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Design and economic analysis of a solar poultry incubator for rural sectors located in Pucallpa-Peru

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Abstract. In this study, an incubator with a capacity of up to 96 backyard poultry eggs was designed mechanically and energetically, using a photovoltaic panel as a source of energy. For this purpose, a thermodynamic study, heat transfer and mechanical design of the incubation process was carried out, considering the temperature (37.5°C), relative humidity (60%), 90° rotation of the eggs in an interval between 90 and 120 minutes, ventilation that occurs in the last 3 days of the incubation process, energy and the environmental conditions of Pucallpa-Perú. The results obtained lead to the sizing of the components of the incubator and the photovoltaic panel, being this renewable energy the novelty of the study for a sustainable use of the inhabitant and the region. It is concluded that local radiation can be used as a power source for an incubator with a capacity of up to 96 eggs, by using this type of energy, the incubator together with the solar kit will become profitable compared to the use of electricity.

Key words. Backyard poultry incubator, photovoltaic panel, economic profitability.

1. Introduction

In the past, chicken was produced in a very rudimentary way, starting with hens and roosters placed in a pen, the hen was in charge of laying the egg, hatching it, waiting for it to hatch, grow and fatten until it reached the right age for consumption. This form of production has always been useful and has been used for many years, but nowadays and due to the improvement of processes and the need to be more competitive, a total transformation of this industry has been made using new automation technologies [1].

The egg incubator allows the production of chicks at any time of the year, without production limits, only those imposed by the equipment and of course at a much lower cost. The design and construction of this equipment is focused on small poultry farmers, who due to their low income and, in many cases, the remoteness of their homes (farms), make it difficult to acquire the newly hatched chicks, which often die during transport, generating economic losses to their owners [2].

The national poultry industry, concentrated mainly in the coastal region and close to the most important consumption centers of the country, has a significant participation in the Gross Value of Agricultural Production and is characterized as an economic activity in continuous growth and faces new challenges to producers due to the requirements of animal food, chicken and chicken eggs [3].

The poultry sector, oriented to the production of poultry and commercial eggs, in January 2021 participated with 28.5% within the Gross Value of Agricultural Production (poultry 23.8% and chicken eggs, 4.7%) and is positioning itself as the first source of animal protein at national and regional level, thus guaranteeing the supply of the main foods of animal origin, ensuring food security [3]. In Peru, there are companies dedicated to the sale of horizontal automatic incubators, with a capacity of up to 500 eggs. Among them are CAIM incubators, Grupo Incutec and AG&C Sistemas. The price of each equipment depends on the egg capacity and ranges from 600 to 2400 soles.

Therefore, in the present study, an incubator with a capacity of up to 96 backyard poultry eggs was designed mechanically and energetically, using photovoltaic panels as energy. By using this type of energy, the incubator together with the solar kit will become profitable compared to the use of electricity in the region of Pucallpa-Peru.

2. Metodology

2.1. Geographical location

The city of Pucallpa belongs to the province of Coronel Portillo that is located in the department of Ucayali, it is located politically between the districts of Calleria, Manantay and Yarinacocha, in the left margin of the river Ucayali. Its geographic coordinates are longitude W74°31'56" and latitude S8°22'58", the altitude value is 157 m.a.s.l. [4].

Figure 1 shows the location of the department of Ucayali and its provinces and/or districts, including Pucallpa.

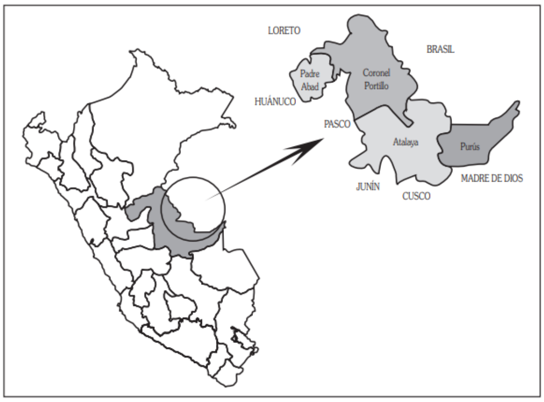

Fig.1. Geographical location of Pucallpa with respect to Peru.

