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Economic performance of off-grid photovoltaic systems for irrigation[1]

Desempenho econômico de sistemas fotovoltaicos off-grid para irrigação

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HIGHLIGHTS:
The implementation costs of off-grid photovoltaic system decreases with increasing generation power.
Off-grid systems with higher powers (22.1 kW) have an energy cost higher than that practiced by the energy concessionaire.
The variation in revenues and implementation costs demonstrates the profitability of photovoltaic projects for rural areas.

ABSTRACT: Renewable energies are alternatives to replace fossil fuels and are crucial for the sustainability of the agricultural sector, besides being an important alternative for pumping water in irrigation. Thus, understanding revenues and expenses is fundamental in economic feasibility. Therefore, the aim of this study was to assess the behavior of economic indicators in off-grid solar energy system for irrigation based on different scenarios. Photovoltaic projects were developed for different irrigation powers ranging from 0.736 to 22.1 kW, and the costs for implementation and operation, as well as the occurrence of economy of scale were evaluated, and the levelized cost of energy for each power analyzed was determined. In addition, sensitivity analyses were performed, considering the variation in product price and investment cost, to demonstrate the responses in relation to economic indicators. Photovoltaic energy projects showed increasing costs with the increase in power, and the normalized cost per kW followed an economy of scale, while the levelized cost of energy showed feasibility, except for the power of 22.1 kW. The sensitivity analyses showed profitability for the analyzed configurations.

Key words: solar power system, stand-alone, levelized cost of energy, sensitivity analysis

RESUMO: As energias renováveis são alternativas para substituição dos combustíveis fósseis sendo crucial para a sustentabilidade do setor agrícola, e importante alternativa para o bombeamento de água na irrigação. Assim, a compreensão das receitas e despesas são fundamentais na viabilidade econômica. Com isso, o objetivo do presente estudo foi verificar o comportamento dos indicadores econômicos em sistema de energia solar off-grid para irrigação com base em diferentes cenários. Foram desenvolvidos projetos fotovoltaicos para diferentes potências de irrigação variando de 0,736 até 22,1 kW, e avaliado os custos para implantação e operação, a ocorrência de economia de escala e verificado o custo nivelado de energia para cada potência analisada. Além disso, foram realizadas análises de sensibilidade, considerando a variação do preço de produto e custo de investimento, para demonstrar as respostas em relação aos indicadores econômicos. Portanto, os projetos de energia fotovoltaicos apresentaram custos crescentes com aumento da potência, e o custo normalizado por kW seguiu uma economia de escala, já o custo nivelado de energia demonstrou viabilidade, exceto para a potência de 22,1 kW. As análises de sensibilidade demonstraram a rentabilidade para as configurações analisadas.

Palavras-chave: sistema de energia solar, sistema isolado, custo nivelado de energia, análise de sensibilidade

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Introduction

Agriculture is constantly modernizing itself, and this process entails increased energy consumption. In irrigation, this occurs due to the demand for electric motors or diesel engines (García et al., 2019). The use of renewable energies is a crucial point for the sustainability of the agricultural sector, being an alternative for water pumping in irrigation (Velasco-Muñoz et al., 2019; Lowitzsch et al., 2020). The increase in fuel and electricity prices favors the use of renewable energies (García et al., 2019).

Photovoltaic solar energy is an abundant and widespread source that can be adopted in several sectors of agricultural production (Gorjian et al., 2021). The system can operate connected to the power grid, not connected or autonomously (Ghenai et al., 2020), and with this last method of operation, solar pumping for irrigation stands out, because it can be an alternative for regions that are away from the electricity grid (Piechocki et al., 2018; Todde et al., 2019).

The price of energy and the solar intensity of the region are relevant factors when defining the benefit/cost ratio in the implementation of these systems. The levelized cost of energy is the minimum cost at which energy must be sold to reach the equilibrium point during the lifetime of the project (Zhao et al., 2017). Thus, the analysis of the feasibility through this methodology enables the comparison of different power generation technologies (Branker et al., 2011; Larsson et al., 2014).

Studies with different scenarios, considering the variation of economic parameters, allow the evaluation of feasibility according to the variations in costs and revenues involved, as well as the sensitivity of the response (Carrêlo et al., 2020). It is a tool for decision making, because it returns different possibilities of profitability for the project (Bustos et al., 2016; Carrêlo et al., 2020). In view of the above, the objective of this study was to assess the behavior of economic indicators in off-grid solar energy system for irrigation based on different scenarios.

Material and Methods

The study was conducted with off-grid photovoltaic system without energy storage, used to supply irrigation pumping stations with different power demands, which ranged from 0.736 to 22.1 kW, as normally used in small areas (Bruning et al., 2020).

