, including differences in air temperature and seasons [54]. The locations with the lowest investment values belong, respectively, to the climate types As, Am, and BSh, which are characterized by well-defined drought periods and relatively short rainy periods [27].

On the other hand, the largest investments are found in the climate types Af, Cfb, and Cfa, characterized by high rainfall and cloudiness throughout the year, which directly interfere in the amount of daily hours of sunshine and irradiance levels to which the panels are subjected [27]. This fact is confirmed when the Cwa and Cwb types are compared with Cfa and Cfb, respectively, because despite their general similarities, the former have a dry period that favors them with better PV generation data. It was also found that the ranking of investment values is equivalent to that of the means of daily insolation hours among the analyzed cities and the irradiance values, as observed in Tables 2 and 3.
Ascencio-Vásquez et al. [55] state that the highest electricity production occurs in places with high irradiation. They concluded that the unit capacity factor (UCF), which represents the percentage of annual time in which the photovoltaic system is operating, can reach more than 20% in locations with high irradiation and a large amount of sunshine hours. Tropical climates show UCFs between 16 and 18%, because, despite the high irradiation, they have rainy and cloudy periods throughout the year. In cloudy places, the values hardly exceed 14% [55].

Pranadi et al. [56] state that the level of receptivity to photovoltaic technology is mainly influenced by the initial value of the project. However, the project’s NPV is most significantly impacted by the cost of local electricity. Cui et al. [21] also identified that the price of electricity had the greatest influence on the increase in NPV, and these variables were directly proportional. This relationship and the good levels of solar energy certainly contributed to Aracaju-SE being considered the location with the best NPV.

However, the best returns of NPV are achieved with the greatest amount of electricity produced [21]. Climatic conditions can influence energy generation, to the point where places with higher tariffs generate lower returns, as occurred with the municipality of Pau dos Ferros-RN and the others. Rocha et al. [10] identified a similar event, where Petrolina-PE obtained better returns than Belém-PA and Uberaba-MG, even with lower tariff, due to its greater solar potential.

Similar case studies, carried out in Brazil, presented results in line with those found in this study. Branco and Affonso [57] concluded in their two cases, which differed from each other in terms of demand, that the NPV is always positive, confirming that both projects are economically robust and attractive. Sorgato et al. [58] analyzed the technical potential of the integration of a thin-film cadmium telluride (CdTe) BIPV system in a commercial building, in six Brazilian locations, and also obtained positive NPV values in all types and scenarios. Gholami et al. [59] proposed a method to establish and quantify, as much as possible, the social and environmental advantages of a BIPV system and import these values into economic analysis to measure their effects in a life-cycle cost analysis. In this scenario, the analysis performed found a positive NPV in the Brazilian cities analyzed.

The practical implications of these results reveal the different factors that impact the feasibility of implementing photovoltaic systems. Facility planning is case-specific and a holistic view of the situation must be taken. Although weather conditions directly affect electricity generation, the value of the local utility’s energy tariff has an important bearing on the return on investment. In addition, qualitative values must be considered, such as the visual impact and the feeling of well-being of the implanted models.

Regarding the application of stochastic simulations for the municipality of Pau dos Ferros-RN, 10,000 NPV values were returned for each of the PV installation models. As shown in Table 8 and Figure 4, in both cases the cumulative frequency and probability of positive NPV return are 100%, reaffirming the economic feasibility and solar potential of the site.

Table 8. Results of stochastic simulations of NPV for the municipality of Pau dos Ferros-RN.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean NPV (R$)</th>
<th>$P_{NPV&gt;0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIPV</td>
<td>3,070,653.92</td>
<td>100%</td>
</tr>
<tr>
<td>Conventional</td>
<td>5,083,210.02</td>
<td>100%</td>
</tr>
</tbody>
</table>

