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TECHNICAL AND ECONOMIC FEASIBILITY OF OFF-GRID PHOTOVOLTAIC SYSTEMS FOR IRRIGATION

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KEYWORDS

solar power, economic indicators, off-grid, water pumping.

ABSTRACT

In rural areas, the electricity supply is affected by problems such as low quality and limited access in some regions. The use of renewable sources, with decentralized generation, can offer an alternative to the existing scenario. The objective of this work is to perform a technical and economic analysis of off-grid photovoltaic systems, without energy storage, intended for irrigation. Photovoltaic systems from different irrigation systems were sized, with power ratings from 0.736 to 29.44 kW. Their technical feasibility was determined based on the energy supply period and the availability of solar radiation as restriction variables. Economic feasibility was determined by the indicators of net present value (NPV), internal rate of return (IRR), benefit/cost ratio (B/C) and profitability index (PI). Feasible operation was found for irrigation systems with motors up to 11.04 kW; however, for systems that required higher powers, the number of operating hours available was less than the minimum required. NPV, IRR, B/C and PI showed increasing values as a function of increasing power. Thus, off-grid photovoltaic systems without energy storage are technically and economically feasible for systems with power of up to 11.04 kW.

INTRODUCTION

The agricultural sector is constantly undergoing various modernization processes, and there is an increasing demand for energy as a result. Irrigation is one of the sectors giving rise to increasing demand for either fossil fuels or electricity (Mantri et al., 2020).

Problems related to environmental issues (Ridzuan et al., 2020) and increases in fuel and electricity costs, which vary continuously over time (García et al., 2019), have stimulated the adoption of alternative energy sources. According to Kirchner et al. (2019) and Torres et al. (2019), the energy used in conventional sprinkler irrigation systems represents approximately 15% of the costs related to irrigation.

Renewable energy sources have economic and environmental advantages over the use of fossil fuels (Jebli & Youssef, 2017), which has driven an increase in their use (Rizi et al., 2019) and a reduction in the dependence on grid electricity and the of generation through fossil fuels for irrigation systems (López-Luque et al., 2015; Reca et al., 2016).

In Brazil, advances have been made in this sector due to the inclusion of solar power into the energy matrix and the introduction of solar energy auctions (Sampaio & González, 2017). According to the Brazilian Association of Photovoltaic Solar Energy (ABSOLAR, 2021), a 68% increase in the solar power plants installed in Brazil was expected in 2021 compared to the previous year, representing an increase of approximately 5 GW.

The main application of solar systems in the agricultural sector is for irrigation in areas where there is a shortage of electricity (Kumar et al., 2020), or as a sustainable alternative, especially in areas with high solar potential. This can provide an adequate energy solution, as the increase in water demand is typically related to increased insolation (Haddad et al., 2015), and offers potential for the social and economic development of several regions due to the use of pumping systems (Benghanem et al., 2018).

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An off-grid photovoltaic system without battery storage can provide electricity for applications such as water pumping to isolated areas (Rezk, 2016). However, there is a dependence on weather conditions, meaning that the amount of water that can be pumped changes throughout the day depending on the intensity of solar radiation on the photovoltaic panel (Sontake & Kalamkar, 2016), which is the biggest disadvantage of this technology (García et al., 2019).

The use of solar power for pumps is more economical than other energy sources, as it involves only the cost of installation. For this reason, this approach has become competitive for use with irrigation systems (Kumar et al., 2020). It offers an attractive alternative in terms of reducing the cost of electricity, and the equipment can be installed in locations that have independent operation, without electricity (Lorenzo et al., 2018).

The initial investment required means that there is a high financial risk associated with implementing these projects, and this represents the main obstacle to the more widespread application of these energy sources in rural areas (Acosta-Silva et al., 2019). In order to make an appropriate decision, feasibility analyses are therefore of fundamental importance when investing in a project or selecting the best alternative from a range of different projects (Pardo et al., 2019).

In view of the above, the present work aims to perform a technical and economic analysis of the use of off-grid photovoltaic systems without energy storage in the area of irrigation, considering different levels of power demand.

MATERIAL AND METHODS

To conduct this study, photovoltaic systems with different power ratings drawn from irrigation pumping stations were sized. Values of drive power ranging from 0.736 to 29.44 kW were tested.

