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Economic analysis of photovoltaic energy in irrigating lettuce crops

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ABSTRACT: Irrigated agriculture is extremely important for Brazil and this technology has increasingly spread among small producers in the country. Irrigation systems located in olive groves add high rates of productivity to plants, especially hardwood vegetables. However, it is necessary to invest in sustainable technologies which reduce energy costs in localized irrigation. Therefore, the objective of this work was to evaluate the technical and economic viability of photovoltaic energy through simulating a drip irrigation system for lettuce crops. Tests were carried out on a hydraulic bench with drip irrigation simulations and set performance curves of the set were compared with the energy from the conventional system (electric grid) and photovoltaic energy. To do so, a direct current electric motor pump and an alternating current electric motor pump were used. The results showed that the use of irrigation for the lettuce crop promoted by photovoltaic energy reduced energy costs by 83.80% when compared to conventional energy.

Key words: cost; electricity; *Lactuca sativa* L.; rip; solar energy

Análise econômica da energia fotovoltaica na irrigação de culturas de alface

RESUMO: A agricultura irrigada é de fundamental importância para o Brasil e, cada vez mais, esta tecnologia tem se difundido entre pequenos produtores do país. Sistemas de irrigação localizada em olerícolas agregam altos índices de produtividade às plantas, principalmente às hortaliças folhosas. No entanto, é necessário investir em tecnologias sustentáveis, que diminuam os custos com energia elétrica na irrigação localizada. Desta forma, objetivou-se com o presente trabalho avaliar a viabilidade técnica e econômica da energia fotovoltaica, através da simulação de um sistema de irrigação por gotejamento, para a cultura de alface. Realizou-se ensaios em uma bancada hidráulica com simulações de irrigação por gotejamento e foram determinadas curvas de desempenho do conjunto, defrontando os gastos com a energia proveniente do sistema convencional (rede) e a energia fotovoltaica. Para tanto, utilizou-se uma motobomba elétrica de corrente contínua e uma motobomba elétrica de corrente alternada. Os resultados encontrados demonstraram que o emprego da irrigação para a cultura de alface, promovida pela energia fotovoltaica, reduziu os custos com energia elétrica em 83,80%, quando comparado à energia convencional.

Palavras-chave: custo; eletricidade; *Lactuca sativa* L.; gotejamento; energia solar

Introduction

In recent years, electricity generation from photovoltaic systems has shown considerable growth around the world, being explained by the reduction in costs of implementing photovoltaic projects, as well as the remarkable reduction of conventional electricity consumption (Pietzcker et al., 2014).

Hernández-Moro & Martínez-Duart (2013) stress that solar photovoltaic projects are of excellent value when compared to conventional power generation systems, having better operational performance mainly in areas whose solar incidence favors the technology. Therefore, it is a viable technology for small and medium projects which require electricity, such as abstraction, pumping and irrigation water usage in agriculture.

Energy is a basic factor for any modern economy. Its availability and reliability are crucial to development of a nation. In this sense, one of the foundations of a country's economic sustainability is its ability to provide logistics and energy for developing its production safely and in competitive and environmentally sustainable conditions (Tolmasquim & Guerreiro, 2014).

Pinto (2018) discusses important comparison values of the solar energy incidence potential in Brazil, where the least sunny region of the country presents about 1642 kWh m^{-2} of energy, while the sunniest region of Germany only presents about 1300 kWh m^{-2} of energy, constituting 40% lower than in Brazil.

The main factors which determine the economic advantage of solar photovoltaic systems compared to conventional systems are: the amount of solar energy that reaches the earth's surface, the final cost per watt peak (Wp) installed, the lifetime system cost and total operating cost (Green & Stephen, 2017).

Technology which involves a photovoltaic system for irrigating small agricultural areas has components such as: photovoltaic generator; power conditioning equipment (inverter, controller, etc.); motor pump group; a reservoir for water storage; and the distribution system (Pinho & Gaudino, 2014). This system is capable of generating enough energy to support localized irrigation projects (micro sprinkler or drip) in crops such as olericultural, tuberous, bulbous, and fruit, among others (Silva et al., 2017).

