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SIZE OF PHOTOVOLTAIC AND HYBRID SYSTEMS, CASE STUDY IN ITAJUBÁ, MINAS GERAIS

Daiane Cristina de Souza

Christian Jeremi Coronado Rodriguez

Universidade Federal de Itajubá – UNIFEI, Av. BPS 1303, Itajubá, MG, Brasil

daianetreira@hotmail.com

christian@unifei.edu.br

***Abstract.** Hybrid systems are those that use two or more sources of energy for electricity generation, that is, they are able to use simultaneously two types of resources, for example, solar and wind energy. The use of this mechanism has been widely used due to the need of using alternative and renewable forms of energy, besides of the efficiency in integrating new or traditional systems. One of the main characteristics of this system is the possibility of complementation: a photovoltaic component for periods when the wind does not blow or blow at low speed, and a wind turbine for the rainy or cloudy periods. Thus, the objective of this work is to perform a technical and economic analysis of the implantation of a photovoltaic an a solar-wind hybrid system to cover the electric power demand of a student residence in Itajubá, Minas Gerais, Brazil, and analyze which system is most economically attractive. The methodology used to develop this work will be based on data collect of solar radiation and wind speed in the chosen town, also in the system sizing, and the technical and economic feasibility for its implementation. The economic analysis includes the calculation of IRR, NPV and Payback, taking into account the sale of surplus electric energy using the system of compensation of electric energy credits according to resolution 482/2012 of ANEEL. The photovoltaic system was the most economically viable due mainly to the local wind profile.*

Keywords: energy, hybrid systems, photovoltaic system, complementation

1. INTRODUCTION

After the first oil crisis in 1973, public agencies began to be aware of the scarcity and finitude of energy resources. Alongside this, the demand for electricity from developed and underdeveloped countries grows exponentially, and in the last decades the world has begun to worry about the environmental consequences of its current mode of development, characterized by consumer behavior (LOPES, 2013). Thus, searches for energy sources that do not harm the environment have expanded significantly, encouraging the development of alternative energy technologies. In addition, it is necessary to deploy renewable and alternative sources in the global energy matrix, in order to reduce the dependency of the countries on fossil fuels, which are non-renewable and polluting sources.

The concept of clean source of energy does not imply that the use of these resources does not generate environmental impacts, but rather they cause changes of lesser intensity, since the exploration of any source of energy modifies the environment. In general, renewable energy sources are renewable, except for thermonuclear energy. This source, although the constant risk of accidents, does not emit pollutants or toxic substances during normal operation, producing less impact than others (VILLALVA, 2015).

Although they have reduced participation in the world energy matrix, the use of renewable and alternative sources has been expanding in several countries and has played an important role in the elaboration of public policies and private investments. Thus, these sources are already considered mature and, due to the increase in the scale of use, the costs associated with the generation of energy are decreasing.

Solar and wind power are very promising since they are widely available all over the world and their exploration is still small, having great potential for expansion. Brazil is one of the most privileged countries when the subject is clean and renewable sources of energy, mainly due to its great territorial area and climate.

Wind energy has been growing in the country in recent years, driven by the Proinfa (Incentive Program for Alternative Sources of Electric Energy) created by the federal government, with the implementation of power plants in some regions, mainly in the Northeast and South. Besides this use, this resource can also be applied to small projects. Photovoltaic solar energy is even more incipient than wind energy in Brazil, although having more regularity in the supply of electric energy and can be implemented around all the country. Brazil presents excellent daily sunshine averages, much higher than those presented by Germany, the country that uses this resource the most. In addition, solar and wind energy can be applied to complement the national energy matrix, based on hydraulic energy, avoiding the use of thermoelectric plants that have a high generation cost and emission of pollutants.

In this way, this work has the objective of analyzing technically and economically the implantation of photovoltaic and solar-wind hybrid systems in a student residence in Itajubá, Minas Gerais. This form of decentralized generation provides better use of electric energy, since it dispenses the use of transmission and distribution lines (generation at the point of consumption), in addition to contributing to the reliability of the national electricity system.