Several different scenarios were simulated. In order to create the photovoltaic system projects, surveys were carried out of the availability of solar resources for power generation to meet a certain demand.

A 16-year historical series (2004–2019) of hourly meteorological data was used as a source of radiation data and precipitation, which were used to determine evapotranspiration and the number of hours required for irrigation during the summer harvest period (November to March). This analysis considered an irrigated soybean crop with an average yield for the region of 102.62 bags ha^{-1}, a value obtained from experiments carried out in Santa Maria over four consecutive seasons (2017–2021) with a conventional sprinkler irrigation system, using five soybean cultivars. The number of hours required for irrigation during the period was defined using an application rate of 8.8 mm h^{-1}.

To define the moment of irrigation application, a fixed interval of seven days was adopted between irrigation periods, during which time there was no precipitation that met the water demand for that period. This was accomplished through the use of irrigation management for the crop based on reference evapotranspiration (ETo), calculated using the Penman-Monteith-FAO equation (Allen et al., 1998). Thus, the need for irrigation was determined according to [eq. (1)]:

$$NI = \frac{ETo - P_{eff}}{Ta} \tag{1}$$

Where:

NI - need for irrigation (h);

ETo - reference evapotranspiration for the period of seven days (mm);

P_{eff} - effective precipitation (mm),

Ta - application rate (mm h^{-1}).

The climatic data referred to the region of Santa Maria-RS, and contained information on the rainfall (mm), maximum and minimum temperatures (ºC), relative humidity (ºC), wind speed (m s^{-1}) and solar radiation (kJ m^{-2}). These data were obtained from the automatic weather station of the National Institute of Meteorology (INMET), located at the Federal University of Santa Maria. The gaps in the historical series were corrected with the help of Clima software, developed at the Agronomic Institute of Paraná (IAPAR) (Faria et al., 2002).

Table 1 presents data on the power and rated current for irrigation systems, which were used for sizing of the photovoltaic solar power generation systems. Solar drives (CC-AC solar voltage inverters) with power 1.3 times higher than that of the motors were used in each of the tested configurations, to supply the minimum motor current required for the drive.

TABLE 1. Technical characteristics of the motors for the tested irrigation systems (Model: Weg motor W22 IR3 Premium)

Motor power (kW)														
0.7	1.1	1.5	2.2	2.9	3.7	4.4	5.5	7.4	9.2	11.0	14.7	18.4	22.1	29.4
Rated current at 380V (A)														
1.68	2.4	3.14	4.53	6.25	7.39	8.88	11.3	14.5	17.3	21.3	28.8	35.2	42.2	57.3
Performance (%)														
80.5	84.0	85.5	86.5	88.5	88.5	88.5	89.5	90.2	91.0	91.0	91.0	91.7	91.7	92.4
Power factor														
0.84	0.83	0.85	0.85	0.82	0.86	0.87	0.83	0.87	0.89	0.86	0.87	0.87	0.86	0.86

Equations (2) and (3) were used to determine the number of solar modules required in series and in parallel for each configuration, respectively:

$$N_{M-series} = V_{INV}/V_{OC} \tag{2}$$

$$N_{M-parallel} = I_{INV}/I_{mp} \tag{3}$$

Where:

$N_{M\text{-}series}$ - number of modules in series;

V_{INV} - inverter voltage (V);

V_{oc} - open circuit voltage of the module (V);

$N_{M\text{-}parallel}$ - number of modules in parallel;

I_{INV} - rated current of inverter (A),

I_{mp} - operating current of the module (A).

The number of solar modules in series determined the voltage of each system, considering the voltage interval of the solar drive. Similarly, the number of modules in parallel met the electric current demand.

The power produced by the module was calculated using [eq. (4)]:

$$P_M = Isc.Vmp \tag{4}$$

Where:

P_M - power of the module (W);

I_{sc} - short-circuit current of the module (A),

V_{mp} - maximum operating voltage (V).

The technical characteristics of the solar drivers and solar module used in this study are summarized in Tables 2 and 3, respectively.

TABLE 2. Technical characteristics of solar drivers.