2.2. Weather conditions in Pucallpa

Following, the behavior of the monthly temperatures (measured at 2 meters) from the year 2017 to 2020 are shown minimum temperatures in figures 1 and 2, maximum direct normal irradiance in figures 3 and 4, minimum direct normal irradiance in figures 5 and 6; figure 7 shows crossing the values of figures

2 and 6 to see the limits for each parameter, figure 8 shows the number of hours of sunshine per day.

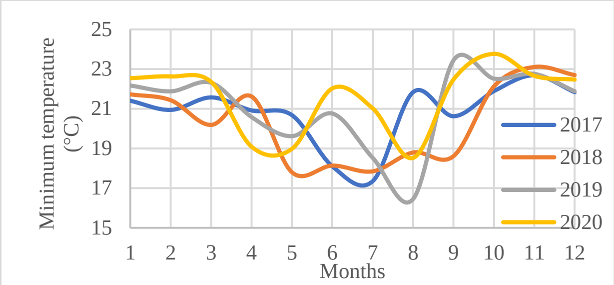

Fig.1. Minimum temperature variation (at 2 meters) monthly from 2017 to 2020.

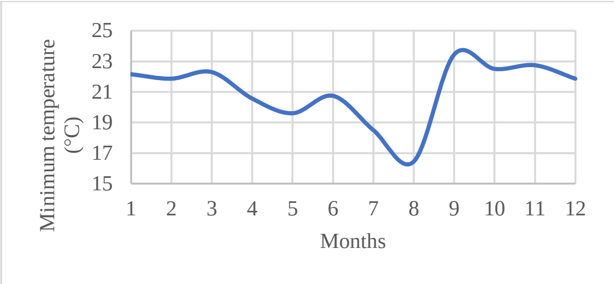

Fig.2. Monthly minimum temperature variation 2019.

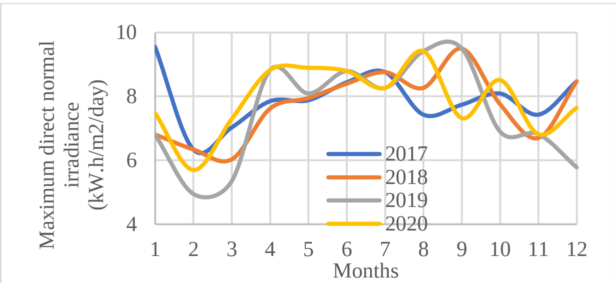

Fig.3. Variation of monthly maximum direct normal irradiance from 2017 to 2019.

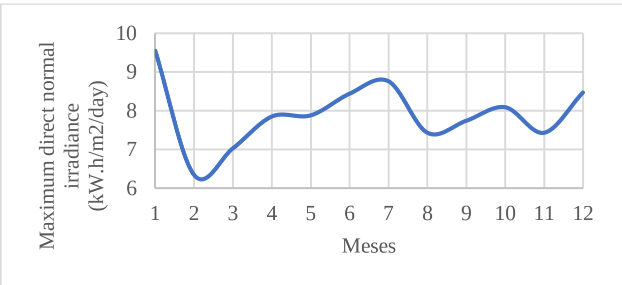

Fig.4. Variation of monthly maximum direct normal irradiance 2017.

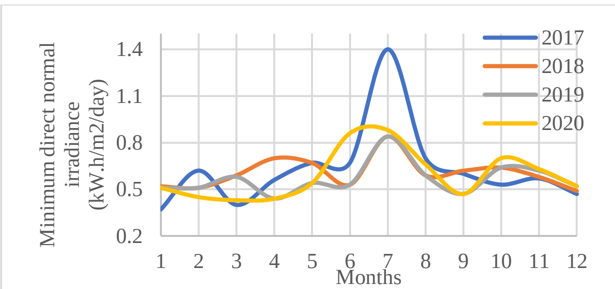

Fig.5. Variation of monthly minimum direct normal irradiance from 2017 to 2020.