Growing demand for irrigation technologies by rural producers is expected to impact the various sectors of electricity generation and distribution, which combined with the high costs of electricity consumption categories may lead to higher prices for agricultural products which are dependent on irrigation management. According to the Energy Research Company (*EPE*) (2016), the agricultural sector is dependent on fuel energy sources from petroleum, electricity and plant material, with diesel oil accounting for 58% of these sources in the field.

The use of alternative and sustainable sources of electricity generation to satisfy agricultural systems and projects is of the utmost importance, as they reduce the use of fossil fuels and contribute to the rural producer being independent of tertiary companies for supplying electricity. Independence for electricity generation by rural producers makes it possible to reduce the costs of water management in irrigation technologies, especially in small production areas such as leafy vegetable products.

Lettuce (*Lactuca sativa* L.) is mainly cultivated by small farmers, being one of the most consumed leafy vegetables in Brazil and with productive potential all year round under adequate water and soil nutrient conditions (Valeriano et al., 2018). Irrigation management in this crop is extremely important to guarantee its production and periodic flow to the final consumer, which demands a high investment from producers in technology and electric power.

Photovoltaic systems for irrigation management may be a viable alternative to small producers of lettuce (Silva et al., 2017). Maggi et al. (2018) indicated that it is possible to obtain maximum yields for the crop using irrigation systems located in limited areas and at lower cost to farmers.

In this sense, the objective of this work was to evaluate the technical and economic viability of photovoltaic energy by simulating a drip irrigation system for lettuce crops.

Material and Methods

The experiment was conducted at the Hydraulic Laboratory of the Federal Institute of Southern Minas (IFSULDEMINAS), Machado campus, MG 453 Highway, Km 3, Santo Antônio, Machado-MG, at the coordinates 21° 40' 00'' South latitude and 45° 55' 00'' West longitude. The climate of the region is CWA (mesothermal rainy) according to the Koppen classifcation with dry winters and rainy summers, and 873 m altitude (Peel et al., 2007).

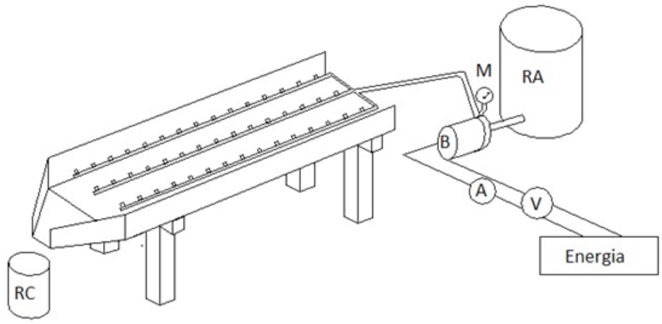
Three cultivation lines (4.5 meters in length each) were adopted to perform the drip irrigation simulation tests, and the 0.3x0.3 m spacing between plants was used as reference, according to Brzezinski et al. (2017) for lettuce crops, totaling 45 plants in the proposed model and a total area of 4.05 m^2.

The designed irrigation system consisted of three polyethylene pipes (Diameter (∅) 13 mm and 4.5 m in length), drippers spaced every 0.3 m, totaling 15 drippers (Agrojet - GA 2, with working pressure of 6 to 50 mca and with a maximum flow of 2.5 L h^{-1}) per line and a pressure gauge for monitoring water pressure (Figure 1).

A hydraulic bench was used for executing the experiment and data collection, (Figure 2), where both photovoltaic and conventional motor pumps were adapted for irrigation simulations and subsequent determination of motor pump performance curves.