Photovoltaic projects were developed through the survey of solar availability that met the power demands of each pumping system. For this, a historical series of 16 years (2004-2019) of hourly meteorological data was used, in which radiation data (kJ m^{-2}) and the need for irrigation during the summer harvest period (November to March) were identified for the region of Santa Maria, RS, Brazil.

In addition to the solar radiation data, hourly data of rainfall (mm), maximum and minimum temperatures (°C), relative air humidity (%) and wind speed (m s^{-1}) were also obtained, through the automatic weather station of the National Institute of Meteorology, located at the Federal University of Santa Maria. These data were used to perform the analysis of the average need for irrigation during the study period. The gaps identified in the historical series were corrected using Clima software (Faria et al., 2002).

For project purposes, soybean crop was used and the required irrigation period was defined with an application rate of 8.8 mm h^{-1}, value based on experiments carried out in an experimental area located in the Polytechnic School of UFSM in the years 2017 to 2021. The interval between irrigation events was fixed and equal to seven days, considering that the water demand of the period was not met by rainfall. Crop irrigation management was performed using the Penman-Monteith-FAO equation (Allen et al., 1998), based on reference evapotranspiration (ET_O). Thus, through experiments carried out during four consecutive harvests (2017-2021), an average yield of 102.62 sc ha^{-1} was used for the crop.

The photovoltaic solar power generation systems were sized to supply pumping systems with the available commercial powers of 0.7, 1.1, 1.5, 2.2, 2.9, 3.7, 4.4, 5.5, 7.4, 9.2, 11, 14.7, 18.4 and 22.1 kW. Solar drives (CC-AC solar voltage inverters) with powers 1.3 times higher than the power of the motors were used in each configuration.

The systems were powered by the energy generated in the set of monocrystalline solar modules with unit power of 400 Wp, maximum operating voltage of 41.7 V, open circuit voltage of 49.8 V, operating current of 9.6 A, short-circuit current of 10.36 A and module efficiency of 19.88%. The arrangements of modules in series and in parallel were sized according to each power demand. The technical characteristics of the solar drives are presented in Table 1.

Hourly energy generation was determined analytically using the method of insolation (Villalva, 2015), according to Eq. 1.

$$E_{generated} = H_{avg} \cdot A_{mod} \cdot \eta_{mod} \cdot N_{mod} \cdot p \quad (1)$$

where:

$E_{generated}$ - energy produced, kW h;
H_{avg} - average hourly solar radiation, kW h m^{-2} h^{-1};
A_{mod} - photovoltaic generator surface, m^2;
η_{mod} - module efficiency, %;
N_{mod} - number of modules used; and,
p - system loss factor, per day.

Table 1. Technical characteristics of the solar drives, all with AC output voltage of 380 V

Nominal current (A)	CC max. input voltage (Vcc)	CC operating voltage CC (Vcc)	Inverter maximum power (cv)
4.3	810	450-760	1.50
4.3	810	450-760	2.00
6.1	810	450-760	3.00
10.0	810	450-760	5.00
14.0	810	450-760	7.50
14.6	780	350-780	7.50
16.0	810	450-760	10.00
24.0	810	450-760	15.00
31.0	810	450-760	20.00
32.0	810	450-760	20.38
45.0	810	450-760	30.00
62.0	780	350-780	40.70

For each solar power generation project evaluated, the costs for its implementation were surveyed, which included the values related to solar panels, inverters, cables, connectors, fixation system, projects, maintenance and insurance, in order to perform an analysis of economy of scale as a function of the increase in installed power.

Economic analysis was performed for the period of 25 years (lifetime of photovoltaic modules), considering the annual cash flow, the profits obtained and the amortization of the initial cost. In order to obtain equivalence with literature results, the values were converted into dollar with a quotation of R$ 5.23 (06/27/2022).

The levelized cost of energy (LCOE) is equal to the sum of the costs incurred during the lifetime of the project, being the sum of the annual, initial, operation and maintenance costs that were paid over the project period, divided by the sum of the energy units produced, according to Eq. 2.

$$\mathrm{LCOE} = \frac{\sum_{i=0}^{N}\left[\frac{\mathrm{Ci}+\mathrm{Li}+\mathrm{OM}+\mathrm{Ii}}{(1+j)^t}\right]}{\sum_{i=0}^{N}\left[\frac{\mathrm{Ei}}{(1+j)^t}\right]} \qquad (2)$$

where:

LCOE - levelized cost of energy, US$ kW h^{-1};
Ci - total cost of system installation, US$;
Li - cost of the land, US$;
OM - costs of operation and maintenance estimated at 2% of the initial investment cost, US$;
Ii - insurance costs, %;
j - discount rate, %;
N - project horizon, years;
t - project time period, years; and,
Ei - energy produced, kW h.