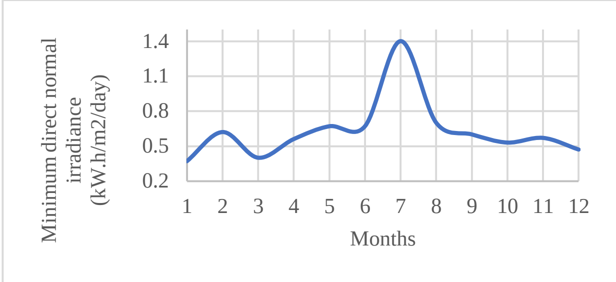

Fig.6. Variation of monthly minimum direct normal irradiance 2017.

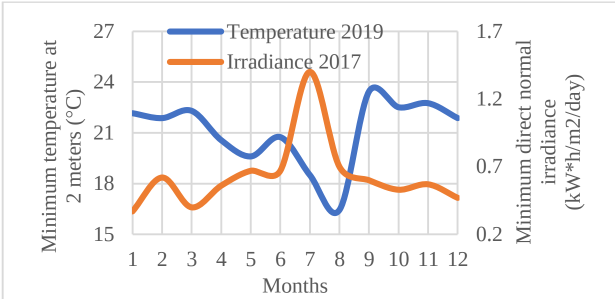

Fig.7. Monthly minimum temperature variation 2019 along with monthly minimum irrradiance 2017.

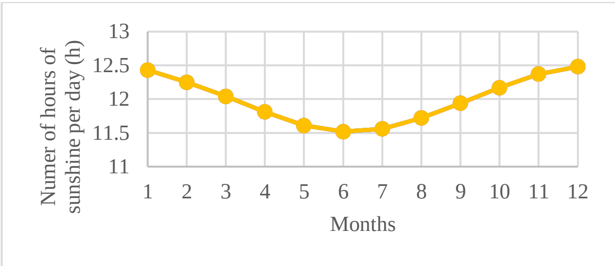

Fig.8. Number of hours of sunshine per day from 2017 to 2020.

2.3. Rural population

In the department of Ucayali reside 496 459 people, representing 1.7% of the total census population of the country (29 381 884), being the urban population 81.0% and the rural population 19.0%; according to the information collected by the National Censuses 2017: XII of Population, VII of Housing and III of Indigenous Communities, executed by the National Institute of Statistics and Informatics (INEI).

The population of this department is made up of 250 567 men and 245 892 women, likewise, according to age, the majority is between 15 and 64 years old, concentrating 60.4% of the population, followed by 34.5% who are aged 0 to 14 years old and 5.1% aged 65 and over [5].

2.4. Conditions of design for the artificial incubation process to happen.

Artificial incubation must provide the egg with optimal environmental conditions, similar to those of the natural process, for embryonic development [6]. The purpose of incubation is to guarantee the necessary temperature and humidity required for the eggs to develop until the chick hatches [7]. The parameters that are controlled during the artificial incubation process are temperature, humidity, egg rotation and ventilation. The following are the optimal conditions for the artificial incubation process to occur properly.

The optimum temperature of 37.8 °C [6] [9] [9] [10] [11] should be kept constant throughout the incubation process to achieve maximum hatching rate and high chick quality [6].

The ideal relative humidity for incubation is 50 to 55% for white eggs and 55 to 60% for brown eggs [7] [10].
Constant air exchange is necessary for the removal of excess heat that may accumulate inside the incubation cabinet and to ensure air purity [7] [10].

Egg turning is one of the main operations to be carried out during the incubation period to ensure that the eggs do not adhere to the eggshell and to obtain good hatching rates. The absence of egg turning would lead to adherence of embryonic membranes to the shell membrane, yolk or other membranes, in addition to a higher incidence of malpositioning [8].