2. METHODOLOGY

The methodology used for the development of this work can be divided into three stages: sizing the photovoltaic system, sizing of the hybrid wind-photovoltaic system and economic analysis, which will be detailed below. All the equations used were obtained in Coronado (2018).

2.1 Sizing of the photovoltaic system

The residence selected for the case study is located at 879 Prefeito Tigre Maia Street, in the town of Itajubá – Minas Gerais. There are 10 students from the Federal University of Itajubá in the house that contains six bedrooms, a living room, a kitchen, two bathrooms with electric shower and a garage.

Firstly, the energy demand (E_{dem}) of the residence was calculated from the average consumption of the last twelve months, contained in the most recent bill of light, resulting in a value of 226 kWh. The class of the selected installation is two-phase low-voltage residential, whose cost of electricity availability, that is, the minimum amount paid in the light bill, is equivalent to 50 kWh and, therefore, it is not necessary to account this amount in the design of the photovoltaic system. Thus, considering the cost of availability, an average demand value of 176 kWh was used as a reference for dimensioning the photovoltaic panels. For calculation purposes, the system design was made for 180 kWh.

In order to obtain the radiation data of the selected site, the software SWERA (Solar Energy Resource Assessment and Wind Energy) was used. This software is managed by the Division of Technology, Industry and Economics (DTIE) of the United Nations Environment Program (UNEP) and gathers datasets of solar and wind energy resources, as well as analysis tools from various international organizations.

SWERA provides annual and monthly solar irradiance values, and in the present work the average annual irradiation of 5.598 kWh/m² was used to perform the calculations.

The design of the photovoltaic system was made considering the technical specifications of the 260 W polycrystalline solar panel of Canadian Solar, shown in Fig. 1.

ELECTRICAL DATA STC*			
CS6P	260P	265P	270P
Nominal Max. Power (P _{max})	260 W	265 W	270 W
Opt. Operating Voltage (V _{mp})	30.4 V	30.6 V	30.8 V
Opt. Operating Current (I _{mp})	8.56 A	8.66 A	8.75 A
Open Circuit Voltage (V _{oc})	37.5 V	37.7 V	37.9 V
Short Circuit Current (I _{sc})	9.12 A	9.23 A	9.32 A
Module Efficiency	16.16%	16.47%	16.79%

Figure 1. Technical specifications of 260 W solar panel (*CanadianSolar*, 2017).

The area of the panel was obtained through the dimensions of length and width included in the catalog, which resulted in 1,608 m².

From the maximum nominal power (P_{max}) and area (A) of the panel, it was possible to calculate the efficiency of the module (η) through Eq. (1) in order to verify the value presented in the catalog.

$$\eta = \frac{P_{max}}{10 \cdot A} \quad (1)$$

The calculated efficiency was 16.16%, as presented in the manufacturer's catalog.

The energy produced daily (E_{prod}) by each panel was obtained by Eq. (2), using the values of solar irradiation (I), area (A) and efficiency of the module (η).

$$E_{prod} = I \cdot A \cdot \eta \quad (2)$$

The value found was 1.45 kWh/day, and the panel produces 43.64 kWh per month.

Thus, through Eq. (3), the number of photovoltaic panels (N°_{panels}) was calculated from the monthly energy produced per panel (E_{prod}) and energy demanded by the system (E_{dem}).

$$N^{\circ}_{panels} = \frac{E_{dem}}{E_{prod}} \quad (3)$$

Since number obtained through Eq. (3) was 4.12, it was necessary to round this value to the next whole number. Thus, five photovoltaic panels of 260 W are necessary to supply the energy demand of the residence. These modules will be installed in series, forming a string.

After obtaining the number of panels, the next step is to select the inverter. For this, the maximum input voltage and the power of the equipment must be considered. Through the short circuit voltage ($V_{OC, panel}$), the number of panels (N°_{panels}) and adopting a safety factor of 10%, the total open circuit voltage of the string ($V_{OC, string}$) was calculated by Eq. (4).

$$V_{OC, string} = N^{\circ}_{panels} \cdot V_{OC, panel} \cdot 1,1 \quad (4)$$

The total open circuit voltage found for the string was 206.25 V.

In addition, the temperature coefficient for the open circuit voltage of the panel, which is shown in Fig. 2, should be considered.