The effect of profitability obtained in each solar power generation project considered the values paid to the energy concessionaire, that is, the electricity tariff (US$ 0.053 kW h), together with the gains corresponding to agricultural production. The average price of the soybean sack, practiced in the Port of Rio Grande, during four years of the experiments, in the state of Rio Grande do Sul, Brazil, was used (US$ 18.82). Input values in the cash flow for each tested configuration were determined by adopting the power per irrigated area ratio according to Bruning et al. (2020). A minimum attractiveness rate (MAR) of 2.5% was considered, which exceeds the annual income of the Special System of Settlement and Liquidation (Selic) rate.

After obtaining the cash flows, sensitivity analyses of the realistic scenarios were performed, considering the variation of the parameters product price and initial investment cost. The variation values for both situations were ± 30%, considering a 5% interval. With these results, it was possible to demonstrate the behavior in relation to the economic indicators net present value (NPV), internal rate of return (IRR), benefit/cost ratio (B/C) and levelized cost of energy (LCOE), according to Eqs. 3 to 5, respectively.

$$\mathrm{NPV} = \frac{\sum_{t=0}^{N}\mathrm{Ft}}{(1+j)^t} \qquad (3)$$

where:

NPV - net present value, US$ ha^{-1};
j - minimum attractiveness rate (MAR), decimal;
N - project horizon, years;
t - project time period, years; and,
Ft - net cash flow in each year, US$ ha^{-1}.

$$\frac{\sum_{j=0}^{N}\mathrm{Ft}}{(1+\mathrm{IRR})^t} = 0 \qquad (4)$$

where:

IRR - internal rate of return, decimal;
j - discount rate or minimum attractiveness rate (MAR), decimal;
n - project horizon, years;
t - project time period, years; and,
Ft - net cash flow in each year, US$ ha^{-1}.

$$\mathrm{B/C} = \frac{\sum_{t=0}^{n}\frac{\mathrm{B}}{(1+j)^t}}{\sum_{t=0}^{n}\frac{\mathrm{C}}{(1+j)^t}} \qquad (5)$$

where:

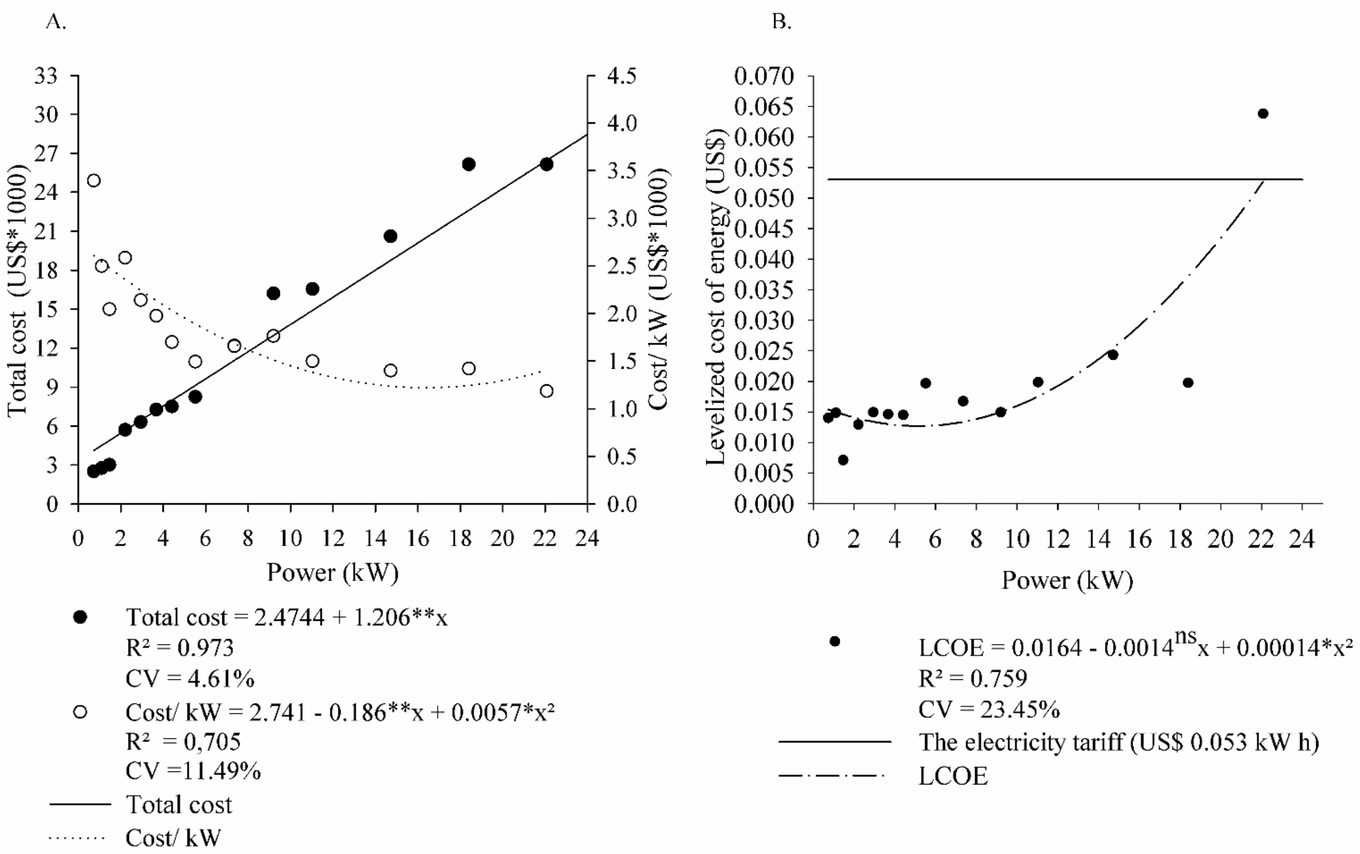
B/C - benefit/cost ratio;
B - revenues, US$ ha^{-1};
C - expenses, US$ ha^{-1}.
n - project horizon, years.; and,
j - discount rate or minimum attractiveness rate (MAR), decimal.

