ORIGINAL ARTICLE

Determination of the Potential of Solar Energy as a Renewable Source for a Swine Center

Determinación del potencial de la energía solar como fuente renovable para un Centro Porcino

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ABSTRACT: The present investigation is oriented to determine the potential of solar energy as a renewable source for a swine center established in the "El Guayabal" University Farm, belonging to the Agrarian University of Havana, Cuba. For this, the number of animals is considered, as well as the movement of the herd, which would make it possible to determine the energy demand, based on the diagnosis of the energy carriers existing in the scenario. Among the main results obtained, it was evidenced that for the existing conditions, it is pertinent to introduce photovoltaic solar energy technology as a renewable source for driving the electric motor of the mill, the water pump and lighting, which implies an initial investment of 645 500 peso (25 820 USD). On the other hand, the introduction of a solar heater is viable, for the sanitation actions of the workers of the pig center, with the budget required for the acquisition of this technology being 9 650 peso (386 USD). The introduction of both technologies contributes directly to caring for the environment by stopping the emission of CO_2 and other greenhouse gases into the atmosphere and its corresponding negative impact on the environment. Finally, it is evident that, with only the commercialization of the pigs to the carcass of the first group, the total amount required for the acquisition of the photovoltaic system and the solar heater is recovered and it is possible to obtain a benefit that amounts to 478 850 pesos (19 154 USD), this element demonstrates the economic feasibility of this investment.

***Keywords*:** Photovoltaic Solar Energy, Thermal Solar Energy, Pig Production, Economic-Energetic Feasibility, Environment Impact.

RESUMEN: La presente investigación se orienta en determinar el potencial de la energia solar como fuente renovable para un centro porcino establecido en la Granja Universitaria “El Guayabal”, perteneciente a la Universidad Agraria de la Habana, Cuba. Para ello se considera la cantidad de animales, así como el movimiento de rebaño, lo cual posibilitaría determinar la demanda energética, sobre el diagnostico de los portadores energéticos existentes en el escenario. Entre los principales resultados obtenidos, se evidenció que para las condiciones existentes, resulta pertinente introducir la tecnología de energía solar fotovoltaica como fuente renovable para el accionamiento del motor eléctrico del molino, la bomba de agua y el alumbrado, lo cual supone una inversión inicial de 645 500 peso (25 820 USD), por otro lado resulta viable la introducción de un calentador solar, para las acciones de higienización de los trabajadores del centro porcino, siendo el presupuesto requerido para la adquisición de esta tecnología de 9 650 peso (386 USD), la introducción de ambas tecnologías contribuye directamente al cuidado del medio ambiente al dejarse de emitir CO_2 y otros gases de efecto invernadero a la atmósfera y por correspondiente su impacto negativo al medio ambiente. Finalmente, se evidencia que, con solo con la comercialización de los cerdos a la canal del primer lote, se recupera el monto total requerido para la adquisición del sistema fotovoltaico y del calentador solar y es posible obtener un beneficio que asciende a 478 850 peso (19 154 USD), este elemento demuestra la factibilidad económica de esta inversión.

Palabras clave: energía solar fotovoltaica, energía solar térmica, producción porcina, factibilidad económico-energética, impacto ambiental.

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INTRODUCTION

According to the International Energy Agency IEA (2021), the average efficiency of commercial silicon photovoltaic (PV) modules has improved in the last ten years by around 0,3% per year, reaching a value of 16% in 2013. The commercial modules with the best performance, based on different manufacturing technologies, reach efficiencies between 19 and 21%. Generally PV modules are guaranteed for a useful life of 25 years, at least during work at 80% of their nominal power, sometimes 30 years at 70% of their nominal power.

Since 2010, the world has added more PV power capacity than in the previous four decades. The new systems were installed in 2013 at a rate of 100 MW of capacity per day. At the beginning of 2014, global capacity exceeded 150 GW.

In 2014 data, China was the main market in 2013 with 11.8 GW of which 500 MW represent isolated systems. China was followed by Japan with 6.9 GW and the US with 4.8 GW. In Latin America, in 2014, 625 MW of PV energy came into operation, compared to the 133 MW installed in 2013. The main architect of this increase was Chile, contributing 75% of the total increase, followed distantly by Mexico and Brazil.

PV system prices have tripled over the past six years in most markets, while PV module prices have fallen fivefold. The cost of electricity from new built systems ranges from 90 USD to 300 USD/MWh, depending on the solar resource; the type, size, and cost of the systems, maturity of the markets and the costs of capital.

To achieve the above statistics, the costs of electricity from PV power in different parts of the world are expected to be reduced by 25% by 2020, 45% by 2030, and 65% by 2050; which leads to a range of 40 to 160 USD/MWh.