TEMPERATURE CHARACTERISTICS	
Specification	Data
Temperature Coefficient (Pmax)	-0.41 % / °C
Temperature Coefficient (Voc)	-0.31 % / °C
Temperature Coefficient (Isc)	0.053 % / °C
Nominal Module Operating Temperature (NMOT)	43±2 °C

Figure 2. 260 W solar panel temperature coefficients (*CanadianSolar*, 2017).

From the temperature coefficient of the open circuit voltage (TC_{Voc}) and the minimum temperature (T_{min}) of the city in which the system will be installed, the percentage variation of the voltage (PVV) was calculated through Eq. (5). For this calculation it was admitted that the minimum temperature of Itajubá is not lower than 0 °C.

$$PVV = (25 - T_{min}) \cdot TC_{VOC} \quad (5)$$

The percentage voltage variation obtained was 7.75%, which means that the $V_{OC, string}$ previously found can reach 222.23 V. The maximum input voltage of the inverter, therefore, must be greater than this value.

Finally, the maximum power of the string ($P_{max, string}$) was calculated from the maximum nominal power (P_{max}) and the number of panels (N°_{panels}), according to Eq. (6).

$$P_{max, string} = P_{max} \cdot N^{\circ}_{panels} \quad (6)$$

The maximum power of the string obtained was 1.3 kW. In this way, the power of the selected inverter must be equal to or greater than this value.

For the voltage and power parameters obtained, the Galvo 1.5-1 inverter from Fronius was selected. This equipment has the maximum power of 1.5 kW and maximum input voltage of 420 V, thus meeting the needs of the system.

2.2 Sizing of wind-photovoltaic hybrid system

The hybrid system, like the photovoltaic, will be sized to meet a demand of 180 kWh / month. As the starting point for this project, it was considered an installation formed by three photovoltaic panels of 260 W, and the energy deficit generated by small wind turbines.

From the number of photovoltaic panels and the energy produced by the 260 W panel, calculated previously by Eq. (2), was obtained a total electricity generation of 130.93 kWh/month. Given that the system will be calculated for

180 kWh/month, there is a deficit of 49.07 kWh/month, this being the minimum amount to be generated by wind turbines.

For the selection of wind turbines, it is necessary to consider the wind speed at the place where it will be installed, the number of daily hours of wind and the number of days per month. The parameters used for the design of this system are presented hereafter.

- Local wind speed: 5 m/s;
- Number of hours per day of wind (h_{day}): 3 hrs/day;
- Number of days per month (d_{month}): 30 days/month.

Wind speed in the city of Itajubá was obtained through the Atlas of Brazilian Wind Potential (2011).

From the power curve of a wind turbine and the parameters mentioned above, it is possible to calculate the monthly amount of energy generated and, thus, to verify if the analyzed wind turbine is able to supply the system demand. Figure 3 shows the power curve of a 1000 W wind turbine from *Energybras* and, given that the wind speed at the site where the system will be installed is 5 m/s, the approximate power that the turbine produces at this speed is obtained.

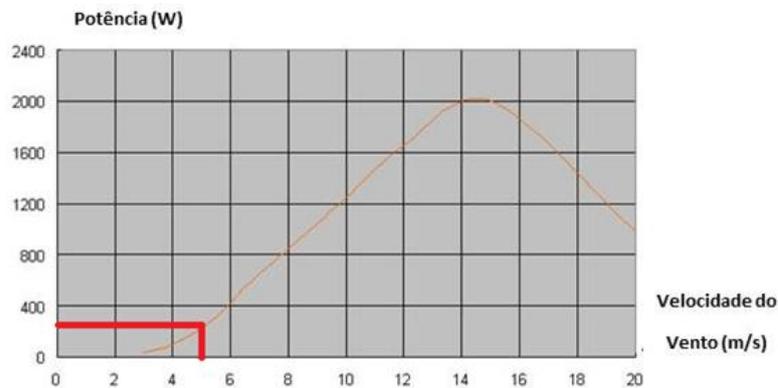


Figure 3. Power curve of the 1000 W wind turbine (*Energybras*, 2017).