Rated current (A)	Maximum power of inverter (cv)	Maximum input voltage CC (Vcc)	Operating voltage CC (Vcc)	Output supply voltage CA (V)
4.3	1.50	810	450–760	380
4.3	2.00	810	450–760	380
6.1	3.00	810	450–760	380
10	5.00	810	450–760	380
14	7.50	810	450–760	380
14.6	7.50	780	350–780	380
16	10.00	810	450–760	380
24	15.00	810	450–760	380
31	20.00	810	450–760	380
32	20.38	810	450–760	380
45	30.00	810	450–760	380
62	40.70	780	350–780	380
76	50.30	780	350–780	380

TABLE 3. Technical characteristics of the monocrystalline solar module.

Electrical parameters solar module			
Maximum operating voltage	*Vmp*	41.7	V
Open-circuit voltage	*Voc*	49.8	V
Operating current	*Imp*	9.6	A
Short-circuit current	*Isc*	10.36	A
Maximum power	*Pmax*	400.32	Wp
Module efficiency		19.88	%
Rated operating temperature		45±2	°C
Temperature coefficient	Pmax	−0.37	%/°C
Temperature coefficient	Voc	−0.28	%/°C
Temperature coefficient	Isc	0.048	%/°C

In order to determine the technical feasibility of using these systems, the energy supply time and the availability of solar radiation were considered as restriction variables. The estimation of hourly energy generation was verified analytically using the insolation method (Villalva, 2015), using [eq. (5)]:

$$E_{generated} = H_{av} . A_{mod} . \eta_{mod} . N_{mod} . losses \quad (5)$$

Where:

$E_{generated}$ - energy produced (kW h);

H_{av} - average hourly solar radiation (kW h m^{-2});

A_{mod} - photovoltaic generator surface (m^2);

η_{mod} - module efficiency (%);

N_{mod} - number of modules used,

losses is a factor representing the losses in the system and is taken here as 5%.

Three aspects of operation were considered for the systems: the time from the start of pumping until the moment when the pump reached its maximum power; the instant of maximum pump power; and the period of decrease in the pump power.

An economic feasibility analysis was carried out for a period of 25 years (representing the guarantee period for photovoltaic modules, as normally used for investment purposes). We considered the annual cash flow, the profits obtained, and the amortization of the initial cost.

To evaluate the profitability, the amounts that would be paid if there was an electricity grid on site were considered, that is, the local electricity tariffs, the input revenues came from the agricultural production provided by each system. The price of a sack of soybeans was set to the average value offered in the port of Rio Grande during the period of the experiments in the state of Rio Grande do Sul (R$102.21).

The ratio of the power to the irrigated area suggested by Bruning et al. (2020) was used to determine the cash flow input values for each of the tested configurations.

TABLE 4. Ratio of power to irrigated area and input values for production of each of the tested configurations (adapted from Bruning et al., 2020)

Power (kW)														
0.7	1.1	1.5	2.2	2.9	3.7	4.4	5.5	7.4	9.2	11.0	14.7	18.4	22.1	29.4
Area power ratio kW/ha														
4.2														
Area irrigated by power (ha)														
0.17	0.26	0.35	0.52	0.69	0.87	1.04	1.30	1.74	2.17	2.6	3.47	4.34	5.21	6.94
Production (sc)														
17.4	26.7	35.6	53.4	71.2	89.0	106.8	133.6	178.1	222.6	267.1	356.1	445.1	534.2	712.3

sc : sack of soybeans

An economic feasibility analysis for solar power generation was carried out based on economic indicators such as the net present value (NPV), internal rate of return (IRR), benefit/cost ratio (B/C) and profitability index (PI).

The input values were set to those that would be paid to an electric utility company if the system were connected to the network plus the agricultural production, while the output values represented all of the costs for the implementation of the photovoltaic power generation systems. A minimum rate of attractiveness (MRA) of 2.5% was considered for cash flow, which exceeded the annual savings income.

The NPV, which is the algebraic sum of the benefits and costs at time $t = 0$, was determined using [eq. (6)]:

$$NPV = \sum_{t=0}^{N} \frac{Ft}{(1+j)^t} \quad (6)$$

Where:

NPV - net present value (R$ ha^{-1});

j - minimum rate of attractiveness (MRA) (decimal);

N - project horizon (years);

t - project period (years),

Ft - net cash flow in each year (R$ ha^{-1}).