In 2014, the market for concentrated solar thermal energy continued with the pace of almost a decade of strong growth. During the course of the year, four new projects with a generation capacity of 0.9 GW were implemented, increasing global capacity to 4.4 GW. In the five years between 2009 and 2014, global operational capacity increased by an annual average of 46%. The United States remains the industry leader for the second consecutive year followed by India.

On the other hand, solar thermal technologies contribute to the production of hot water in many countries, heating and industrial processes. Globally, 55 GW of solar heating capacity was installed, up from 54.1 GW in 2012. An estimated 53.3 GWth of new installations in 2013 were glazed, while the remainder were non-glazed water heating systems, swimming pools (3.1%) and air collector systems (0.1%).

In Latin America there are incentives in countries like Chile, Mexico and Uruguay to implement solar heating. In Uruguay, a subsidy of 50% discount applicable directly from the electricity bill is guaranteed. In Mexico, subsidies are given for the use of solar collectors in social housing programs. In Chile, subsidies are awarded for the implementation of solar water heaters in the reconstruction of areas affected by natural phenomena (Rodes-Díaz, 2017).

There have been several investigations carried out on the introduction of solar energy in agricultural production systems, in which the feasibility of this renewable source in this productive line has been demonstrated (Bazen & Aristega, 2009; Talavera *et al.*, 2010; Smyth, 2012; Bazilian *et al.*, 2013; Ekman & Jonsson, 2014).

Considering current trends in solar energy, both for electricity generation and heat production, the objective of the research was to determine the potential of solar energy as a renewable source for a pig farm.

MATERIALS AND METHODS

The "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.. The existing soil in it is classified as Typical Red Ferralitic according to Hernández *et al.* (2015) in its entirety. It has a flat relief, height above sea level of 120 m and annual insolation of 1825kWh/m^2. The meteorological variables recorded during the period 2015-2021 at Tapaste Meteorological Station, showed that the maximum temperatures reached in the region exceeded 26 ºC between the months from June to September and the coldest dropped 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 expressed its maximum peak of 5,46 km/h during the month of February. The behavior of these climatic variables allows to satisfactorily developing pig breeding.

Within its facilities, the pig center is. It has a total capacity of 425 pigs in all productive categories, as shown in Table 1. The feeding system is alternative and uses Cuban silage feed as part of the energy fraction that the pigs need for their development, and balanced dry feed to cover the protein they require for their development.

Table 1 shows the data obtained regarding the movement of the animal mass in the pig farm.

For the operation of the productive system, there is a forage mill that has an electric motor with an power

TABLE 1. Movement of the pig herd in the Farm "El Guayabal"

Herd Movement	Initial Existence	End Existence	Animals/day	Average Mass , kg
Pigs stallions	5	5	5	130
Breeding sows	20	30	25	100
Fattening pigs	100	140	120	90
Pre-fattening pigs	100	100	100	25
Baby pigs	200	150	175	7
Total	**425**	**425**	**425**	**70.40**

of 4.5 kW for the processing of alternative foods, which is used for an average of two hours daily.

In the cleaning and water supply tasks, a hydraulic pump with a power of 5.5 kW is used, which drives the water from a pumping station, which is located relatively far from the pig farm (approximately 80 m), to elevated tanks placed 4 m above ground level; it is used six hours a day on average.

The lighting system has 40 luminaires of 40 W, which are used on average 10 hours a day.

Likewise, there is a sanitary bathroom with showers for the disinfection of the four workers during the entrance and exit of the facility, which on average use 60 L of water per capita daily.

For the establishment of the specific methodologies for the sizing of the photovoltaic system and the solar heater, the fundamentals raised by Morejón-Mesa *et al.* (2022).

Methodology for the Sizing and Installation of Photovoltaic Panels

To determine the energy that the photovoltaic installation must deliver, the losses involving the batteries, the inverter and the conductors must be considered.

To calculate the average daily consumption (E_{mdn}) of the installation, the actual average critical load consumption (E_{md}) will be taken into account and not the average consumption for constant loads or the number of inventories.

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

Where:

$E_{md:}$ Critical actual average consumption of the load,kWh; η_{bat}: battery efficiency; η_{inv}: inverter efficiency; η_{cond}: drivers efficiency.

If there is no electric counter in the research scenario, it is possible to determine the energy demand by surveying the means and electrical equipment located in the area under study, determining the power (N) and the daily operating time (To) of each of them. With these two parameters, it is possible to determine the energy consumed daily (E_{md}) in the installation, which can be determined using the following expression:

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

Where:

N: Power of electrical equipment and means, kW; T_o: Daily operating time, *h*.