Analyzing Fig. 3, it can be seen that the power of the wind turbine at a speed of 5 m/s (P_{speed}) is approximately 250 W.

Using Eq. (7) it is possible to calculate the energy produced monthly by the wind turbine ($E_{prod-windturbine}$).

$$E_{prod-windturbine} = P_{speed} \cdot h_{day} \cdot d_{month} \quad (7)$$

The monthly energy produced by the wind turbine is 22.5 kWh. Thus, it is noted that only one wind turbine is not sufficient to supply the remaining energy demand of the residence. It is necessary, therefore, the use of three wind turbines, totalizing in a monthly production of 64.5 kWh. In this way, the hybrid system consisting of three 260 W photovoltaic panels and three 1000 W wind turbines, results in an energy surplus of 18.4 kWh/month, which would be injected into the grid. The selected wind turbines are of the H3.1 brand of the *Energybras* brand.

After obtaining the number of panels and wind turbines that will constitute the hybrid system, the inverters must be selected. It is important to emphasize that photovoltaic generation is given in direct current, while wind generation in alternating current, thus, there is an inverter for each system. The *Energybras* selected wind turbines are already equipped with an inverter, and the selection is not necessary.

On the other hand, the selection of the inverter for the panels was done in a way analogous to the one realized for the exclusively photovoltaic system. From Fig. 1, the V_{OC} of the 260 W photovoltaic panel is 37.5 V and, through Eq. (4), which already considers a safety factor of 10%, the maximum voltage of the string was obtained, whose value is 123.75 V.

The voltage percentage variation of 260 W panel, already calculated through Eq. (5), is 7.75%. Thus, the V_{OC} , string can reach 133.34 V. In addition, through Eq. (6), the maximum power of the string was calculated, whose obtained value was 780 W. In this way, the selected inverter must have maximum voltage of input and power greater than the values found.

Due to the difficulty of finding 1 kW inverters with maximum input voltage higher than the system, the Galvo 1.5-1 inverter from Fronius was selected, with a power output of 1.5 kW and a maximum input voltage of 420 V.

2.3 Analysis of economic viability of systems

In order to analyze the economic viability of the dimensioned systems, an analysis of the dynamics of the electric energy compensation system was made, according to Normative Resolution 482 (ANEEL, 2016). CEMIG (Minas Gerais Energy Company) is the distributor responsible for the supply of electricity in the city of Itajubá and the value of the biphasic voltage tariff used for calculations was R \$ 0.8247577. In addition, for this type of voltage, the cost of energy availability is equivalent to the value, in reais, of 50 kWh. The results obtained through this analysis will be detailed in the next section.

The annual savings provided by the installation of the photovoltaic and hybrid projects, obtained through the electric energy compensation system, were the values used as input for the calculation of the economic analysis of its respective system. The initial investments of each facility were estimated at current market prices. In addition to the annual savings and the initial investment, other parameters were considered for the economic analysis of both systems, which are presented hereafter.

- Shelf life: 25 years;
- Inflation: 10%;
- Minimum Attractiveness Rate (MAR): 10%;
- Administrative expenses: 5%;
- Taxes: 30%;
- Interest: 7%;
- Amortizations: 20 years;
- Financing time: 3 years.

3. RESULTS

The following are the calculations made to obtain the annual savings of the photovoltaic system. The analysis was performed according to the electric energy compensation system, and the compensation of energy credits was made in a way that, when possible, the consumer pays only the cost of availability.

Table 1 presents the results obtained in this analysis for the system consisting of five panels of 260 W.

Table 1. Dynamics of electricity compensation of the photovoltaic system.