The IRR is the value of the discount rate needed to make the NPV equal to zero, i.e., the potential return for the project, which was equal to the present value of revenues to the present value of costs, as shown in [eq. (7)]. The MRA and IRR were compared, and the project was accepted when the IRR was greater than or equal to the MRA.

$$\sum_{j=0}^{N} \frac{Ft}{(1+\rho)^t} = 0 \quad (7)$$

Where:

ρ - internal rate of return (decimal);

j - discount rates or minimum rate of attractiveness (MRA) (decimal);

N - project horizon (years);

t - project period (years),

Ft - net cash flow in each year (R$ ha^{-1}).

The B/C ratio makes it possible to verify whether the updated benefits are greater than the updated expenses. In the case where the B/C ratio is higher than one, a positive NPV is assumed, and the investment is determined to be economically feasible based on the discount rate employed. The B/C ratio was calculated using [eq. (8)]:

$$B/C = \frac{\sum_{t=0}^{n} B/(1+j)^t}{\sum_{t=0}^{n} C/(1+j)^t} \tag{8}$$

Where:

B/C - benefit/cost ratio;

B - revenues (R\$ ha^{-1}),

C - expenses (R\$ ha^{-1}).

The PI represents the amount of profit or loss from the project over a given period of time. It was calculated by dividing the NPV by the initial investment, as shown in [eq. (9)]:

$$PI = \frac{VPL}{Initial\ Inv.} \tag{9}$$

PI values of > 1 indicate that the investment can be accepted, where the higher the PI value, the more attractive it becomes. On the other hand, PI values of < 1 mean that the investment must be rejected.

A regression analysis of all economic parameters was performed with the help of SigmaPlot® 11.0 software.

RESULTS AND DISCUSSION

The average monthly values of hourly solar radiation throughout the year are shown in Figure 1 for the city of Santa Maria-RS. We found that the highest amounts of available solar radiation occurred between October and March; this corresponded to the cultivation period of the main crops in the state, especially soybeans, which formed the object of study in this work.

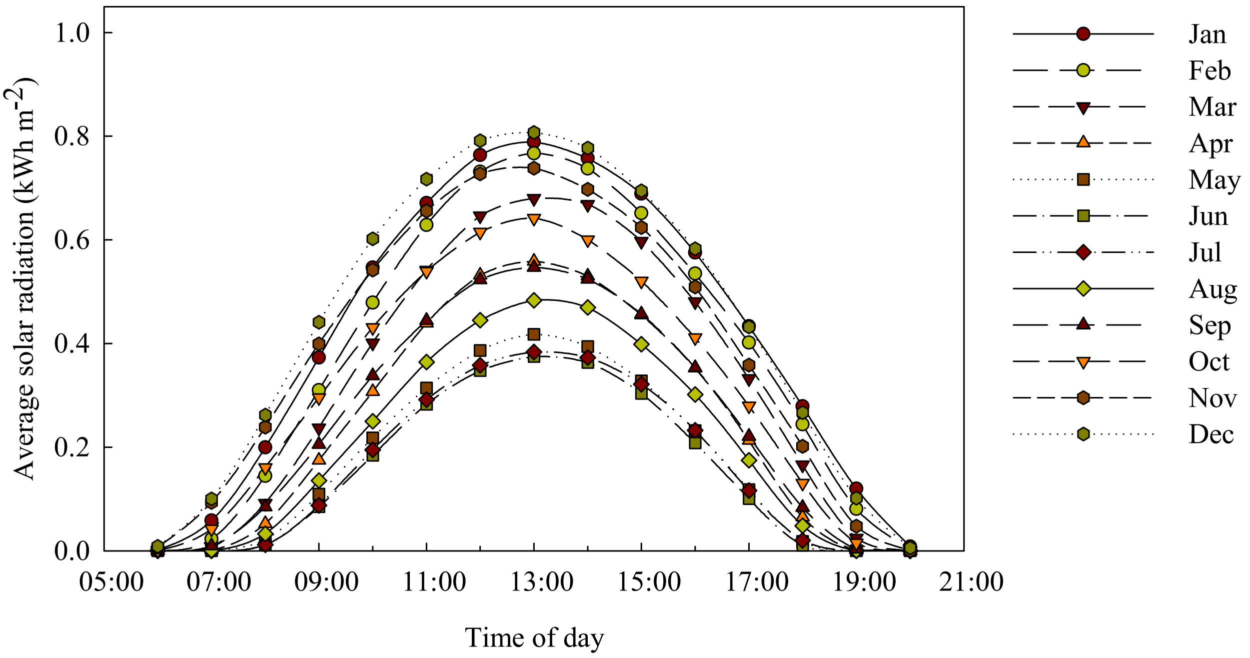

FIGURE 1. Average monthly solar radiation for the city of Santa Maria, RS, Brazil.