Sizing of the Photovoltaic Generator

To determine the number of solar panels required, it is possible to use the criteria based on the estimate of the consumption of Amperes-hours of the installation Hernández (2007); León-Martínez *et al.* (2021). The average daily current consumption required is calculated as follows:

$$Q_{Ah} = \frac{E_{mdn}}{V_{bat}}, \frac{Ah}{día} \quad (3)$$

Where:

V_{bat}: Battery voltage, V.

Likewise, according to Alonso (2011; 2017), the current that a photovoltaic collection field must generate in the most critical month of solar radiation (I_{GFV}) is determined as:

$$I_{GFV} = \frac{Q_{Ah}}{TS_{crit}}, \text{A} \quad (4)$$

Where:

TS_{crit}: Peak sun hours of the most critical month, *h*.

Then (I_{GFV}) the current generated by the photovoltaic capture field (the total number of solar panels installed), is divided by the unit current of each photovoltaic module (I_{MOD}), and the total number of modules necessary connected in parallel is obtained by the formula:

$$Np = \frac{I_{GFV}}{I_{MOD}} \quad (5)$$

Where:

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

Dimensioning of the Accumulation System

According to Mascarós-Mateo (2015), to calculate the number of batteries required for a photovoltaic installation, the following must be considered:

- The autonomy time desired for the photovoltaic installation;
- The maximum seasonal discharge depth of the batteries;

- The maximum daily discharge depth of the batteries.

According to Alonso (2011), the nominal capacity of the battery based on the maximum seasonal discharge is determined according to:

$$C_{ne} = \frac{E_{mdn} \cdot N_{DA}}{P_{Dmax,e} \cdot F_{ct}}, kWh \quad (6)$$

$$C_{neAh} = \frac{C_{ne}}{V_{bat}}, Ah \quad (7)$$

Where:

N_{DA}: Number of days of autonomy of the installation; $P_{Dmax,e}$: Seasonal maximum depth of discharge of batteries; F_{ct}: Total charge factor of the batteries; C_{neAh}: Nominal battery capacity based on seasonal peak discharge, Ah.

Likewise, the nominal capacity of the battery based on the maximum daily discharge is determined according to:

$$C_{nd} = \frac{E_{mdn}}{P_{Dmax,d} \cdot F_{ct}}, kWh \quad (8)$$

$$C_{ndAh} = \frac{C_{nd}}{V_{bat}}, Ah \quad (9)$$

Where:

$P_{Dmax,d}$: Batteries maximum daily discharge depth; C_{ndAh}: Nominal battery capacity based on maximum daily discharge, Ah.

After determining the nominal capacity of the batteries based on the values of maximum stationary and daily discharge, the one with the highest value is taken and divided by the nominal current capacity of one of the batteries, to obtain the number of these necessary:

$$N_{bat} = \frac{C_{nAh}}{C_{nAh,bat}} \quad (10)$$

Sizing of the Regulator and Inverter

To determine the capacity of the regulator, the current at its input and at its output must be determined. So that:

$$I_{ent} = \left(1 + F_{seg}\right) \cdot N_r \cdot I_{mod,sc}, A \quad (11)$$

Where:

F_{seg}: Safety factor to avoid occasional damage to the regulator; Nr: Number of branches in parallel; $I_{mod,sc}$: Unit current of the photovoltaic module in short-circuit conditions, *A*.

$$I_{sal} = \frac{\left(1 + F_{seg}\right) \cdot E_{md,max}}{\eta_{inv} \cdot T_{tpc} \cdot V_{bat}}, A \quad (12)$$

Where:

$E_{md,max}$: Load consumption, kWh; T_{tpc}: Time of maximum load demand, h.

Mascarós-Mateo (2015), refers that to determine the power of the inverter required for the installation, proceed according to:

$$P_{inv} = \left(1 + F_{seg}\right) \cdot P_{AC}, W \quad (13)$$

Where:

P_{AC} – Starting power, W

Alonso (2011) states that many of the household appliances and equipment that have motors have current peaks at start-up. This means that these devices, at start-up, will have a power demand greater than the nominal, sometimes up to 4 or 5 times more than expected. For this reason, it is advisable to consider the effect of motor starting peaks when sizing the inverter whenever necessary to guarantee satisfactory operation of the installation.

When a photovoltaic solar park is used, clean, renewable and safe energy is being used efficiently. Contributing directly to the reduction of greenhouse gases that cause climate change, and significantly improving 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 yearly) with the implementation of this photovoltaic solar park (Canvi Climatic, 2011).