Month	Consumption (kWh)	Generation (kWh)	Accumulated credits (kWh)	Invoice without the panels	Invoice with the panels	Difference between invoices
January	11	218	207	R\$ 41.24	R\$ 41.24	R\$ 0.00
February	0	218	425	R\$ 41.24	R\$ 41.24	R\$ 0.00
March	103	218	540	R\$ 84.95	R\$ 41.24	R\$ 43.71
April	506	218	302	R\$ 417.33	R\$ 41.24	R\$ 376.09
May	277	218	293	R\$ 228.46	R\$ 41.24	R\$ 187.22
June	341	218	220	R\$ 281.24	R\$ 41.24	R\$ 240.00
July	222	218	220	R\$ 183.10	R\$ 41.24	R\$ 141.86
August	182	218	256	R\$ 150.11	R\$ 41.24	R\$ 108.87
September	321	218	203	R\$ 264.75	R\$ 41.24	R\$ 223.51
October	295	218	176	R\$ 243.30	R\$ 41.24	R\$ 202.07
November	290	218	154	R\$ 239.18	R\$ 41.24	R\$ 197.94
December	165	218	207	R\$ 136.09	R\$ 41.24	R\$ 94.85
					Total:	R\$ 1,816.12

As mentioned earlier, the compensation of energy credits was done in such a way that, wherever possible, the consumer pays only the cost of availability, that is, the cost of 50 kWh. From Table 1 it can be observed that in the first three months the consumption was lower than the generation of the photovoltaic panels, accumulating credits, which is given by the difference between the amount of energy generated and consumed added to the credits that had of the previous month.

In April consumption exceeded what was generated by the panels, being necessary the use of credits accumulated in the previous months. Making the difference between what was consumed and generated, it is verified that "lack" 288 kWh. As the minimum to pay is the equivalent of 50 kWh, only 238 kWh of the previously accumulated credit

(540 kWh) is deducted, leaving, therefore, 302 kWh. In this way, the consumer pays the minimum. The same logic is maintained throughout the filling of the table.

The invoice without modules is given by the multiplication of consumption by the value of the tariff and the invoice with modules, in this case, was the cost of availability. The last column represents the difference between the values of the invoices without and with panels and the total is the value that would be saved during one year due to the implantation of the photovoltaic system.

The initial investment of the system, estimated from current market data, is R\$ 10,000.00. Thus, considering this value, the annual savings of R\$ 1,816.12 and the other parameters previously mentioned in the methodology, the economic analysis of the photovoltaic project was made. Table 2 presents the results of IRR, NPV and Payback for the case of 100% of own funds, while Fig. 4 shows the behavior of the IRR in relation to the value of the financing.

Table 2. Economic results of the photovoltaic system.

IRR	21.96%
NPV	R\$ 18,725.21
Payback	5.9 years

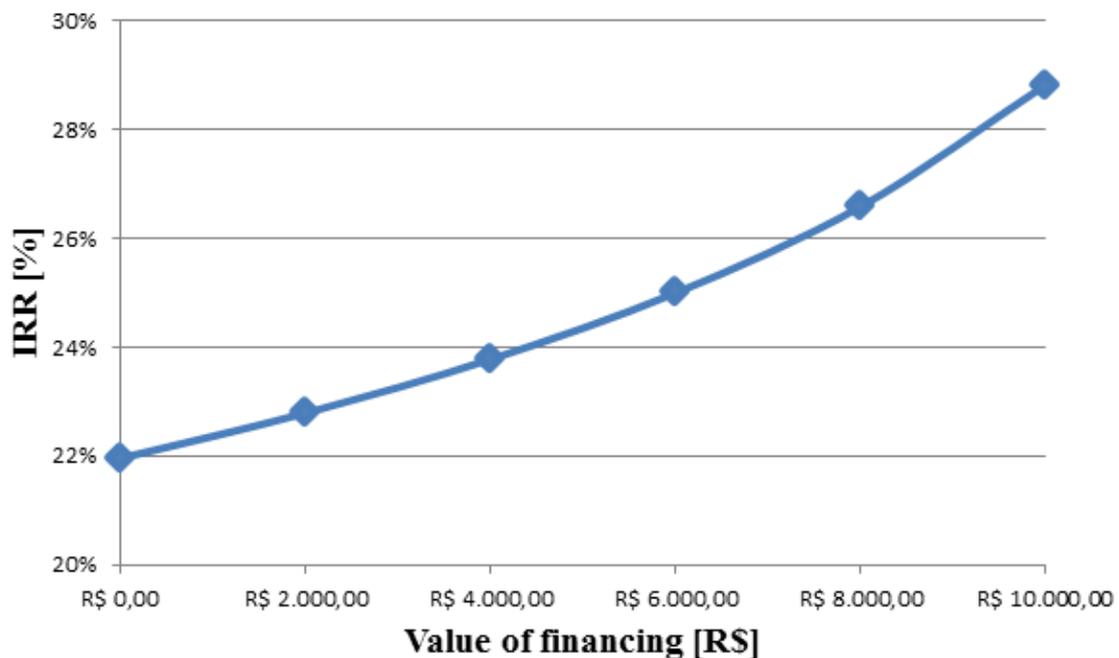


Figure 4. Ratio of the IRR to the value of financing for the photovoltaic system.