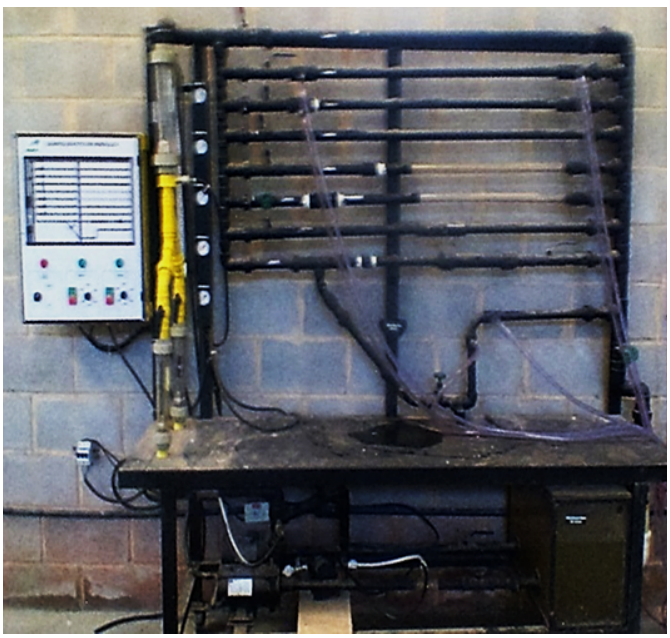
Conventional and photovoltaic pumping system

The conventional equipment used in the experiment (AC motor pump: Pressurizer RW9 9.0 mca -220 V Rowa) has an average market cost of approximately R$367.00, with a useful life of 43800 hours according to the manufacturer. The energy used to drive the alternating current (AC) motor pump



Source: Author's own elaboration (2018).

Figure 1. Irrigation system for conducting the experiment. Collection retainer (RA), power receiver (RC), pressure gauge (M), ammeter (A), voltmeter (V), solar or conventional motor pump (B), power source (conventional or photovoltaic).



Source: Author's own elaboration (2018).

Figure 2. Hydraulic bench used for gauging irrigation simulations.

came from the local power grid supplied by the *Companhia Energética de Minas Gerais - CEMIG*, and the operation of the direct current (DC) motor pump was provided by the energy generated by a photovoltaic panel.

The photovoltaic system consisted of the following components: photovoltaic module, charge controller, battery for energy storage and model 698 SEAFLO direct current pump.

The values of each component are broken down as follows:
Photovoltaic module .... R$580.00
Charge controller .... R$50.00
Battery .... R$69.50
Motor pump .... R$83.80

According to the literature in the area and manufacturers' information, a 30-year period for the life expectancy of photovoltaic panels, 5 years for batteries and motor pumps and 10 years for charge controllers was set (Akikur et al., 2013).

A model KM(P)140 KOMAES SOLAR photovoltaic module was installed on the roof of the building where the experiment was carried out, with an inclination angle of 11° according to the roof inclination and facing north for greater efficiency in capturing solar radiation. The panel connection was made to a Lorben 10a Solar Charge Controller and a Unicobra Unipower 12V 7Ah Up1270 battery, respectively. Charge controllers are responsible for maximum power transfer from the photovoltaic panel to the battery in order to charge it correctly.

Next, the battery was directly connected to the DC motor. It is known that water flow velocities may vary in photovoltaic pumping systems according to the solar radiation incidence level on the solar cell; a fact which hinders stability in maintaining constant velocities and consequent determination of curves. In this sense, using a battery is desirable, as it is able to maintain the voltage and current requirements for functioning the DC motor and without oscillations occurring in a power supply at 12 V voltage.

Simulations and evaluations

Six tests were analyzed for each motor pump in the same hydraulic test bench with data collection observing the behavior of the motor pumps powered by photovoltaic energy and the utility company. When the water pumping was performed, the performance curves were measured to determine: the flow in liters per hour ($L\ h^{-1}$) and the pressure in meters of water column (mwc) in order to verify the simulated circuit performance.

After determining the performance curves, the viability of each drive system was measured by the energy consumed in kWh^{-1} and the total cost in US dollars per millimeter of applied spray (R$ mm^{-1}).

Testing was only initiated after the air had been eliminated from the system to prevent errors of this nature in data readings.

The drip flow rate was measured by collecting the total water pumped and collected in a graduated container (Figure 1), being timed until the total volume of the container was completely filled. Voltage data were collected in Volts (V) by a digital multimeter (Dt-830B brand), the electric current in Amperes (A) using a 50-mm digital clamp meter (model ET-3200, MINIPA® brand) and pressure gauge in meters of water column (mwc) using a Class A2 pressure gauge in order to calculate the energy consumed in each motor pump used in the system.