2.5. Mathematical model used

2.5.1 Heat required to raise air temperature from 23°C to 37.5°C

The heat generated by the incubator is calculated, which implies that the heat required to raise the temperature inside the incubator will be the same heat required to raise the temperature of the air, eggs, water and plastic wall, which were determined with the thermodynamics equations along with heat transfer presented below [12]. The heat required to raise the temperature of an egg is obtained with equation 1 [13],

$$Q_{huevo} = M_{huevo} * C_{huevo} * \Delta T_{huevos} \quad (1)$$

The amount of heat to maintain all eggs at incubation temperature will be calculated, which is obtained with equation 2,

$$Q_{huevos} = \frac{Q_{huevo} * n_{huevos}}{t_{vacio}} \quad (2)$$

The volume of air in the incubation chamber will be calculated with equation 3,

$$V_{aire} = L_{incub} * A_{incub} * H_{incub} \quad (3)$$

The mass of air inside the incubation chamber will be obtained with equation 4,

$$M_{aire} = V_{aire} * \rho_{aire} \quad (4)$$

The heat value required to raise the air temperature will be obtained from equation 5,

$$Q_{aire} = \frac{M_{aire} * C_{aire} * \Delta T_{aire}}{t_{vacio}} \quad (5)$$

2.5.2 Design of ventilation holes

The fan radius value will be obtained from equation 6,

$$r_{vent} = \frac{d_{vent}}{2} \quad (6)$$

The fan speed value will be obtained from equation 7,

$$V_{vent} = w_{vent} * r_{vent} \quad (7)$$

The cross-sectional area value of the ventilation hole shall be obtained from equation 8,

$$A_{T\_vent} = \frac{V_{aire}}{t_{aire} * V_{vent}} \quad (8)$$

The vent hole radius value will be obtained from equation 9,

$$r_{hole\_vent} = \sqrt{\frac{A_{T\_vent}}{\pi}} \quad (9)$$

2.5.3 Total heat loss through the walls of the incubator

The area of the interior, exterior and insulation walls is calculated with equation 10,

$$A_{pared} = L_{pared} * H_{pared} \quad (10)$$

The heat loss by conduction of the walls will be calculated with equation 11,

$$Q_{pared} = \frac{A_{pared} * \Delta T_{\text{pared}}}{\frac{E_{pared}}{K_{pared}}} \quad (11)$$

2.5.4 Heat loss by air convection on the outer surface of the walls

The Prandtl number value is calculated with equation 12,

$$Pr = \frac{v_{aire}}{\alpha_{aire}} \quad (12)$$

The Grashof number value is calculated with equation 13,

$$Gr_L = \frac{1}{0.5 * (T_S - T_\infty)} * \frac{g * L^3 * (T_S - T_\infty)}{{v_{aire}}^2} \quad (13)$$

The Rayleight number value is calculated with equation 14,

$$Ra_L = Pr * Gr_L \quad (14)$$

The Nusselt number will be calculated with equation 15,

$$Nu_L = 0.59 * {Ra_L}^{0.25} \quad (15)$$

The convective heat transfer coefficient is calculated with equation 16,

$$h_c = \frac{Nu_L * k_{aire}}{L} \quad (16)$$

The convective heat loss of the air is calculated with equation 17,

$$Q_{conv} = h_c * A_{pared} * (T_S - T_\infty) \quad (17)$$

2.5.5 Amount of heat lost through ventilation holes

The lost heat value through the ventilation holes is calculated with equation 18,

$$Q_{vent} = \rho_{aire} * \frac{V_{aire}}{t_{vacio}} * \Delta T_{aire} * C_{aire} \quad (18)$$

2.5.6 Amount of heat lost by humidification

The volume of water occupied in the incubation chamber will be calculated with equation 19,

$$V_{agua} = L_{\text{bandeja}} * A_{\text{bandeja}} * H_{\text{bandeja}} \quad (19)$$

The total mass of water inside the incubation chamber is calculated with equation 20,

$$M_{\text{agua}} = \frac{V_{\text{agua}} * \rho_{\text{agua}}}{t_{incub}} \quad (20)$$