From the use of these photovoltaic solar parks, a certain amount of electrical energy is saved in a month, for which:

$$Q_{CM} = E_{md} \cdot D_m, kWh \quad (14)$$

Where:

D_m: days in a month.

Being the energy saved in a year:

$$Q_{CA} = 12 \cdot Q_{CM} D_m, kWh \quad (15)$$

To determine the cost of energy saved in a year, the provisions of Bérriz & Álvarez (2014); Aguilera-Proenza (2021), were considered, where the electricity rates are established in Cuban currency (peso) for the collection of electricity service. In the specific case of the tariff system for high voltage with continuous activity, the energy consumed during daylight hours, was considered. Being the cost of energy saved in one day:

$$C_{día} = (a \cdot K + b) \cdot Q_{cdía}, peso/day \quad (16)$$

Where:

a, *b*: Coefficients to apply according to the type of rate (1,5282 y 0,7273 respectively), peso/kWh; *K*: Fuel Price Variance Adjustment Factor; $Q_{cdía}$: Energy consumption in one day, kWh/day.

Similarly, the cost of energy saved in one year can be determined based on:

$$C_{año} = (a \cdot K + b) \cdot Q_{CA}, peso/year \quad (17)$$

Where:

Q_{CA}: Energy consumption in one year, *kWh/year*.

Methodology for the Determination of Solar Heaters

To determine the number of solar heaters that must be installed, it is necessary to know the water consumption demanded by the installation through the following expression:

$$C_{H_2O} = \frac{N_{C(H_2O)} \cdot C_{hd} \cdot W}{100}, L \quad (18)$$

Where:

$N_{C(H_2O)}$: Water consumption standard, *L/animal*; C_{hd}: number of animals in the herd or people in the dwelling ;W: Site occupancy rate, *%*.

In Cuba the average solar radiation per day, in the months of November to February, is 4200 kcal/m^2; being this period of less insolation in the year. A 200 L capacity vacuum tube heater can supply, under these conditions, around 300 L of hot water at 50.ºC per day.

It is valid to point out that this technology can also favor the family that resides in the livestock scenario, where in general, in the specific case of Cuban families, they have habits of carrying out various eating activities throughout the day (considering breakfast, lunch and dinner), plus hot water to wash the dishes, with a norm of 20 L per person with a temperature of 55ºC (Bérriz & Álvarez, 2014; Aguilera-Proenza, 2021).

The hot water demand of a location can be determined according to:

$$C_{H_2Oc} = \frac{N_{C(H_2Oc)} \cdot C_{hd} \cdot W}{100}, L \quad (19)$$

Where:

$N_{C(H_2Oc)}$: Hot water consumption standard, L/ person or L/animal;

Knowing the amount of water required by a site, the number of heaters necessary to meet its needs can be calculated, according to the expression:

$$N_{cs} = \frac{C_{H_2Oc}}{C_{ae}} \quad (20)$$

Where:

C_{ae}: Amount of water delivered by a heater with a given insolation, *L/day*.

According Canvi Climatic (2011), to determine the energy required to heat the water (Q_C) to be used, it is necessary to take into account the temperature jump, from 15 *ºC* to 50 *ºC*, so that:

$$Q_c = K_{CU} \cdot m \cdot C_e \left(T_f - T_i\right), kWh \quad (21)$$

Where:

K_{CU}: 3,6(10^6 J */kWh* ; *m*: Water mass, *kg*; C_e: specific heat of water, 4187*J/ºC(kg*; T_i: initial temperature, *ºC*; T_f: end temperature, *ºC*.

With the use of this water heating equipment, a certain amount of electrical energy is saved in a month. (Q_{CM}) whereby:

$$Q_{CM} = Q_c \cdot D_m, kWh \quad (22)$$

Where:

D_m: days in a month.

Being the energy saved (Q_{CA}) in a year:

$$Q_{CA} = 12 \cdot Q_{CM} \quad (23)$$

RESULTS AND DISCUSSION

Starting from the nominal power of the means and equipment that demand electrical energy in the pig center, the dimensioning of a photovoltaic system that allows covering the energy demand, was determined.

Table 2 shows the values of real critical hourly energy consumption (E_{md}) and average daily (E_{mdn}) energy consumption, obtained from the nominal values of the plate power of each piece of equipment and technical data of the luminaire, as there are no independent readings of a meter-counter in the swine center. As can be seen, the highest value corresponds to the hydraulic pump due to the daily connection time (6 hours) for cleaning and water supply tasks.

With this energy demand, it is necessary to use 192 photovoltaic panels that are equivalent to 48 modules, for which an area of 150 m^2 is required. The DSM-250 model with amorphous-crystalline silicon solar cells was chosen. Its nominal power is 250 Wp, with a voltage of 30,5 V and a current of 8,19 A at the maximum power point.