Calculated parameters

The calculation of the given water spray is shown by Eq.1 (Quitaiski et al., 2018).

$$WS = \frac{Q}{A} \quad (1)$$

in which;

WS - water spray in mm h^{-1};

Q - flow rate, in L h^{-1}; and,

A - simulated area, in m².

The electric power generated in the photovoltaic module (Pfv) was estimated from Eq. 2 (EPE, 2016; Bhandari et al., 2015).

$$\text{Pfv} = \text{V} \cdot \text{I} \quad (2)$$

in which:

Pfv - photovoltaic system electrical power (kW) watts;

V - voltage in volts (V); and,

I - electric current in amps (A).

The hourly cost of the photovoltaic system was calculated by Eq. 3 (Bhandari et al., 2015).

$$\text{Csf} = \frac{\text{Cef}}{\text{ELefv}} \quad (3)$$

in which:

Csf - system cost, in reais per hour (R\$ h^{-1});

Cef - equipment cost, in reais (R\$); and,

ELefv - equipment life in hours (h).

The total irrigation cost of the lettuce crop using the photovoltaic system was calculated by Eq. 4.

$$\text{C}_{\text{TIPV}} = \text{Hi} \cdot \text{Cps} \quad (4)$$

in which;

C_{TIPV} - total cost of lettuce photovoltaic irrigation, in reais (R\$);

Hi - irrigation hours required to reach lettuce spray cycle (h); and,

Cps - photovoltaic system cost in R\$ h^{-1}.

Cost of conventional system equipment, Eq. 5 (Marquezan & Brondani, 2016).

$$\text{Ceqc} = \frac{\text{Vmp}}{\text{Lmp}} \quad (5)$$

in which:

Ceqc - cost of conventional system equipment (R\$ h^{-1});

Vmp - value of the conventional motor pump, in reais (R\$); and,

Lmp - motor pump life in hours (h).

The cost of conventional electricity was calculated by Eq. 6 (EPE, 2016).

$$\text{Cce} = \text{Cc} \cdot \text{Pc} \quad (6)$$

in which:

Cce - cost of conventional electricity, in R\$ h^{-1};

Cc - cost of electricity from conventional utility company (R\$0.46079 kW h^{-1}, normal rural value according to the rate of CEMIG (2018); and,

Pc - electrical power of the conventional system in kW.

The hourly cost of the conventional system, adapted from Turco et al. (2009), was calculated by the equipment cost and the energy cost of the utility company, Eq. 7.

$$\text{Csec} = \text{Cec} + \text{Ceqc} \quad (7)$$

in which:

Csec - conventional system cost, in reais per hour (R\$ h^{-1});

Cec - cost of conventional electricity, in R\$ h^{-1}; and,

Ceqc - cost of conventional equipment, in reais (R\$ h^{-1}).

The total irrigation cost of lettuce crop using the conventional system was calculated by Eq. 8 (Freitas et al., 2017).

$$\text{C}_{\text{TIC}} = \text{Hi} \cdot \text{Csec} \quad (8)$$

in which:

C_{TIC} - total cost of conventional irrigation, in reais (R\$);

Hi - irrigation hours required to reach lettuce spray cycle (h); and

Csec - conventional system cost, in R\$ h^{-1};

Results and Discussion

The motor pumps presented the minimum flow and pressure conditions necessary to drive the irrigation system, according to the performance curves verified for the motor power-driven pump and the photovoltaic-powered motor pump. In general, the photovoltaic pump proved to have a higher flow-to-pressure ratio than the utility-powered pump, under similar flow conditions (Figure 3 A and B).

Taking the 550 L h^{-1} flow as a reference, the pressure for the conventional motor pump is approximately 1.0 mcw when compared to the pressure of 5 mcw for the photovoltaic motor, i.e. the pressure of the conventional motor pump for this flow (550 m L h^{-1}) is 5 times lower than the photovoltaic motor pump. For flow rates close to 430 L h^{-1}, the conventional motor pump pressure was 4.67 times lower than that of the photovoltaic motor pump (Figure 3 A and B). Corroborating these results, Almeida et al. (2018), verified the direct relation of the lower head with the highest flow values of the set.