To demonstrate the behavior of the variables of total cost, cost kW^{-1} and LCOE, regression analyses were performed using Sigma Plot 11.0 software.

Results and Discussion

The total investment costs for the implementation of each power generation project that supplies certain powers are shown in Figures 1A and B, which present the levelized cost of energy for the power range tested.

The total costs increased with the increase of installed power, following a linear trend (Figure 1A). Total costs ranged from US$ 2,498.16 to US$ 26,142.54 (Figure 1A), showing a diseconomy of scale, since the cost values were increasing with the increase in installed power. However, the costs related to the installation of each kW demonstrated an economy of scale, as they followed a decreasing behavior, that is, there was a reduction in the cost of kW for the implementation of projects with higher power. The values per kW found in this study ranged from US$ 3,394.24 for the power of 0.736 kW to US$ 1,183.99 for the power of 22.1 Kw (Figure 1A). These



CV - Coefficient of variation; ns - Not significant; * - Significant at $p \leq 0.05$; ** - Significant at $p \leq 0.01$

Figure 1. Total costs for implementing the power generation system (left y axis), costs per kW of energy generated (right y axis) (A) and - levelized cost of energy as a function of installed powers (B)

values represent a 65% reduction at the highest powers. The mean of economy of scale was 47.1% with a standard deviation of 12.6% among the powers analyzed.

This behavior corroborates those reported by Carrêlo et al. (2020), who worked with energy generation systems using powers ranging from 40 to 360 kW and demonstrated that the investment cost for irrigation systems with photovoltaic generation showed an increasing behavior as a function of the increase in installed power. Similarly, the cost normalized by power followed a similar behavior, but with lower values, with an average reduction of 15% with the increase of power.

Based on the methodology used in the comparison of electricity generation technologies, the levelized cost of energy showed an increasing behavior as a function of the installed powers, as shown in Figure 1B.

Knowing that the LCOE is the point that makes a photovoltaic system feasible compared to the values that would be paid to use the electricity grid (Zhao et al., 2017), it was found that for the powers up to 18.4 kW (Figure 1B) the values were lower than the possible electricity tariffs for the rural sector. For the power of 22.1 kW, the LCOE value was higher than the electricity tariff, thus not being an economically feasible alternative, since the implementation costs were relatively high in comparison to the electricity generation potential for the analyzed period.

The average of LCOE values that were below the energy tariff was US$ 0.016 with a standard deviation of US$ 0.004, and these values were lower than those found by Hwang et al. (2021), who obtained results for LCOE of US$ 0.115 kW h^{-1} and US$ 0.156 kW h^{-1} in a study conducted in different cities. For an off-grid photovoltaic system with power reserve, Ouedraogo et al. (2015) obtained a LCOE of US$ 0.75 kW h^{-1}. This value is higher than those found in the present study. The use of energy storage in batteries justifies this difference, since, for this type of system, there is an increase in costs with the acquisition and maintenance of batteries for energy storage.