The heat required to raise the temperature of the water in the incubation chamber is calculated with equation 21,

$$Q_{\text{agua}} = M_{\text{agua}} * \Delta h_{\text{agua}} \quad (21)$$

2.5.7 Total amount of heat lost in the incubator

The total heat lost in the incubator is calculated with equation 22,

$$Q_{perdido\_total} = Q_{huevos} + Q_{aire} + Q_{cond} + Q_{conv} + Q_{vent} + Q_{agua} \quad (22)$$

2.5.8 Heat produced by eggs

The amount of heat produced by metabolic activities is calculated with equation 23,

$$Q_{meta\_huevos} = n_{huevos} * Q_{meta\_huevo} \quad (23)$$

2.5.9 Minimum amount of heat required to equalize heat losses in the incubator

The minimum amount of heat required for the incubator is calculated with equation 24,

$$Q_{min} = Q_{perdido\_total} - Q_{meta\_huevo} \quad (24)$$

2.5.10 Biot number

The characteristic length L_c is calculated by equation 25,

$$L_c = \frac{V_{huevo}}{A_{huevo}} \quad (25)$$

The Biot number is calculated by equation 26,

$$B_i = \frac{\alpha_{aire} * L_c}{K_{huevo}} \quad (26)$$

2.5.11 Consumption estimation and load calculation for photovoltaic components

To design the photovoltaic system which will be the power supply during the whole egg incubation procedure, all the power required during the 21 days has to be calculated, such as the electrical resistance, fan and motor of the transmission system. The energy consumption of all loads in the incubator will be calculated with equation 27,

$$E_T = P_B * t_B + 2 * P_M * t_M + P_V * t_V \quad (27)$$

The average daily load energy consumption will be calculated with equation 28,

$$E_L = \frac{E_T}{1\ day} \quad (28)$$

The equilibrium efficiency of the system is calculated with equation 29,

$$n_{bo} = n_{inverter} * n_{wire\_losses} \quad (29)$$

The temperature reduction factor is calculated with equation 30,

$$f_{temp} = 1 - \Upsilon * (T_{cell_{eff}} - T_{STC}) \quad (30)$$

The temperature reduction factor is calculated with equation 31,

$$K_{loss} = f_{man} * f_{temp} * f_{dirt} \quad (31)$$

The output power of the PV array is calculated with equation 32 [15],

$$P_{V\_array} = \frac{E_L}{n_{bo} * K_{loss} * H_{tilt}} * PSI \quad (32)$$

The number of photovoltaic panels in series is calculated with equation 33,

$$N_{ms} = \frac{V_{sistema}}{V_{modulo}} \quad (33)$$

The number of photovoltaic panels in series is calculated with equation 34,

$$N_{mp} = \frac{P_{V\_array}}{N_{ms} * P_{modulo}} \quad (34)$$

The capacity required by the battery is calculated with equation 35,

$$C_x = \frac{h_{\sin\_sol} * E_L}{DOD_{max} * V_{sistema} * n_{out}} \quad (35)$$

The number of batteries required is calculated with equation 36,

$$N_{bat\_req} = \frac{C_x}{C_{bateria}} \quad (36)$$

The number of batteries in series is calculated with equation 37,

$$N_{bs} = \frac{V_{sistema}}{V_{bateria}} \quad (37)$$

The number of batteries in parallel is calculated with equation 38,

$$N_{bp} = \frac{N_{bat\_req}}{N_{bs}} \quad (38)$$

The power of simultaneously operating devices in the incubator is calculated with equation 39,

$$P_{RS} = P_B + 2 * P_M + P_V \quad (39)$$

The power required by the inverter is calculated with equation 40,

$$P_T = (P_{RS} + P_{LS}) * 1.25 \quad (40)$$

The current for the voltage regulator is calculated with equation 41,

$$I_{rated} = N_{bp} * f_{safety} * I_{SC} \quad (41)$$

3. Results

Table 1 shows the dimensional parameters of the incubator which were used to find the heat related to the incubation process and which are shown in Table 2.