This photovoltaic module is produced at "Che Guevara" Combine, in Pinar del Rio Province. The maximum dimensions of the aluminum frame are of 1,650 x 990 x 40 mm (length x width x height).

Based on the demand for hot water in the swine center, we proceed to determine the number of solar heaters needed.

The following table 4 shows that with the use of a vacuum tube solar heater, a total energy demand of 3.49 kWh is satisfied, consisting of personal hygiene, with a consumption of water to be transferred of 60 L/ percapita.

The technology based on the use of solar energy, both photovoltaic and thermal, show satisfactory results, in terms of annual energy saving possibilities. On the other hand, the useful life of both technologies

TABLE 2. Energy parameters for electrical consumers on the farm

Means and/or Equipment	E_{md}, *kWh*	E_{mdn} *kWh*
Animal feed mill	9.0	17.6
Hydraulic pump	33.0	64.5
Lighting	16.0	31.3
Total	**58**	**113.3**

TABLE 3. Initial investment cost for photovoltaic system technology

Materials	Cost, peso
48 photovoltaic modules DSM-250	588 000
1 Control system (Inverter, Electric board, Battery charge regulator, Direct and alternating current protection)	32 500
1 Battery bank 12 V	25 000
Total investment cost (initial)	**645 500**

Peso: Refers to the national currency (MN), the exchange rate is considered 25 MN = 1 USD

TABLE 4. Energy parameters for water heating in the swine center

Materials	UM	Quantity	Unitary Price, peso/u	Cost, peso
solar heater module	u	1	6 000	6 000
Tank of 55 Gal	u	1	2 500	2 500
Pipes for collecting and conducting water	Accessories: Unions, elbows, cleaner and PVC glue, shut-off valves (the amount varies depending on the distance)		550	550
Pipes for water supply	Pipes of 13.75 mm (0.5”) (2): 5 m/cu		300	600
Total investment cost (initial)				**9 650**

peso: refers to the national currency (MN), the exchange rate is considered 25 MN = 1 USD

with proper management and maintenance can reach up to 25 years and contribute to a positive impact on the environment by ceasing to emit CO_2 annually into the atmosphere.

The initial investment cost for the acquisition of the required photovoltaic system amounts to 645 500 pesos (25 820 USD), with the installation of this technology, the activation of all electric motors and lighting would be guaranteed.

Regarding solar thermal energy technology, specifically the use of solar heaters for the conditions of the pig farm, the investment cost amounts to 9 650 pesos (386 USD). In the same way, with the introduction of this technology, the greenhouse gas emissions and their corresponding negative impact on the environment are considerably reduced.

When carrying out a study of the time required for the total recovery of the investment (655 150 pesos, equivalent to 26 206 USD), based on the productive yields of the swine center, without considering the savings from electricity consumption, it is appreciable that at the conclusion the productive cycle of raising pigs, there would be 140 animals with an average mass of 90 kg. Once slaughtered, these animals would average a mass of 67,5 kg carcass (considering a decrease in the carcass of 25%); therefore, a total production of pork carcass of 9 450 kg would be reached. Consequently, considering that the price of pork to the carcass, on the basis of the production cost sheet in this university pig center, reaches the value of 120 peso/kg; then, for each batch of pigs that are slaughtered every four months, it is possible to collect an amount of 1 134 000 pesos (45 360 USD), which means that with the commercialization of the first group, the total investment is recovered and a benefit of 478 850 pesos (19 154 USD) is obtained. These economic elements demonstrate the feasibility and viability of introducing these technologies in agricultural production scenarios, even when investment costs can be considered high.

CONCLUSIONS

- For the existing conditions in the pig center of the university farm "El Guayabal", it is pertinent to introduce photovoltaic solar energy technology as a renewable source to drive the electric motor of the mill, the water pump and lighting, which supposes an initial investment of 645 500 pesos (25 820 USD), but it contributes to caring for the environment by ceasing to emit CO_2 into the atmosphere.
- The introduction of a solar heater is viable, for the sanitization actions of the workers of the pig center and for the acquisition of this technology the investment cost amounts to 9 650 pesos (386 USD). Likewise, the introduction of this technology, considerably reduces greenhouse gas emissions and the corresponding negative impact on the environment.
- Only with the commercialization of the first group of pigs to the carcass, the total amount required for the acquisition of the photovoltaic system and the solar heater is recovered and it is possible to obtain a benefit that amounts to 478 850 pesos (19,154 USD), this element demonstrates the economic feasibility of this investment.

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