The results found in the flow vs. yield curve pressure of the photovoltaic pump indicate that the daily water demand for the lettuce crop made available by this system is able to supply the needs of the plants throughout the field cycle, agreeing with the irrigation tests performed by Vicentin et al. (2016). In using photovoltaic irrigation simulation models in grape and sunflower crops, López-Luque et al. (2017) and

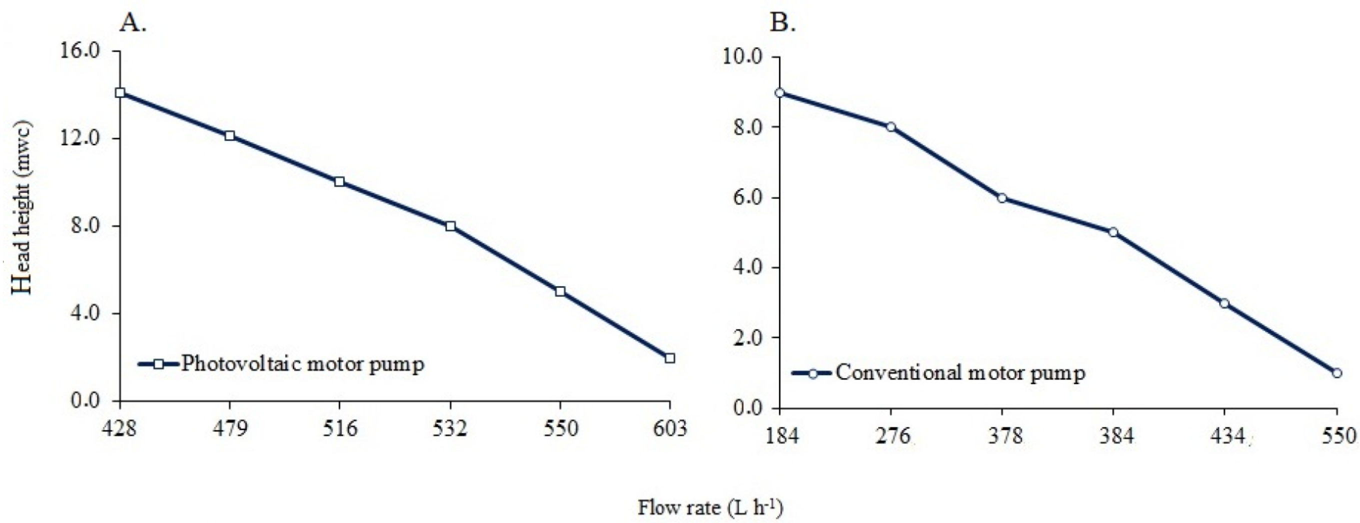


Figure 3. Flow curves vs. pump pressure, conventional (A) and photovoltaic (B), respectively.

Silva et al. (2017) also observed that the use of photovoltaic motor pumps presented better operational performance than the utility-powered motor pumps, being able to increase the irrigation sectors for the same area and make the project more efficient in capturing, distributing and using water for crops.

The mean flow rate of the photovoltaic system was 26.30 L h^{-1}. According to Vilas Boas et al. (2008), the most representative yields (total and commercial) for curly lettuce were obtained by applying 240 mm of irrigation spray. Thus, taking this value of applied spray as a reference, the water spray in the simulated area was estimated at 6.49 mm h^{-1}, which would require 37 hours of irrigation for the total lettuce cycle. Gherbi et al. (2017) verified the efficiency of direct current photovoltaic pumps and pointed out that the use of solar photovoltaic energy as a power source for water pumping systems is viable compared to conventional systems. However, because electric power generation is dependent on the solar radiation incidence, the irrigation time to apply the required spray may increase.