Based on the statistical treatment for comparing samples of simulated NPV values between the two suggested photovoltaic models, it was possible to affirm that the conventional is more profitable. A $p$-value of 0.000 was obtained through the two-sample t-test, so the null hypothesis, which establishes equality between the samples, was rejected. The mean value of the NPV of the conventional model was significantly higher than that of the BIPV model, with a difference of around 66%. Figure 5 shows the dispersion pattern of the samples.
Based on the statistical treatment for comparing samples of simulated NPV values was used. The sample of values of the conventional model has great dispersion, ranging from R$ 2,097,118.71 to R$ 9,874,294.74, with an average value of R$ 5,083,210.02. The BIPV sample has lower dispersion, with minimum of R$ 948,587.38 and maximum of R$ 6,596,273.94, with an average of R$ 3,070,653.92. Both have outliers. In any case, the results of the present study do not indicate unfeasible implementation of BIPV systems because the savings with the construction materials that would be used if the conventional model were not considered and the benefits of BIPV systems go beyond economic barriers and reflect the concepts of design, thermal control, and real-estate appreciation [60], which were not included in the objectives of this analysis.

4. Conclusions

Photovoltaic energy is seen internationally as a sustainable alternative to achieving energy security and mitigating climate change. Therefore, the number of solar installations has grown greatly in recent years. This prosperous scenario requires strategic planning to ensure that a favorable financial return is achieved for the investor, making the best use of locally available climate characteristics.

From the economic analyses performed in the present study, it was possible to verify that both proposed systems are feasible in all predominant climate types of Brazil. It was observed that there is a deep relationship between the peculiarities of each climate type...
and the results obtained. The municipalities with higher levels of irradiation and hours of daily insolation had higher values of electrical generation and, consequently, better returns of NPV with lower initial costs. These are found in locations corresponding to the climate types monsoon, tropical with dry season, and semi-arid, all in the Northeast region of Brazil.

However, with this research it was observed that it is not only climatic factors interfere in the return on investment. The values of local electricity tariffs play a key role in the value of the NPV. Locations with lower levels of solar irradiation still proved to be viable, despite the greater investment required, due to the compensation of the higher tariffs charged.

The municipalities of Pau dos Ferros-RN and Aracaju-SE have the lowest investment value and the highest simulated NPV, respectively. Manaus-AM and Irati-PR have the highest investment and lowest NPV, in this order. In any case, the conventional model was more attractive than the BIPV model, from the point of view of application and return values.

Regarding the stochastic simulations in the municipality of Pau dos Ferros-RN, the results remained equivalent to the previous ones. Both systems obtained 100% cumulative probability of NPV > 0. The conventional model continues to have more attractive values than the BIPV model, with a significantly higher mean of NPV. Although it does not have the best results, the BIPV model is still considered feasible for the studied locations, with positive values in all NPVs calculated. In addition, its benefits go beyond monetary barriers, acting in the areas of thermal control and design and even in real estate appreciation, due to its architectural differential.

Despite reaching economic viability, a statistically significant difference was identified between the NPV results of conventional and BIPV technologies. However, the advantages of BIPV technology must be recognized, in particular, the greater areas for installation and the reduction of construction material costs. It can be seen that the main barriers to BIPV technologies are technical and financial. In this way, public policies to encourage this technology necessarily involve a greater capacity for research resources, seeking its evolution with consequent cost reduction, in addition to better financing conditions and tax exemptions.

As a suggestion for future studies, researchers could consider savings with construction materials, lighting, and cooling and/or heating, in specific environments due to integration of photovoltaic systems to the respective facades and to other climatic particularities such as temperature and wind speed. In addition, consideration could also be given to different types of materials in the composition of the photovoltaic cells used, as well as the energy payback time (EPBT), the greenhouse gases payback time (GPBT), and the return at the end of the equipment’s useful life, through the sale of recyclable materials.


**Funding:** The authors are grateful for the support provided by the National Council for Scientific and Technological Development—CNPq Brazil (Grants 306783/2018-5, 308021/2019-3, 302751/2020-3, and 308753/2021-6), the Federal University of Paraiba (Grants PVK13163-2020 and PVK13150-2020), the Coordination for the Improvement of Higher Education Personnel—CAPES Brazil (Process No. 88887.518299/2020-00), the Paraiba State Research Foundation—FAPESQ Brazil (Process No. 3060/2021); the Minas Gerais Research Funding Foundation—FAPEMIG Brazil (Grant No. APQ-00378-21); and the Czech Science Foundation—Czech Republic (Grant No. 22-19617S).
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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