ORIGINAL ARTICLE

Feasibility of the Introduction of a Solar Photovoltaic System in a Dairy Agroecosystem

Factibilidad de la introducción de un sistema solar fotovoltaico en un agroecosistema lechero

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ABSTRACT: This research is aimed at determining the feasibility of introducing a photovoltaic solar system in 021 Dairy Farm of "El Guayabal" University Farm belonging to the Agrarian University of Havana. The consumption of electrical energy was evaluated and the feasibility of three variants was determined in terms of the number of solar panels (342, 126 and 128) that the photovoltaic solar system must have to satisfy the energy demand. An analysis of the economic and environmental impact of the proposed installation was carried out, which showed that it will allow a saving of electrical energy higher than 43,781.75 kWh/year. With the three variants analyzed, savings were obtained in terms of energy not consumed, avoiding the emission of at least 49.47 t of CO_2 into the atmosphere annually, and the consumption of at least 11.47 t of fossil fuel. The preliminary cost to establish the installation proposed was estimated at: 386,255.2 CUP, 419,586.6 CUP and 1,048,290 CUP, according to the variants: without considering the current pumping system, considering the current pumping system and assessing the introduction of the solar pumping system PS2-150 C-SJ5-8, respectively. The energy storage system was not included in any of the variants.

Keywords: Energy, Solar Panels, Milk Production.

RESUMEN: La presente investigación se orienta en la determinación de la factibilidad de la introducción de un sistema solar fotovoltaico en la Vaquería 021 de la Granja Universitaria “El Guayabal” perteneciente a la Universidad Agraria de La Habana. Se evaluó el consumo de energía eléctrica y se determinó la factibilidad de tres variantes en cuanto a la cantidad de paneles solares (342, 126 y 128) con que debe contar el sistema solar fotovoltaico para satisfacer la demanda energética. Se realizó un análisis del impacto económico y medioambiental de la instalación propuesta, el cual, arrojó que la misma permitirá un ahorro de energía eléctrica no menor a 43 781,75 kWh/año. Con las tres variantes analizadas se obtuvo un ahorro por concepto de energía no consumida, dejándose de emitir a la atmósfera anualmente al menos 49,47 t de CO_2, y de consumir al menos 11,47 t de combustible fósil. El costo preliminar para establecer la instalación propuesta se estimó en: 386 255,2 CUP, 419 586,6 CUP y 1 048 290 CUP, de acuerdo con las variantes “sin considerar el sistema de bombeo actual, considerando el sistema de bombeo actual y valorando la introducción del sistema de bombeo solar PS2-150 C-SJ5-8”, respectivamente. El sistema de acumulación de energía no se incluyó en ninguna de las variantes.

Palabras clave: energía, paneles solares, producción lechera.

INTRODUCTION

Milk is a basic and indispensable food in human diet due to its excellent nutritional quality and energy content. In the Latin American and Caribbean region, 185 kcal/capita/day are consumed (Acosta *et al.*, 2017). For Cuba, it represents a link of eminent importance within the agricultural scenario due to its high consumption demand. In 2016, a national production of 612,800 t was reached (ONEI-Cuba, 2017). However, these volumes do not meet neither industry nor consumers demand, for which the country is forced to invest millions of dollars annually, in the importation of significant amounts of dairy products Martínez *et al.* (2017), aspect that makes dairy production a matter of national security.

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On the other hand, the depletion of fossil energy sources, the instability of oil prices in international markets and the accumulated negative effects on the environment due to the burning of hydrocarbons are sufficient elements that indicate the urgency of defining conscious and determined strategies for the use of renewable energy sources, on a local and global scale (Funes, 2009; Hernández *et al.*, 2019). In Cuba, great efforts are made to achieve a development that integrates the efficient use of ene rgy resources, to the expectations of quality of life of the population (Blanco *et al.*, 2014).