The mean conventional system flow rate collected during the simulated irrigation test was equal to 36.78 L h^{-1}. The spray required for this flow rate for the 4.05 m² area would be 9.08 mm h^{-1}, whereas the conventional irrigation system would take 26.43 hours to perform the whole crop cycle irrigation.

The photovoltaic system power consumed during the test performance was 76.4 W (0.0764kW), resulting in a power consumption of 2.8 kWh during the simulation period (37 hours of irrigation, total lettuce cycle). In contrast, the electrical power required for the conventional system during the performance test was 99.0 W (0.099 kW), consuming 2.6 kWh over a simulation period of 26.43 hours of irrigation (total lettuce cycle), as shown in the data breakdown in Table 1.

The investment for the conventional system was R$367.00, considering only the motor pump. For the photovoltaic system, the photovoltaic panel, batteries, motor pump and charge controllers were considered, totaling an investment of R$783.30. The investment in the photovoltaic system was 2.13 times higher than the conventional system.

Table 1. Data collected during the test for the photovoltaic system and the conventional system (powered by the utility).

System data	Photovoltaic	Conventional
Flow rate (L h^{-1})	26.30	36.78
*Applied water spray (mm h^{-1})	6.49	9.08
Irrigation time throughout the cycle (h)	37	26.43
Test Power (W)	76.4	99.0
Total power consumed in the cycle (kW h^{-1})	2.8	2.6

* Vilas Boas et al. (2008).

Considering the useful life of each component of the photovoltaic system: photovoltaic panel, batteries, motor pump and load controller, each value being divided by the number of hours of useful life, generates the total implementation cost for the photovoltaic irrigation system of R$0.006276 h^{-1}, which is multiplied by the required hours of irrigation throughout the crop cycle, resulting in a total of R$0.23 for the lettuce crop. The conventional equipment cost (Ceqc) was R$0.008378 h^{-1}. In comparing the equipment life of the systems, the photovoltaic system has a lower installation investment.

However, the conventional system consumes electricity from the grid, which has a cost (Cc) of R$0.46079kWh^{-1}, which results in electricity consumed R$0.0456182 (Cec = Cc . Pc), totaling a cost (Csec = Cec + Ceqc) of R$0.05399kWh^{-1}, the total cost of conventional irrigation for the whole lettuce crop cycle (Ctic), considering the usage time of the motor pump of 26.43 h, was R$1.42.

The cost of conventional irrigation (R$1.42) was approximately R$1.19 above the cost of the photovoltaic irrigation system (R$0.23), which represents a savings of approximately 83.80% of the photovoltaic system when compared to conventional data reported in Table 2.

Table 2. Photovoltaic system and utility company energy costs.

System data	Photovoltaic	Conventional
Equipment costs (R$)	783.00	367.00
Utility company energy cost (R$ h^{-1})	----	0.46079*
Total cost of equipment divided by useful life (R$ h^{-1})	0.0062276	0.008378
System cost (R$ kW h^{-1})	----	0.05399**
Total irrigation cost (R$)	0.23	1.42

* normal rural electricity value according to the rate of CEMIG (2018); **Cec = Cc . Pc; Csec = Cec + Ceqc.

In comparing irrigation systems with electric, diesel and photovoltaic grid electric drives by means of simulations, Freitas et al. (2017) concluded that the photovoltaic system presented a larger initial investment than the others. In contrast, the annual cost of electricity was zero reais; a fact which demonstrated the energy efficiency of this system in relation to diesel and also the non-emission of carbon into the atmosphere by the use of fossil fuels.

Considering the values found in this study for an area of 1 hectare, the savings would be R$2,938.27 for a lettuce crop irrigated under the photovoltaic system, so it is possible to estimate that the reduction in electricity costs would cover the investment in acquiring the photovoltaic system in only one lettuce crop cycle.

Conclusions

The purchase of equipment used for the photovoltaic irrigation system requires greater initial investment.

The photovoltaic system has a longer life than the conventional system, reducing costs over time.

The cost of the electricity supplied by the grid is the main factor that impacts the irrigation costs of the conventional system.

Photovoltaic irrigation reduced costs by 83.80% compared to the conventional grid-supplied irrigation.

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