The state of Rio Grande do Sul has four well-defined seasons (Alvares et al., 2013), which directly influence the intensity of available solar radiation. In September (early spring), there is an increase in the availability of solar radiation, and April (early autumn) marks the beginning of a reduction in its intensity.

The highest radiation levels were found in January and December at around 13:00 h, with values of 0.79 and 0.81 kWh m^{-2}, respectively. This trend was seen for all months of the year, with the lowest value in June (0.37 kWh m^{-2}) at the same time of day.

In a study conducted in Australia, McCormick & Suehrcke (2018) observed an amplitude of daily solar radiation that was similar to the results found in the present study, and higher maximum values for December. Urrego-Ortiz et al. (2019) investigated the highest values of solar radiation in March, July and August of 2016 and January and February of 2017, finding values higher than 0.9 kWh m^{-2}. This difference in the maximum values of solar radiation in these months compared to the present study is due to the variation in latitude between sites.

The historical data series evaluated here represents a volume of precipitation that is capable of meeting the evapotranspiration demand of the crop, as shown in Figure 2. However, the poor distribution of this precipitation over the years means that the use of supplementary irrigation is essential to maintain the stability of crop production.

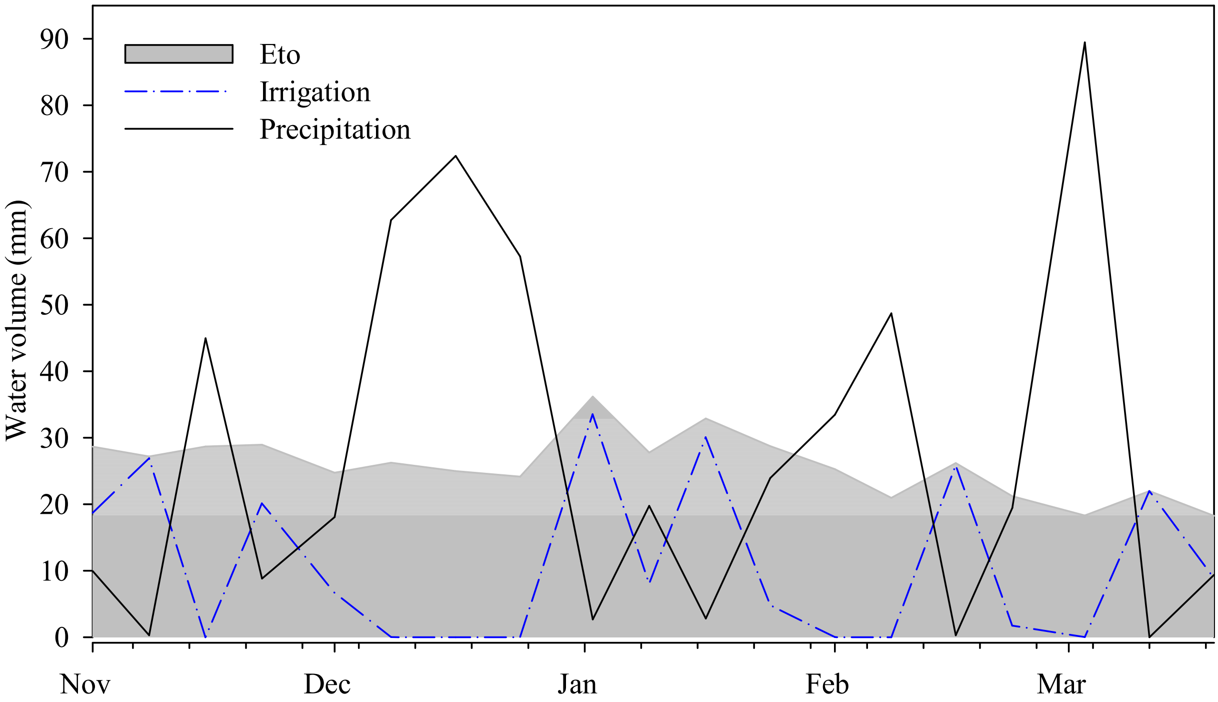

FIGURE 2. Distribution of precipitation and evapotranspiration demand for the region during the study period.