Santos & Lucena (2021) conducted a study on LCOE in several cities in Brazil and found an average value of US$ 0.434 kW h^{-1}, and the lowest value was US$ 0.395 kW h^{-1}, obtained for the north of the country. These values are higher than those found in the present study. However, the electricity tariff in urban perimeters is higher than that practiced for rural enterprises, increasing the cost of urban photovoltaic systems and thereby raising the LCOE.

Lorenzo et al. (2018) compared irrigation systems powered by photovoltaic energy, diesel engines and grid power in seven countries and observed savings in the photovoltaic system that ranged from 30 to 84% compared to systems with diesel engines and connected to the grid, respectively. The LCOE for photovoltaic system ranged from US$ 0.045 to US$ 0.17 kW h^{-1} for the same comparison.

In projects of photovoltaic solar systems some variables such as the price of the product and the cost for implementing the system are fundamental for analysis. However, these variables are often uncertain, making it difficult to make decisions about the project. Thus, sensitivity analysis can help in solving these uncertainties and giving reliability to photovoltaic solar power generation projects, as reported by Carrêlo et al. (2020).

Table 2 presents the results of the sensitivity analysis regarding the variation of product price according to the financial indicators.

Table 2. Sensitivity analysis in relation to the variation of product (soybean) price for each pumping system power (kW)

Pumping system power (kW)	Percentage variation of product price												
	30%	25%	20%	15%	10%	5%	0%	-5%	-10%	-15%	-20%	-25%	-30%
	NPV (1000 US$)												
0.7	4.3	4.0	3.7	3.4	3.1	2.8	2.5	2.2	1.9	1.5	1.2	0.9	0.6
1.1	8.0	7.5	7.1	6.6	6.1	5.7	5.2	4.7	4.3	3.8	3.4	2.9	2.4
1.5	11.7	11.0	10.4	9.8	9.2	8.6	8.0	7.3	6.7	6.1	5.5	4.9	4.3
2.2	18.7	17.8	16.8	15.9	15.0	14.1	13.1	12.2	11.3	10.4	9.4	8.5	7.6
2.9	23.1	21.9	20.6	19.4	18.2	16.9	15.7	14.5	13.2	12.0	10.8	9.5	8.3
3.7	29.9	28.3	26.8	25.2	23.7	22.1	20.6	19.1	17.5	16.0	14.4	12.9	11.3
4.4	37.9	36.1	34.2	32.3	30.5	28.6	26.8	24.9	23.1	21.2	19.4	17.5	15.7
5.5	48.7	46.4	44.0	41.7	39.4	37.1	34.8	32.5	30.2	27.8	25.5	23.2	20.9
7.4	63.4	60.3	57.2	54.1	51.0	47.9	44.8	41.8	38.7	35.6	32.5	29.4	26.3
9.2	77.8	74.0	70.1	66.2	62.4	58.5	54.7	50.8	46.9	43.1	39.2	35.4	31.5
11.0	97.1	92.5	87.9	83.3	78.6	74.0	69.4	64.7	60.1	55.5	50.8	46.2	41.6
14.7	131.9	125.7	119.5	113.3	107.2	101.0	94.8	88.6	82.5	76.3	70.1	63.9	57.8
18.4	165.3	157.6	149.9	142.1	134.4	126.7	119.0	111.3	103.5	95.8	88.1	80.4	72.7
22.1	205.6	196.3	187.1	177.8	168.6	159.3	150.0	140.8	131.5	122.2	113.0	103.7	94.5
	IRR (%)												
0.7	14.6	13.8	13.1	12.3	11.5	10.7	9.9	9.1	8.3	7.4	6.5	5.6	4.6
1.1	21.4	20.4	19.4	18.5	17.5	16.5	15.5	14.5	13.5	12.5	11.4	10.3	9.2
1.5	26.8	25.7	24.5	23.4	22.2	21.1	19.9	18.7	17.5	16.3	15.1	13.9	12.6
2.2	20.7	19.7	18.8	17.9	16.9	16.0	15.0	14.1	13.1	12.1	11.1	10.0	9.0
2.9	25.6	24.5	23.4	22.3	21.2	20.1	18.9	17.8	16.7	15.5	14.4	13.2	12.0
3.7	28.0	26.8	25.6	24.4	23.2	22.1	20.9	19.7	18.4	17.2	16.0	14.7	13.4
4.4	33.0	31.6	30.3	28.9	27.6	26.2	24.8	23.5	22.1	20.7	19.3	17.9	16.5
5.5	37.8	36.3	34.7	33.2	31.6	30.1	28.5	27.0	25.4	23.9	22.3	20.7	19.1
7.4	33.9	32.5	31.1	29.7	28.3	26.9	25.5	24.1	22.7	21.3	19.8	18.4	16.9
9.2	31.7	30.4	29.1	27.8	26.4	25.1	23.8	22.5	21.1	19.8	18.4	17.1	15.7
11.0	37.6	36.1	34.6	33.0	31.5	29.9	28.4	26.9	25.3	23.8	22.2	20.6	19.0
14.7	40.5	38.8	37.2	35.6	33.9	32.3	30.6	29.0	27.3	25.7	24.0	22.3	20.6
18.4	39.9	38.3	36.6	35.0	33.4	31.8	30.2	28.6	27.0	25.3	23.7	22.0	20.4
22.1	48.2	46.3	44.4	42.5	40.5	38.6	36.7	34.7	32.8	30.9	28.9	27.0	25.0
	B/C												
0.7	2.2	2.1	2.0	1.9	1.8	1.7	1.7	1.6	1.5	1.4	1.3	1.3	1.2
1.1	2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.2	2.0	1.9	1.8	1.7	1.6
1.5	3.6	3.5	3.3	3.2	3.1	2.9	2.8	2.6	2.5	2.4	2.2	2.1	2.0
2.2	3.0	2.8	2.7	2.6	2.5	2.4	2.3	2.2	2.1	1.9	1.8	1.7	1.6
2.9	3.5	3.4	3.3	3.1	3.0	2.9	2.7	2.6	2.5	2.3	2.2	2.0	1.9
3.7	3.9	3.7	3.6	3.4	3.3	3.1	3.0	2.8	2.7	2.5	2.4	2.2	2.1
4.4	4.6	4.4	4.3	4.1	3.9	3.7	3.6	3.4	3.2	3.0	2.9	2.7	2.5
5.5	5.1	4.9	4.7	4.5	4.3	4.2	4.0	3.8	3.6	3.4	3.2	3.0	2.8
7.4	4.7	4.5	4.3	4.1	4.0	3.8	3.6	3.4	3.2	3.1	2.9	2.7	2.5
9.2	4.4	4.2	4.1	3.9	3.7	3.6	3.4	3.2	3.0	2.9	2.7	2.5	2.4
11.0	5.1	4.9	4.7	4.5	4.3	4.1	3.9	3.7	3.5	3.3	3.1	2.9	2.8
14.7	5.5	5.3	5.1	4.9	4.7	4.4	4.2	4.0	3.8	3.6	3.4	3.2	3.0
18.4	5.6	5.3	5.1	4.9	4.7	4.5	4.3	4.1	3.9	3.6	3.4	3.2	3.0
22.1	6.7	6.4	6.2	5.9	5.7	5.4	5.1	4.9	4.6	4.4	4.1	3.9	3.6