Due to the depletion of world oil reserves, which is used as a direct source of energy, or to generate other energies (electricity, for example), this irreversible phenomenon has been called "Energy Crisis". The reasons can be many: increase in electricity consumption due to constant growth, both in the residential sector and in the industrial sector, which are the ones that demand the greatest amount of energy, increase in the number of automobiles, depletion of natural resources such as fresh water, along with the aforementioned oil. Faced with this crisis, the need has arisen to take better advantage of the available energy resources, ways have been devised to take advantage of different types of natural energies with the purpose of converting them into electrical energy, which also have the advantage of being renewable (León *et al.*, 2021).

Solar radiation is used directly in thermal and photovoltaic transformations, that is, in the form of heat and electricity. Thermal conversion is currently the most efficient economically and advantageous way of using solar energy. The widespread domestic use of solar hot water for personal hygiene, washing up and cooking food, means considerable savings in the consumption of polluting fuels. The consumption of fuels in heating water and other fluids in industry, commerce, tourism and in social buildings such as schools and hospitals, is also very high; it could be satisfied with solar installations, in a sustainable and environmentally healthy way (Bérriz y Álvarez, 2008; Bérriz *et al.*, 2016).

In the specific case of photovoltaic solar energy, it consists of the direct transformation of solar radiation into electrical energy, taking advantage of the properties of semiconductor materials through photovoltaic cells. The base material for the manufacture of photovoltaic panels is usually silicon. When sunlight (photons) strikes one of the faces of the solar cell, it generates an electrical current. This generated electricity can be used as a source of energy (Sánchez *et al.*, 2017; Perpiñán, 2020; Kaffman, 2021).

At present, the economic feasibility of introducing a photovoltaic solar system with static changes that satisfies the demand of 021 Dairy Farm of "El Guayabal" University Farm is not known, so it is considered that the characterization of the proposal for a photovoltaic solar system may be conceived from the perspective dimensioning of electrical energy consumption. Coherently, the objective of this research was to determine the feasibility of introducing a photovoltaic solar system in said agroecosystem.

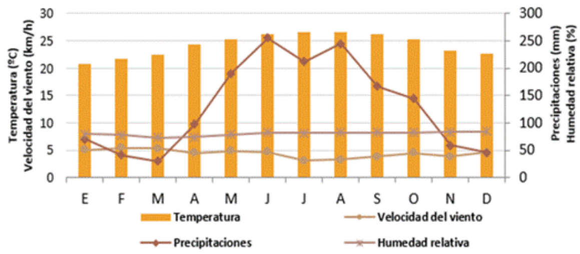

FIGURE 1. Monthly averages of climatic variables in 021 Dairy Farm, period 2015-2021. Source: Tapaste Meteorological Station.

MATERIALS AND METHODS

Characterization of the Experimental Area

The 021 Dairy Farm of "El Guayabal" University Farm, belonging to the Agrarian University of Havana (UNAH), is located at 23°00'12.5" North latitude, and 82°09'57.9" West longitude in San José de Las Lajas Municipality, Mayabeque Province, Cuba. It limits to the northwest with 023 Dairy Farm, to the northeast with the National Highway, to the southeast with 025 Dairy Farm and to the southwest with 022 Dairy Farm. The total area is 36 ha, with typical Red Ferralitic soil (Hernández *et al.*, 2019) in all its extension. It has a flat relief at 120 m above sea level and annual insolation of 1825 kWh/m2 (Díaz, 2018). The meteorological variables recorded during the period 2015-2021 at Tapaste Meteorological Station (Figure 1), showed that the maximum temperatures reached in the region exceeded 26 ºC between the months of June and September and the coldest fell on average to 20 .76 ºC in January. Rainfall showed increases from May, and indicated the highest average values in June and August with 255.50 and 245.16 mm, respectively. The relative humidity varied between 72.8% (minimum, in March) and 84.6% (maximum, in December), while the wind speed reached its maximum of 5.46 km/h during the month of February. The behavior of these climatic variables allows the satisfactory development of dairy farming.