According to the historical data series analyzed here, the need for complementary irrigation was 203 mm for one cultivation cycle, corresponding to 23.07 h of operation of the irrigation system. Figure 3 shows the number of possible hours of operation for each irrigation system evaluated, and a comparison with the amount of hours available.

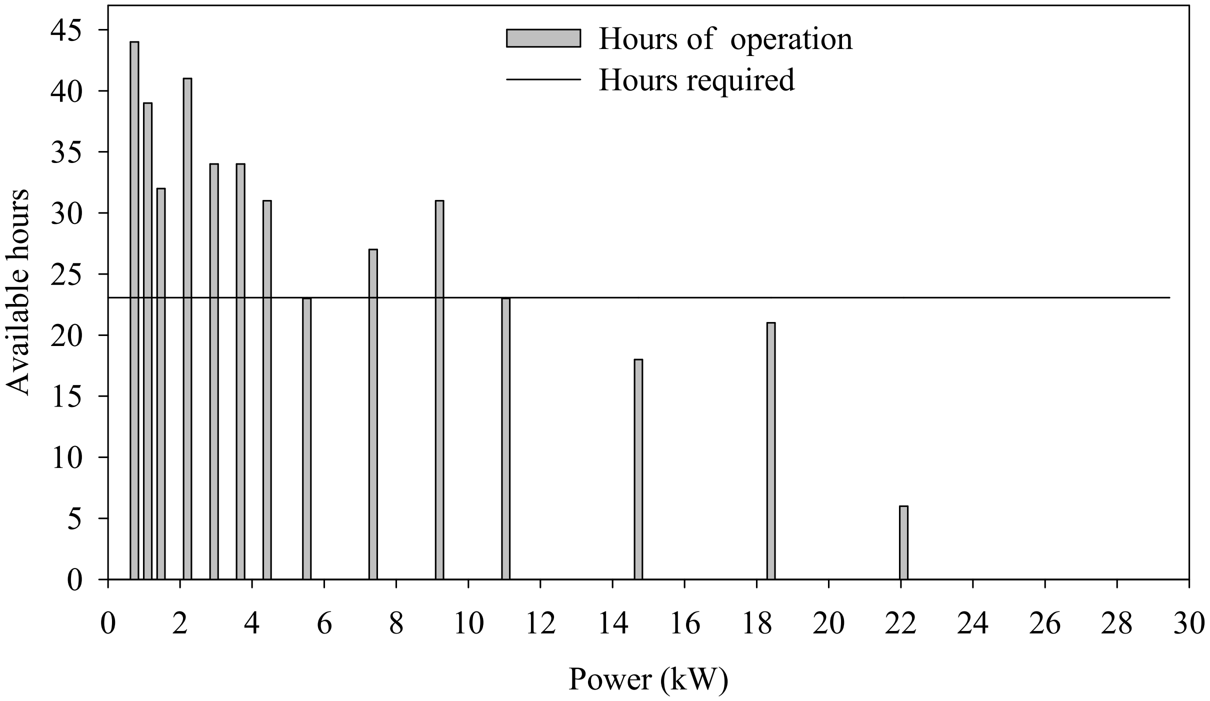

FIGURE 3. Number of hours of operation according to the power (kW) of the electric motors.

We can see that there is availability for the operation of irrigation systems using motors of up to 11.04 kW. However, for systems that require higher power, such as 14.72, 18.4, 22.08 and 29.44 kW, the number of potential hours of operation is lower than the minimum required to meet the need of the crop, meaning that operation is prevented when a 40 cv motor is used.

Corroboration of the analysis presented here is provided by Medeiros et al. (2021), who state that regional historical climate trends should be used for long-term planning in order to determine the power generation potential of a region or country. Habib et al. (2020) also noted that the potential for photovoltaic power generation was limited to the amount of solar radiation available, weather conditions, terrain topography and conversion efficiencies of the systems.