NPV - Net present value; IRR - Internal rate of return; B/C - Benefit/cost ratio

The results show that, although the selling price of the product had a 30% reduction and for the lowest power used, the NPV, although low, is positive. IRR is higher than the minimum attractiveness rate, resulting in 4.60% for the worst-case scenario, which is -30%. This analysis is repeated for the B/C ratio, which was equal to 1.2, representing a gain of 20% compared to the costs. Thus, with either the increase of power in the system or an improvement in the selling price of the product, the indicators were positive, making the projects feasible in all configurations analyzed.

A sensitivity analysis was also performed considering the variation of the costs of implementation of off-grid solar power generation systems, presenting the variation of the indicators NPV, IRR, B/C and LCOE relative to these variables. Regarding this variation, the NPV, IRR and B/C indicators presented in Table 3 showed an increasing variation as a function of the reduction of project implementation costs.

Despite the increase in costs, the systems can be considered economically feasible (Table 3) since the NPV for all scenarios showed positive results, the IRR showed values that exceed the minimum attractiveness rate (Table 3), higher than 5.9%, and consequently the B/C ratio showed values ranging from 1.3 to 7.3, demonstrating the profitability of the projects.

These results corroborate those found by Bustos et al. (2016), who used a sensitivity range of ± 30% and observed that the initial cost had a greater impact on the NPV, with variations of ± 81 and ± 43%, and a major impact on the results of IRR.

In relation to the variation of LCOE, this indicator showed an increase as a function of the increase in costs (Table 3). The minimum value was US$ 0.005 kW h^{-1} for the 1.5 kW power and the maximum value was US$ 0.083 kW h^{-1} for the 22.1 kW power. Thus, for this power the results showed unfeasibility, since they were higher than the value of the energy tariff practiced in the region.