By analyzing the obtained results, it is concluded that the project is economically feasible, since, for both the case without financing and those with the bank's assistance, it has an IRR greater than MAR and positive NPV.

In addition, from Fig. 4 it is possible to perceive that the higher the value of the financing, the more advantageous is the project. This behavior occurs because of the low amount of interest charged on this type of project.

The economic analysis of the hybrid system was performed in an analogous way to the exclusively photovoltaic system. Table 3 presents the dynamics of electric energy compensation for the system consisting of three 260 W photovoltaic panels and three 1000 W wind turbines.

Table 3. Dynamics of electric energy compensation for the hybrid system.

Month	Consumption (kWh)	Generation (kWh)	Accumulated credits (kWh)	Invoice without the panels	Invoice with the panels	Difference between invoices
January	11	198.4	187.4	R\$ 41.24	R\$ 41.24	R\$ 0.00
February	0	198.4	385.9	R\$ 41.24	R\$ 41.24	R\$ 0.00
March	103	198.4	481.3	R\$ 84.95	R\$ 41.24	R\$ 43.71
April	506	198.4	223.7	R\$ 417.33	R\$ 41.24	R\$ 376.09
May	277	198.4	195.2	R\$ 228.46	R\$ 41.24	R\$ 187.22
June	341	198.4	102.6	R\$ 281.24	R\$ 41.24	R\$ 240.00
July	222	198.4	102.6	R\$ 183.10	R\$ 41.24	R\$ 141.86
August	182	198.4	119.0	R\$ 150.11	R\$ 41.24	R\$ 108.87
September	321	198.4	46.4	R\$ 264.75	R\$ 41.24	R\$ 223.51
October	295	198.4	0	R\$ 243.30	R\$ 41.35	R\$ 201.96
November	290	198.4	0	R\$ 239.18	R\$ 75.52	R\$ 163.66
December	165	198.4	33.4	R\$ 136.09	R\$ 41.24	R\$ 94.85
					Total	R\$ 1,781.72

Analyzing Table 3 it is possible to notice that until the month of March credits were accumulated, which were being discount in the following months. It can be noticed that the accumulated energy between the months of June and July does not change, although the consumption is greater than the generation. This is because the difference between consumption and generation is less than 50 kWh.

In the month of October it is noticed that approximately 97 kWh were consumed more than the energy generation of the panels. As there was only 46.4 kWh of accumulated credit, it was not possible to make the invoice only the cost of availability (50 kWh), the invoice being, therefore, a consumption of 50.1 kWh. As a result, the accumulated credits of the residence have ceased.

In November the energy consumed was again higher than the generation. Thus, the value of the invoice refers to the difference between consumption and generation, that is, 91.6 kWh, since there were no accumulated credits. Finally, in December, energy production exceeded consumption, causing new credits to be generated and resulting in an invoice equivalent to the minimum value. Through this analysis and making the difference between the values of the invoices without and with the hybrid system, we have that the annual savings is R\$ 1,781.72.

For the economic analysis of the system consisting of three photovoltaic panels and three wind turbines of 1000 W was considered an initial investment of the project of R \$ 22,900, an annual savings of R \$ 1,781.72 and the other parameters already mentioned in the methodology. Table 4 presents the results of IRR, NPV and Payback considering that the investment is made without financing, that is, 100% own funds. In addition, an analysis was made of the behavior of the IRR in relation to the financing value, which is presented in Fig. 5.

Table 4. Economic results of the hybrid system.