Reca et al. (2016) considered irrigation in greenhouses with autonomous irrigation systems with direct solar pumping, and pointed out that this approach offers a technically and economically feasible alternative provided that irrigation is subdivided into sectors. Kumar et al. (2020) highlighted that the main advantage of solar-powered pumping systems is that they do not need to use fossil fuels for operation, which reduces environmental pollution.

In a study comparing pumping systems connected to the grid with isolated solar systems, Shojaei & Akavan (2020) found that solar-powered water pumping had greater economic efficiency when these systems were at least 500 m from the electricity grid, and that the economic efficiency improved with the distance from the grid.

Figure 4 shows the behavior of the financial indicators NPV, IRR and B/C a function of the power increase; it can be seen that these parameters show an increase with power, with coefficients of determination greater than 88%. This is justified because the cost per unit power is higher at the lowest values of power.

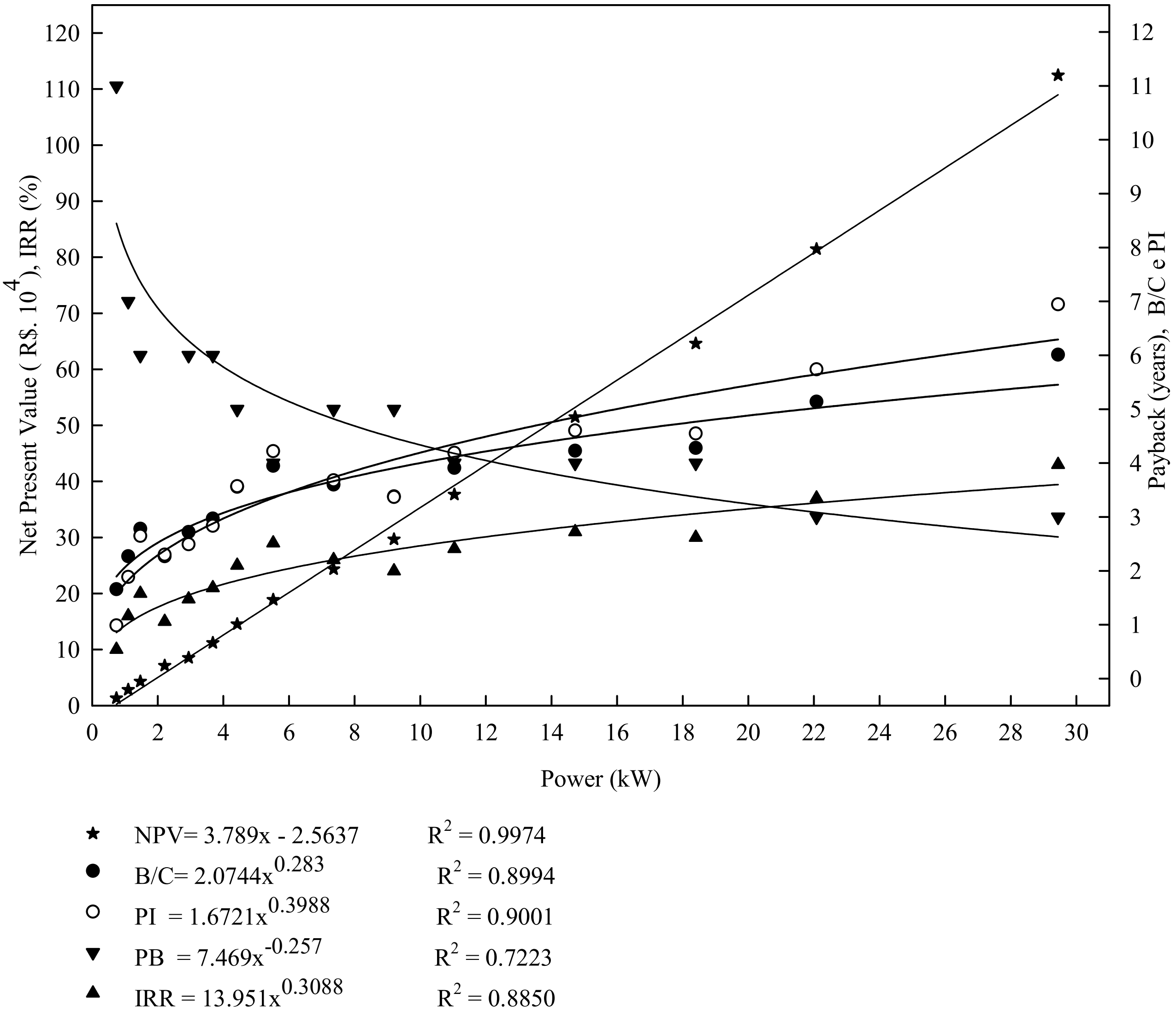

FIGURE 4. Net present value (NPV), internal rate of return (IRR), benefit/cost ratio (B/C), payback and profitability index (PI) for the values of power tested here.

Our results for NPV are in line with those of Jiménez-Castillo et al. (2020) and Bendato et al. (2018), who reported increasing NPV values with an increase in system power. In contrast, Reca et al. (2016), who evaluated the sectorization of solar-powered irrigation, observed positive NPV results for irrigation systems with at least four sectors per hectare, when operating individually, indicating that these systems are profitable in particular cases. López-Luque et al. (2015) proved that direct solar powered pumping systems are a technically and economically feasible alternative to current systems, with a high NPV.

The results the present study for payback showed a decreasing behavior as a function of the increase in power, with a value of 72% for R². The IRR was higher than the MRA for all the values of power evaluated in the study, with the lowest return obtained for the 0.736 kW motor (IRR = 10%), and the highest for the 29.44 kW motor (IRR = 43%).

In a study of water pumping for irrigation, Niajalili et al. (2017) compared a solar-powered system with a gasoline-powered one at a power of 0.37 kW, and found a payback period of only nine years, even with the high installation costs involved. These data agree with those found in the present study, where the payback was 11 years for a power of 0.74 kW; this slightly longer period is due to the difference in the power considered in the two studies.