Table 3. Sensitivity analysis for the variation of the costs of implementing the off-grid solar power generation systems for each pumping system power (kW)

Pumping system power (kW)	Percentage variation of the implementation costs												
	30%	25%	20%	15%	10%	5%	0%	-5%	-10%	-15%	-20%	-25%	-30%
							NPV (1000 US$)						
0.7	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.8	3.0	3.2	3.4	3.6
1.1	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.8	6.0	6.2	6.4
1.5	6.6	6.8	7.1	7.3	7.5	7.7	8.0	8.2	8.4	8.6	8.8	9.1	9.3
2.2	11.5	11.8	12.0	12.3	12.6	12.9	13.1	13.4	13.7	14.0	14.2	14.5	14.8
2.9	13.0	13.4	13.9	14.3	14.8	15.2	15.7	16.2	16.6	17.1	17.5	18.0	18.4
3.7	17.5	18.0	18.5	19.0	19.6	20.1	20.6	21.1	21.6	22.2	22.7	23.2	23.7
4.4	23.6	24.2	24.7	25.2	25.7	26.3	26.8	27.3	27.8	28.4	28.9	29.4	29.9
5.5	31.2	31.8	32.4	33.0	33.6	34.2	34.8	35.4	36.0	36.6	37.1	37.7	38.3
7.4	39.7	40.5	41.4	42.2	43.1	44.0	44.8	45.7	46.6	47.4	48.3	49.2	50.0
9.2	47.8	48.9	50.1	51.2	52.4	53.5	54.7	55.8	57.0	58.1	59.3	60.4	61.6
11.0	62.2	63.4	64.6	65.8	67.0	68.2	69.4	70.5	71.7	72.9	74.1	75.3	76.5
14.7	86.0	87.5	88.9	90.4	91.9	93.4	94.8	96.3	97.8	99.2	100.7	102.2	103.6
18.4	108.1	109.9	111.7	113.5	115.4	117.2	119.0	120.8	122.6	124.4	126.2	128.1	129.9
22.1	139.2	141.0	142.8	144.6	146.4	148.2	150.0	151.8	153.7	155.5	157.3	159.1	160.9
							IRR (%)						
0.7	5.9	6.5	7.1	7.7	8.4	9.1	9.9	10.8	11.7	12.7	13.9	15.1	16.5
1.1	10.7	11.4	12.1	12.8	13.7	14.5	15.5	16.6	17.7	19.0	20.4	22.0	23.8
1.5	14.3	15.1	15.9	16.8	17.7	18.8	19.9	21.1	22.5	24.0	25.7	27.6	29.8
2.2	10.4	11.0	11.7	12.5	13.3	14.1	15.0	16.0	17.2	18.4	19.8	21.3	23.0
2.9	13.6	14.3	15.1	16.0	16.9	17.9	18.9	20.1	21.4	22.9	24.5	26.3	28.4
3.7	15.2	15.9	16.8	17.7	18.6	19.7	20.9	22.1	23.5	25.1	26.8	28.8	31.0
4.4	18.4	19.3	20.2	21.2	22.3	23.5	24.8	26.3	27.9	29.7	31.7	33.9	36.5
5.5	21.3	22.3	23.3	24.5	25.7	27.1	28.5	30.2	32.0	34.0	36.3	38.9	41.8
7.4	18.9	19.8	20.8	21.8	22.9	24.2	25.5	27.0	28.6	30.5	32.5	34.8	37.5
9.2	17.6	18.4	19.3	20.3	21.4	22.5	23.8	25.2	26.7	28.5	30.4	32.6	35.1
11.0	21.2	22.1	23.2	24.3	25.6	26.9	28.4	30.0	31.8	33.9	36.1	38.7	41.6
14.7	22.9	24.0	25.1	26.3	27.6	29.0	30.6	32.4	34.3	36.4	38.9	41.6	44.7
18.4	22.6	23.6	24.7	25.9	27.2	28.6	30.2	31.9	33.8	35.9	38.3	41.0	44.1
22.1	27.7	28.9	30.2	31.6	33.1	34.8	36.7	38.7	41.0	43.5	46.4	49.6	53.3
							B/C						
0.7	1.3	1.3	1.4	1.4	1.5	1.6	1.7	1.7	1.8	2.0	2.1	2.2	2.4
1.1	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.7	2.8	3.0	3.2
1.5	2.1	2.2	2.3	2.4	2.5	2.6	2.8	2.9	3.1	3.3	3.5	3.7	4.0
2.2	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.7	2.8	3.0	3.2
2.9	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.9	3.0	3.2	3.4	3.6	3.9
3.7	2.3	2.4	2.5	2.6	2.7	2.8	3.0	3.1	3.3	3.5	3.7	4.0	4.2
4.4	2.7	2.8	3.0	3.1	3.2	3.4	3.6	3.7	4.0	4.2	4.4	4.7	5.1
5.5	3.0	3.2	3.3	3.4	3.6	3.8	3.9	4.2	4.4	4.6	4.9	5.3	5.6
7.4	2.8	2.9	3.0	3.1	3.3	3.4	3.6	3.8	4.0	4.2	4.5	4.8	5.1
9.2	2.6	2.7	2.8	2.9	3.1	3.2	3.4	3.6	3.8	4.0	4.2	4.5	4.8
11.0	3.0	3.1	3.3	3.4	3.6	3.7	3.9	4.1	4.3	4.6	4.9	5.2	5.6
14.7	3.3	3.4	3.5	3.7	3.8	4.0	4.2	4.4	4.7	5.0	5.3	5.6	6.0
18.4	3.3	3.4	3.6	3.7	3.9	4.1	4.3	4.5	4.8	5.0	5.3	5.7	6.1
22.1	4.0	4.1	4.3	4.5	4.7	4.9	5.1	5.4	5.7	6.0	6.4	6.8	7.3
							LCOE (US$ kW h^{-1})						
0.7	0.018	0.018	0.017	0.016	0.015	0.015	0.014	0.013	0.013	0.012	0.011	0.011	0.010
1.1	0.019	0.019	0.018	0.017	0.016	0.016	0.015	0.014	0.013	0.013	0.012	0.011	0.010
1.5	0.009	0.009	0.009	0.008	0.008	0.007	0.007	0.007	0.006	0.006	0.006	0.005	0.005
2.2	0.017	0.016	0.015	0.015	0.014	0.014	0.013	0.012	0.012	0.011	0.010	0.010	0.009
2.9	0.019	0.019	0.018	0.017	0.016	0.016	0.015	0.014	0.013	0.013	0.012	0.011	0.010
3.7	0.019	0.018	0.018	0.017	0.016	0.015	0.015	0.014	0.013	0.012	0.012	0.011	0.010
4.4	0.019	0.018	0.017	0.017	0.016	0.015	0.014	0.014	0.013	0.012	0.012	0.011	0.010
5.5	0.026	0.025	0.024	0.023	0.022	0.021	0.020	0.019	0.018	0.017	0.016	0.015	0.014
7.4	0.022	0.021	0.020	0.019	0.018	0.018	0.017	0.016	0.015	0.014	0.013	0.013	0.012
9.2	0.019	0.019	0.018	0.017	0.016	0.016	0.015	0.014	0.013	0.013	0.012	0.011	0.010
11.0	0.026	0.025	0.024	0.023	0.022	0.021	0.020	0.019	0.018	0.017	0.016	0.015	0.014
14.7	0.032	0.030	0.029	0.028	0.027	0.026	0.024	0.023	0.022	0.021	0.019	0.018	0.017
18.4	0.026	0.025	0.024	0.023	0.022	0.021	0.020	0.019	0.018	0.017	0.016	0.015	0.014
22.1	0.083	0.080	0.077	0.073	0.070	0.067	0.064	0.061	0.057	0.054	0.051	0.048	0.045