As a result of studying the behavior of electricity consumption in 021 Dairy Farm, during the year 2021, a high consumption equivalent to a monthly average of 3102,083 kWh was verified.

The dairy has 34 milking cows, which reached an average daily milk production of 7.4 L/cow during 2021, so this dairy collects a total of 251.6 L/day on a daily basis.

Estimation of the Consumption in the Dairy Farm

For dimensioning the photovoltaic solar installation, the critical average daily consumption of the load to which energy has to be supplied was initially determined. This parameter is associated with the days with the highest energy consumption. Due to the fact that, in Cuba, the behavior of the incidence of solar radiation does not vary abruptly during the 12 months of the year, the monthly mean value of the incident radiation for an angle of inclination of 18°-25° degrees to the south is of 5.00 kWh/m^2 (Bérriz *et al.*, 2016).

To determine the energy to be delivered by the photovoltaic system, the losses involving the batteries, the inverter and the conductors were considered.

To calculate the average daily consumption of the dairy farm, the average consumption for constant loads and the number of inventories were taken into account, due to the fact that the equipment used in the area under study is subjected to static loads, as is the case of fodder mill, refrigeration system, mechanized milking system, water pump, electric fence and illumination. Static electrical charges are considered those that have a fixed consumption of electrical energy over time (Prado, 2008; Encuentra, 2020).

Therefore, considering the methodology proposed by León *et al.* (2021), it is possible to determine the average daily consumption of the installation, using the following expression:

$$L_{mdn} = \frac{L_{md}}{\eta_{bat} \cdot \eta_{inv} \cdot \eta_{cond}}, kWh \quad (1)$$

where:

L_{md}: Critical real average consumption of the load, kWh;

η_{bat}: Battery efficiency;

η_{inv}: Inverter efficiency;

η_{cond}: Conductor efficiency.

To determine the energy demand of the productive scenario, a survey of the electrical means and equipment located in the area under study is carried out, determining the power (N) of each of them and the daily operation time (To), with these two parameters, the energy consumed daily L md in the dairy farm can be determined using the following expression:

$$L_{md} = N \cdot T_0, kWh \quad (2)$$

where:

N: Power of electrical equipment and means, kW;

T_o: Daily operation time, h.

Methodology for Dimensioning the Photovoltaic System

To determine the number of solar panels required, a criterion was used based on the estimation of the consumption of Ampere-hours (Ah) of the installation as recommended by Hernández (2007), being the average daily current consumption required:

$$Q_{Ah} = \frac{L_{mdn}}{V_{bat}}, Ah/day \quad (3)$$

where:

V_{bat} : Battery voltage (12 V), V.

Likewise, according to Alonso (2011) & Cantos (2016), the current that a photovoltaic system must generate in the critical month of solar radiation is determined as:

$$I_{gfv,mpp} = \frac{Q_{Ah}}{HPS_{crit}}, \text{A} \quad (4)$$

where:

HPS_{crit} : Peak sun hours of the critical month, h.

Then, being $I_{gfv,mpp}$ the current generated by the photovoltaic system (the total number of solar panels installed) and dividing it by the unit current of each photovoltaic module, the total number of modules necessary to connect in parallel is obtained (Alonso, 2011). So that:

$$Np = \frac{I_{gfv,mpp}}{I_{mod}} \quad (5)$$

where:

I_{mod} : Specific unit current of each photovoltaic module, A.

Each photovoltaic module is made up of four panels, a 250 W grid injection micro-inverter and occupies an area of 3.12 m2.

Methodology for the Dimensioning of the Accumulation System

In this investigation, the determination of an accumulation system was not considered, since conceiving this would considerably increase the cost of introducing photovoltaic solar energy in the scenario under study.