Although the best results for the financial indicators were obtained at the highest values of power, technical limits meant that these could not be used; this is because it was not possible to obtain an arrangement of solar panels for the region under study that would supply the necessary starting current, meaning that the electric motor would not start operating. This makes it technically unfeasible to use higher power configurations with off-grid generation systems without energy storage.

Thus, the best scenario in terms of economic and technical feasibility involves motors with power ratings of 5.52 and 11.04 kW. Rodrigues et al. (2016) reported that photovoltaic systems connected to the power grid with 5 kW power delivered better results when compared to 1 kW photovoltaic systems, which is justified by the higher costs of investment per watt of installed power.

In terms of the B/C ratio, we note that Dalfovo et al. (2019) studied the generation of solar energy to meet different levels of power demand, and found a constant ratio for the increase in power. Their results are different from those obtained in the present study, where the ratio increased with the power rating.

For all of the power values tested here except one, investment was feasible, with PI values greater than one; the exception was a power rating of 0.736 kW, with a value of 0.99. This parameter showed behavior with R^2 values of 90%. This indicates that the investment is recovered during the analysis period (in this case, 25 years).

The performance observed in this study showed opposite behavior in comparison to that reported by Zeraatpisheh et al. (2018) for photovoltaic systems connected to the grid, which were shown to be more profitable for systems with lower power. Rodrigues et al. (2016) observed that in Brazil, systems with ratings of 1 kW and 5 kW did not give feasible results in any scenario, which was one of the worst results among the countries studied. Brodziński et al. (2021) studied different sizes of solar plants, and observed based on an analysis of IRR and PI values that plants with higher capacity gave the best results in terms of investments.

CONCLUSIONS

For the power ratings considered here, off-grid photovoltaic systems are found to be an economically viable alternative to grid electricity based on the NPV, TIR, B/C, payback and IRR parameters. The use of photovoltaic systems can also contribute to the socioeconomic development of remote sites.

In regions with radiation characteristics similar to that of this study, it would be possible to use configurations of boards and inverters to meet levels of power demand in the range (0.74, 1.1, 1.5, 2.2, 2.9, 3.7, 4.4, 5.5, 7.4, 9.2, 11.04 kW), thus technically offering an viable alternative method of supply. However, depending on the water requirements, the area to be irrigated, and the crop being grown, the range of feasible power generated may increase or decrease.

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