Table 1 – Incubator parameters

Incubator sizing values	Unit	Value
Number of eggs	-	96
Lenght of the inner chamber of the incubator	mm	420
Width of the inner chamber of the incubator	mm	449
Height of the inner chamber of the incubator	mm	410
Ventilation hole radius	mm	7.6
Thickness of the inner wall of the incubator	mm	3
Water reservouir lenght	mm	420
Water reservouir width	mm	449
Water reservouir height	mm	27

Table 2 – Heat related to the incubation process

Values of the heats for sizing of the incubator	Unit	Value
Amount of heat to maintain all eggs at incubation temperature	W	27.716
Amount of heat to maintain the air the incubation temperature	W	0.119
Heat loss by conduction from the walls	W	67.469
Air convection heat loss	W	4.929
Heat lost through ventilation holes	W	0.1187
Heat lost by humidification	w	6.986
Total heat loss	W	107.337
Amount of heat produced by metabolic activities by the 96 eggs inside the incubator	W	14.016
Minimum amount to match the losses inside the hatchery	W	93.321

The figure 9, is obtained by replacing the various values of the hours of sunshine in the day shown in figure 15, which allows us to find the capacity required by the battery through equation 35,

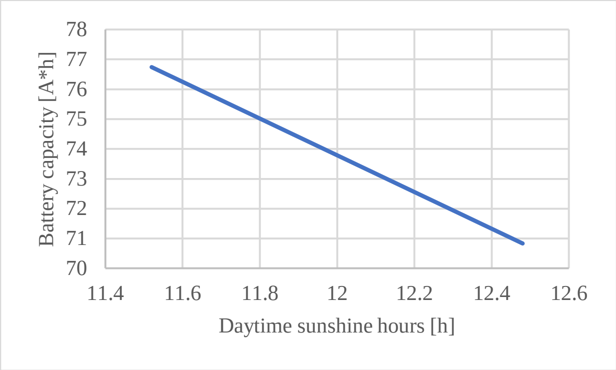

Fig.9. Battery capacity with respect to daytime sunshine hours

The description and technical specifications of the photovoltaic components calculated to be used with the incubator are shown in Table 3, and the prices of these components and their selected model are shown in Table 4.

Table 3 – Description of photovoltaic components

Component	Component description	Result
Load estimation	Total load estimate	100.375 W
Photovoltaic panel	Photovoltaic panel capacity	150 W
	Number of panels in series	1
	Number of panels in parallel	1
	Total number of panels	1
Battery	Battery capacity	100 A.h
	Number of batteries in series	1
	Number of batteries in parallel	1
	Total number of batteries	1
Regulator	Regulator capacity	20 A
	Number of regulators required	1
Inverter	Inverter capacity	200 W

Table 4 – Prices of photovoltaic components

Component	Model	Unit price (S/.)
Photovoltaic panel	QN_06 150W 12V	408
Battery	QN_06 100A.h	648
Regulator	QN_06 20A	128
Inverter	QN_06 200W	98
Total cost		1282

The monthly price saved by the use of the photovoltaic kit is shown in Table 5, and the income from the sale of the newly hatched chicks is shown in Table 6.

Table 5 – Price of electricity saved by using the photovoltaic kit

Price of electricity	
Total power (kW.h)	50.589
Price unit (S/. /kW.h)	0.7888
Monthly price (S/.)	39.905

Table 6 – Income from sale of newborn chicks

Chicks for sale	
Chick price (S/.)	2
Number of chicks	85
Monthly price (S/.)	170

An additional expense to the total investment is the purchase of the eggs to be incubated, which total 96, as shown in Table 7.

Table 7 – Purchase of hatching eggs

Purchase of eggs	
Purchase of eggs (S/.)	1
Number of eggs	96
Monthly price (S/.)	96

Considering that the project is thought for rural people, it was taken into account that a bank loan should be considered to start with the project, the total amount to start the project which is shown in Table 8,

Table 8 – Loan requested

Bank loan	
Amount required (S/.)	2100
Annual rate (%)	0.4
Total amount (S/.)	2940

The figure 10 shows the payback time in months of the total amount to start the project together with the first purchase of hatching eggs, the entire investment for the project would be recovered after the 27th month, which is the equivalent of 2 years and 3 months.