NPV - Net present value; IRR - Internal rate of return; B/C - Benefit/cost ratio; LCOE - Levelized cost of energy

These results agree with those of Carrêlo et al. (2020), demonstrating that the variation in the cost of investment in the behavior of IRR was decreasing as a function of the increase in costs, while the LCOE shows the opposite behavior. The same authors emphasize that sensitivity analysis shows the robustness of the profitability of photovoltaic systems against the variation of the system's investment cost.

Ouedraogo et al. (2015) emphasize that understanding the price of photovoltaic energy is an important factor in determining the cost of the electricity generated. These authors demonstrate the occurrence of sensitivity to the reduction of system costs in relation to the LCOE indicator, which tends to decrease with the price of the photovoltaic system. These reductions in the costs of photovoltaic system technologies have a relevant impact on the reduction of LCOE, as they enable a rapid implementation of the system based on a real energy market (Hwang et al., 2021).

Conclusions

1. Photovoltaic power generation projects for irrigation systems have increasing costs as a function of increasing power. However, the cost normalized by power followed an economy of scale, reaching 65% at the highest powers.

2. The levelized cost of energy showed the feasibility of the generation systems as a function of the powers used, except for the 22.1 kW power.

3. Based on the sensitivity analysis, the photovoltaic power generation systems are profitable in relation to the variation of the product prices.

4. For the variation of the implementation costs, the power of 22.1 kW has values higher than the energy tariff in the region.

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