Methodology for Estimating the Economic Impact of the Installation

When a photovoltaic solar system is used, clean, renewable and safe energy is used efficiently. It contributes significantly to the reduction of greenhouse gases that cause climate change and considerably improves air quality, since the use of fossil fuels is significantly reduced. As a result of the above, it is necessary to know how much fossil energy is no longer consumed (number of kWh of electricity avoided monthly and annually) with the implementation of this photovoltaic solar system (Canvi climàtic, 2011; Acevedo 2016). Acevedo (2016) points out that from the use of these photovoltaic solar systems, a certain amount of electrical energy is saved in a month, for which:

$$Q_{CM} = L_{md} \cdot D_m, kWh \quad (6)$$

where:

D_m : Days in a month.

Being the energy saved in a year:

$$Q_{CA} = 12 \cdot Q_{CM} \cdot D_m, kWh \quad (7)$$

To determine the cost of energy saved in a year, the provisions of RESOLUTION 66/2021 Bolaños (2021) of the Ministry of Finance and Prices of the Republic of Cuba were considered, which establish electricity rates in Cuban pesos (CUP) for the collection of electric service. For the specific case of the present investigation, since it is a dairy farm, whose corporate purpose is the production of bovine milk, the system of high voltage rates with continuous activity is considered, specifically the one that responds to the energy consumed during business hours' day:

$$Cday = (a.K + b).Qcday, CUP/day \quad (8)$$

where:

a, b: Coefficients to be applied according to the type of rate (1.5282 and 0.7273 CUP/kWh, respectively); K: Fuel price variation adjustment factor; Qcday: Energy consumption in one day, kWh/day.

By analogy, the cost of energy saved in a year can be calculated, which is possible through the equation:

$$Cyear = (a.K + b).QcA, \frac{CUP}{year} \quad (9)$$

Methodology for Estimating the Environmental Impact of the Installation

In order to implement these heat machines, it was necessary to know the amount of emissions avoided into the atmosphere. The mass of CO_2 emitted into the atmosphere from the burning of fossil fuels was determined according to Ruisánchez (2018):

$$M_{CO_2} = \iota \cdot Q_{CM}, \frac{kg}{month} \quad (10)$$

where:

ι : Emission rate, kg/kWh

According to the National Electrical Union UNE-Cuba (2021), each kWh produced at the generation plant level emits 1.13 kg of CO_2 into the atmosphere. The mass of fossil fuel needed to produce a given amount of energy in one month was determined by:

$$M_{CM} = \gamma \cdot Q_{CM}, kg/month \quad (11)$$

where:

γ : Fuel consumption index, kg/kWh

The assumed value for the consumption rate is 0.262 kg/kWh (ICG-Brasil, 2012; UNE-Cuba 2021)

RESULTS AND DISCUSSION

Assessment of the Electrical Energy Consumption of 021 Dairy Farm

In 021 Dairy Farm, static electrical loads are basically evident. Systems that have a static load are those in which their electrical consumption does not depend significantly on their state of load (Prado, 2008; Encuentra, 2020). Examples of this type of systems are those that involve low and medium power electric motors. Such is the case of electric forage mills and water pumps, among others. In the particular case of the dairy farm under study, a significant part of electricity consumption is associated with water supply and the processing of animal feed (forage milling) and human feed (obtaining and refrigerating milk). That is why its electrical consumption has a great variability, as it is shown in Figure 1.

Based on the analysis, it was found that, during 2021, the highest daily energy consumption was obtained in the months of January, February and April with values of 106,141.5 and 115.9 kWh, respectively, which shows that 021 Dairy Farm is a high consumer of electricity.

Proposal for a Photovoltaic Solar System for the 021 Dairy Farm

For the realization of the proposal of a photovoltaic solar system in areas of 021 Dairy Farm, solar panels marketed by the Cuban company COPEXTEL were used. The corresponding technical data are shown in Table 1.

In addition, Trojan batteries were selected, whose technical data are shown in Table 2.

For this proposal, the inverter that COPEXTEL sells was also taken into account, with a power 20% greater than that demanded by the equipment.