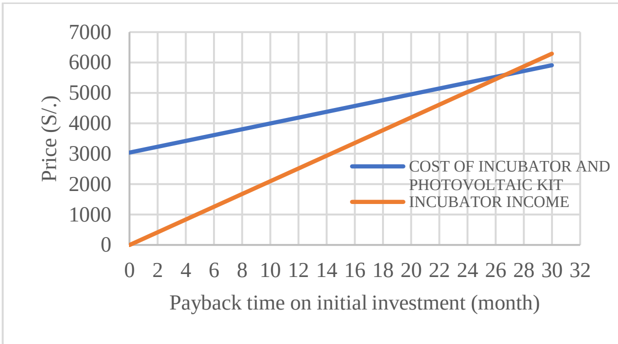

Fig.10. Payback time

In Figures 19 and 20 the design of the incubator for the present project is shown, with its dimensions in millimeters.

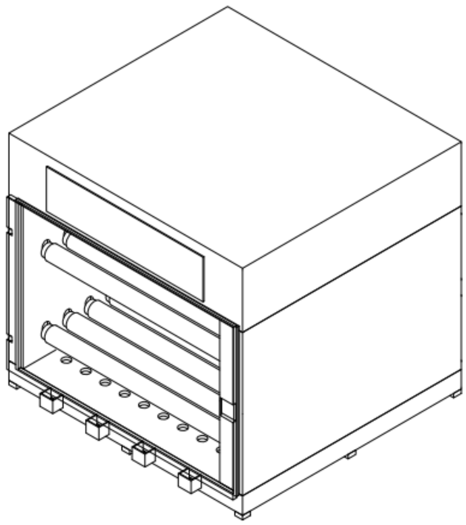

Fig.19. Incubator design

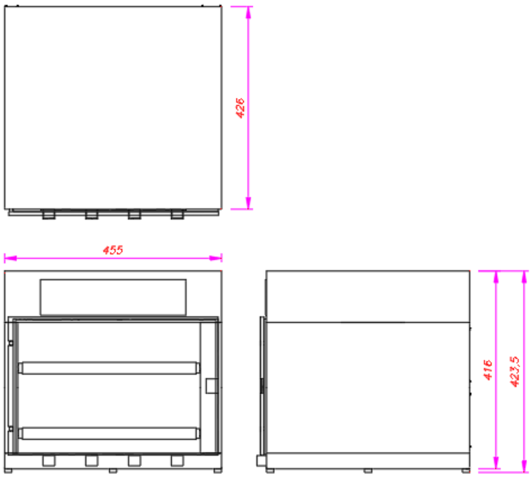

Fig.20. Incubator design

4. Discussion

According to the analysis of Agidi, Gbabo; Liberty, J.T; Gunre, O.N., & Owa, G. (2014) for the total calculation of the heat required for the incubation process to occur, the heat lost by humidification was not considered, which is also part of the analysis for the calculation of the power of the electrical resistance to be used in the incubator, also shown is the calculation of the Biot number which corroborates that all the heat will be equivalent over the entire surface of the incubation chamber [14].

According to Ishaq, M., & Ibrahim, U. H (2013) in their analysis for sizing the photovoltaic components, the average values of the variations of the normal direct radiation should be considered, which would comply in cases where there are no outliers that are not so pronounced nor such high margins. That said, it was considered to work with the lowest value peaks to comply with all values throughout the year.

5. Conclusions

In the present study we conclude the following: 1) To calculate the photovoltaic components we considered the most critical climatological data and the minimum radiation in Pucallpa. 2) The technical specifications of the photovoltaic components are as follows: panel with a capacity of 150 W, 100A.h battery, 20A voltage regulator and 200W inverter, concluding that local radiation can be used as a continuous power source for an incubator with a capacity of up to 96 eggs. 3) With the price of the photovoltaic components and the price of the incubator, considering a loan at 40% interest, the return would be in 27 months, concluding that by using this type of energy the incubator together with the solar kit will become profitable compared to the use of electricity. 4) The heat loss due to humidification is equivalent to 6.5% of the total heat loss in the incubator.

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