IRR	10.73%
NPV	R\$ 1,567.02
Payback	10.2 years

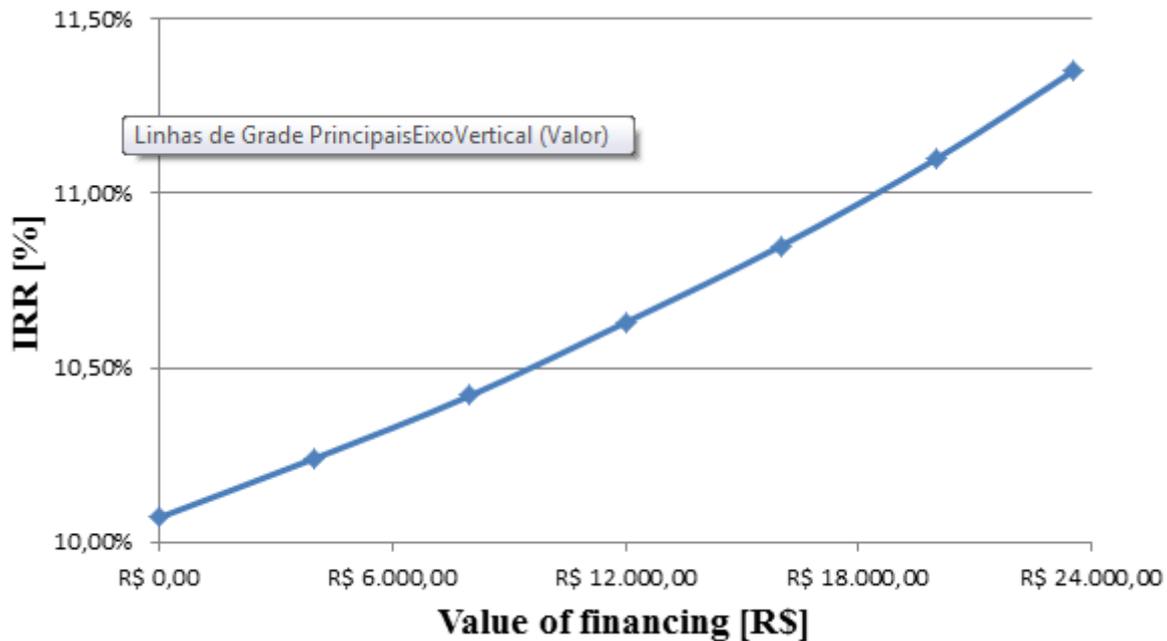


Figure 5. Ratio of the IRR to the financing value for the hybrid system.

From the results, it is noticed that the hybrid project is economically feasible, since it presents IRR greater than MAR and NPV positive. In addition, due to low interest rates, it can be seen from Fig. 5 that increasing the value of financing makes the project more attractive.

When comparing the hybrid system and the photovoltaic system, it is verified that the latter has better economic performance, since it has significantly lower initial investment and greater annual savings. In this way, the alternative with more benefits for the residence analyzed is the implantation of photovoltaic panels of 260 W.

Photovoltaic systems, in general, stand out when compared to the hybrid systems by several factors. This sector of photovoltaic energy is more expanded and consolidated in the market, mainly in small systems, with lower initial cost of investment. In addition, the solar resource has greater availability than the wind resource in the analyzed site, because the speed and the number of daily hours of wind are low.

4. CONCLUSION

From the results of the research, it is concluded that the photovoltaic system is economically feasible, having IRR of 21.96%, NPV of R\$ 18,725.21 and can be fully paid in less than six years. In addition, it is possible to finance partially or totally the cost of the system, since this alternative also presented attractive results.

The hybrid system also resulted in an economically viable project, with IRR of 10.73%, NPV of R \$ 1567.02 and Payback of just over ten years. Similar to the photovoltaic system, for the hybrid the partial or total financing of the initial investment showed an improvement in the IRR, as a consequence of the low interest rate.

When comparing the two systems, it is concluded that the photovoltaic project is more economically attractive for the residence analyzed, since the IRR and NPV of this project are superior to the hybrid system. This result is due in large part to the profile and speed of the wind at the site and the greater diffusion of the photovoltaic sector in the market, which reduces the cost of this technology.

5. ACKNOWLEDGEMENTS

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