In this case, the use of a maximum power point monitoring regulator is not considered, since the photovoltaic systems that include it constitute systems that improve the efficiency of the installation between 10 and 25%. The fundamental problem with these regulators lies in their high cost for small and

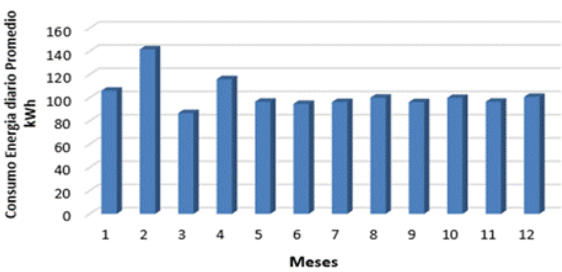

FIGURE 2. Behavior of the average daily energy consumption of 021 Dairy Farm (2021).

TABLE 1. Technical data of the solar panels marketed by COPEXTEL

Parameter	Specification
Module peak power under standard conditions, W	270
Maximum module voltage, V	55,10
Module short circuit current, A	5,30
Module maximum unit current, A	4,9
Investor performance	0,9
Conductors performance	1
Battery performance	0,95

TABLE 2. Technical data of the proposed Trojan monoblock batteries

Parameter	Specification
Maximum Seasonal Discharge Depth, %	70
Maximum Daily Discharge Depth, %	15
Performance	0,9-0,95
Voltage, V	12
Current capacity, A	240

medium-sized installations. In the case of the proposal, due to the volume of energy to be generated, it would require a large-capacity regulator with maximum power point tracking capacity, which would raise the total cost of the installation by at least 30 to 40% more just for this concept. (Gasquet, 2004; Acevedo, 2016).

Dimensioning of the Parts of the Proposed Photovoltaic Solar System

Before proceeding to determine the dimensioning of the solar photovoltaic system for the areas of 021 Dairy Farm, a survey of the existing means and equipment in the scenario under study was carried out, as well as their operating time, which were reflected in Table 3.

As it can be seen in Table 3, 102.85 kWh of electrical energy are consumed daily in this dairy farm, an element that demonstrates the high consumption of this production scenario. It is important to point out that 62,9% of the energy consumed is due to water pumping, so the dimensioning of the photovoltaic solar system was determined for three variants:

- Considering the current pumping system
- Without considering the current pumping system
- Assessing the introduction of a solar pumping system PS2-150 C-SJ5-8 Brand LORENTZ.

In the specific case of the last variant, this solar pumping system is made up of: two solar panels, a PS2-150 Controller and a submersible pump with a maximum load of 20 m and a maximum output of 4.6 m3/h (1 .2 L/s, these elements are shown in Figure 3 (a, b and c)

Table 4 summarizes the values of the dimensioning parameters of the photovoltaic solar system, considering the existing pumping system.

As it can be seen in Table 4, with the use of photovoltaic solar energy, it is possible to reduce costs for conventional fuels to produce electricity. The cost of the electrical energy not consumed from the use of the energy generated from the proposed variants is 241,320.7 CUP/month (considering the current pumping system), 88,917.52 CUP/month (without considering the current pumping system) and 89,535 CUP/month (considering the introduction of the PS2-150 C-SJ5-8 solar pumping system) per month, respectively. On the other hand, if the milk production of the dairy is considered, which amounts to 251.6 L/day and the price of milk is equivalent to 20 CUP/L, then it is possible to collect 5,032 CUP/day (150,960 CUP /month), so that for each case analyzed it is possible to recover the investment in: 1.6 months when considering the pumping system, 0.6 months without considering the pumping system and 0.6 months with the introduction of the PS2-150 C-SJ5-8 solar pumping.

TABLE 3. Energy characteristics of the means and electrical equipment existing in 021 Dairy Farm

Electrical means and equipment	Power, kW	Operating time, h	Energy consumed per day, kWh/day
Fodder mill	5,5	1	5.5
Water pump	18,5	3,5	64.75
Refrigeration system	4	4	16
Mechanized milking system	5	3	15
Electric fence	0,04	10	0.4
Luminaires	0,1	12	1.2
Total			**102.85**

a) b) c)

FIGURE 3. Component parts of the solar pumping system PS2-150 C-SJ5-8 LORENTZ brand: a) Photovoltaic panels b) PS2-150 controller c) submersible pump.

TABLE 4. Dimensioning of the photovoltaic solar system for the three variants and economic analysis of the proposals

Parameter	Symbol	Value
Average daily consumption of the dairy farm	L_{mdn}, kWh	119.95
Average daily power consumption	$Q_{Ah}, Ah/day$	9995.83
Current that the photovoltaic field must generate in the critical month of solar radiation	$I_{gfv,mpp}, A$	1675.80
Considering the current pumping system		
Total solar panels	Np	342
Total photovoltaic modules	Nm	85
Required area	Ar, m^2	267
Energy to produce with the photovoltaic system	Ep, kWh	2567.24
Investment cost	C_{inv}, CUP	1 048 290
Without considering the current pumping system		
Total solar panels	Np	126
Total photovoltaic modules	Nm	32
Required area	Ar, m^2	99
Energy to produce with the photovoltaic system	Ep, kWh	945.93
Investment cost	C_{inv}, CUP	386 255.2
Considering the solar pumping system PS2-150 C-SJ5-8 Brand LORENTZ		
Total solar panels	Np	128
Total photovoltaic modules	Nm	33
Required area	Ar, m^2	101
Energy to produce with the photovoltaic system	Ep, kWh	952.50
Investment cost	C_{inv}, CUP	419 586.6

However, the volume of production under current conditions and its economic value allow the investment in the acquisition of the photovoltaic solar system to be recovered in a period of 0.21 years (considering the current pumping system), 0.23 years (without considering the current pumping system) and 0.57 years (considering the acquisition of the PS2-150 C-SJ5-8 solar pumping system). Taking into account the acquisition of the PS2-150 C-SJ5-8 solar pumping system, this investment is recovered in 0.23 years.

If both, the saving of energy carriers in the form of fossil fuels and the environmental and productive impact are considered, it can be affirmed that the installation of a photovoltaic solar system is feasible to satisfy the demand of 021 Dairy Farm of the Guayabal Farm.

Analysis of the Environmental Impact of the Proposed Installation

Photovoltaic systems, when using a clean energy source to produce electricity, do not consume any type of fossil fuel, thus, with equation (6), the electrical energy that would not be consumed in one day was determined. In addition, with these results it is possible through expression (10) to know the mass of CO_2 not emitted into the atmosphere, being reflected in Table 5.

As evidenced in Table 5, due to the reduction of the fossil fuel required for the production of electrical energy and the mass of CO_2 not emitted into the environment, the economic and environmental feasibility of the introduction of the photovoltaic system in 021 Dairy Farm is demonstrated.

TABLE 5. Results of the environmental impact as a consequence of the proposed installation

Parameter	Estimated value
Electrical energy not consumed, kW/day.	119.95
Electrical energy saved, kWh/year.	43 781.75
Mass of CO2 not emitted to the atm, t/year.	49.47
Mass of fossil fuel to produce electricity, t/year.	11.47

CONCLUSIONS

- The volume of production under current conditions and its economic value allow the investment in the acquisition of the photovoltaic solar system to be recovered in a period of 0.21 years (considering the current pumping system), 0.23 years (without considering the current pumping) and 0.57 years (considering the acquisition of the PS2-150 C-SJ5-8 solar pumping system).
- The proposed installation would have a positive impact on the environment, since with the three variants analyzed, electrical energy savings of no less than 43,781.75 kWh/year were obtained; thus, at least 49.47 t of CO_2 would be avoided being

emitted annually, and at least 11.47 t of fossil fuel would not be consumed.

- The installation of the photovoltaic solar system is feasible energetically, economically and environmentally, since there would be significant savings for energy not consumed.

GRATEFULNESS

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