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INNOVATIVE HYBRID GEOTHERMAL/AIR HEAT SYSTEM FOR BIOGAS PRODUCTION

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Abstract: In the Bioeconomy chain, Biogas is already a reality for large producers. However, there are still difficulties in taking this technology to medium and small producers. Among the difficulties is the issue of sludge temperature. In Brazil, for example, the two states that have the largest swine population (Paraná and Santa Catarina, located in the south of the country) have an average air temperature below 20°C during seven months of the year, which difficult the Biogas production, keeping most of the time in psychrophy range. This research work presents the advantages of an innovative project of a hybrid geothermal/air heat pump for heating the sludge and increasing the production of Biogas. A Biodigester used for 30 cows generated 75 kW/day of gross energy using a 15kW electric power to supply the heat pump.
Keywords: Biogas, heat-pump biogas, geothermal heat pump, biogas production.

INTRODUCTION

The demand for energy continues to grow even with the war in Ukraine. In 2022 it grew by 2%. In the Americas, Brazil is the second largest consumer of energy (IEA, 2023). Developed countries, in general, have a higher energy consumption per inhabitant than developing countries. For example, the United States of America (USA) had an average consumption per inhabitant of 12,154 kWh, Japan 7,150 kWh, Germany 6,306 kWh, while countries like Egypt have 1,500 kWh and Angola 326 kWh, Zimbabwe 505 kWh, Brazil 2,830 kWh (EIA, 2023; DATA, 2023). To generate balance between developed and developing countries there will be a higher growth in energy consumption among developing countries. Only 8% of people living in the hottest regions of the planet have air conditioning. It is estimated that will go from the current 1.6 billion pieces of equipment to 5.6 billion pieces of air conditioning equipment in 2050. Only air conditioning in 2050 will be able to consume the joint energy of the entire European Union (EU), USA and Japan on the base date of 2019 (IEA, 2022).

Among the demands that are growing in the world is the consumption of meat. It is estimated that the growth in meat consumption in the world will increase in this decade by 14% until 2030, due to income and population growth. Among the meats that tend to grow above 10% is swine with 13.1%. China alone will be responsible for approximately 70% of the increase in swine consumption from the reference period to 2030 (OECD, 2022).

Fatty foods (e. g. meat) are highly rewarding and trigger a stimulus-reward relationship. Several transmitters including dopamine (DA) and others are implicated in these food effects. There is reward modulation in the consumption of fatty foods such as meat using the same strategy as other addictions (stimulus and reward) (Volkow *et al.*, 2010; Kenny *et al.*, 2013).

In addition to population growth and better economic conditions, the rewarding effect generated in meat consumption may be one of the driving reasons for increased production and consumption. According to the OECD, Asia will be where meat consumption will grow the most by 2030 (MLA, 2023).

There are challenges in meat production. One of them is the production of residues (excrement). In 1995, a national study was carried out in the USA ("United States National Animal Health Monitoring System") with 184 pig sheds. The conclusion was that the pigs produce 8.4% of their body weight of waste per day, i.e. 84 kg of meat per 1000 kg of feed (Losinger & Sampath, 2000). A pregnant sow produces 11 kg of manure and urine per day., In lactation 18 kg per day and a male pig of 25-100 kg produces 6 kg per day. The general average is 5.8 kg per day (Oliveira, 2023). Compared to a human, the difference is very large, close to 4 times (Rose, 2015). In Brazil, only in the state of Santa Catarina, in 2021, the production of pigs was 15.93 million animals for slaughter (3tres2, 2023). In this case, a sewage network, and considering the feces and urine of a pig that is 4 times that of a human, there is a need for an equivalent structure for almost 60,000,000 people. Considering that the population of Santa Catarina is a little more of 7 million inhabitants, it is almost 10 times the population in manure production. As the population of pigs in Brazil exceeds 38 million (Cherobini *et al.*, 2014), this population generates around 90.2 billion kg of manure per year. If it were possible to extract the best performance from the system (suinoculturaindustrial, 2022), it would be possible to generate a load of manure of 90.2 billion kg/year, and 900,000,000 m^3 of methane, corresponding to 1,287,000,000 kWh year, enough energy to meet the annual demand of 454,770 Brazilians, or almost 4,000,000 Angolans. Thus, it would be more than 10% of the population of Angola with energy, and this is referring to the production of Biogas from pigs in Brazil only (Macrotrends, 2022).

Among the main global actors to supply the growth of the meat industry is Brazil. It is the main global producer, exporter and the third world consumer of meat (Hotzel, Vandresen, 2022), Santa Catarina is the largest producer of swine in Brazil (Silva, 2021), and the neighboring state Paraná is the largest producer of animal protein in Brazil and the main producer of chicken meat in Brazil (Aen, 2023).

The largest swine producing state in Brazil is also the state with the lowest temperatures, reaching temperatures as low as -14°C (Pezza, 2004). Low temperatures, below 20°C, reduce the production of Biogas. It can even make the production of this energy unfeasible (Tavares *et al.*, 2016).

A difference of 25°C to 31°C can represent a variation close to 50% in Biogas production. So, how to make better use of Biogas production technology, even in low temperature climates and still using more sustainable solutions with low environmental impact? (Silva, 2016).

STATE OF ART

The environmental impacts of fossil fuels are one of the major themes of today. One of the smart ways of generating energy is the development of Waste to Energy (WtE) technology, including the production of bioenergy, that is, biogas produced from various wastes through Anaerobic Digestion (AD). It is considered one of the potential measures that corroborate with the sustainable development objectives of the United Nations (UN). One of the ways to catalyze the production of Biogas is the use of solar energy associated with Biogas (Mahmudul *et al.*, 2021).

The biodigestor is a reservoir of organic waste that, through anaerobic digestion, produce biogas. To obtain the best yield from the biodigestion process, it is necessary to that the biodigester has an ideal temperature. There are three temperature ranges where the microbial growth takes place: the psychrophilic (0° to 20°C), mesophilic (20° to 45°C) and thermophilic (45° to 70°C). For the biodigester to work in its best condition, the best temperature range is the mesophile, with optimum operating rates between 30° and 35°C, since temperature is responsible for rate of metabolism of microorganisms. As the temperature increases, the relative rate of digestion undergoes an abrupt drop, as shown in the Graphic 1, where there was a drop when the temperature reached 40°C (Costa, 2009; Silva *et al.*, 2012).

Knowing that the best production of Biogas is in the range of 30 to 35°C, it is important to check the average temperatures in Brazilian cities in southern Brazil. Using the ASHRAE (American Society of Heating, Refrigerating and Air conditioning Engineers) Data Viewer as a basis, it is found the values shown in Graphic 2 and Graphic 3.

The air temperature in southern Brazil is so low that in the largest city in the region, Curitiba, 73% of the annual time the temperature is below 20°C. Even Londrina, the hottest city available in data from ASHRAE Weather Data Viewer, the temperature is below 20°C in 36.5% of the time. These low temperatures reduce the yield of biogas production (ASHRAE, 2022).

In addition, the winter and summer temperature variations in southern Brazil are large, generating a huge temperature range (ABNT, 2008) as shown in Table 1.

Place/City	T_{summer} (°C)	T_{winter} (°C)
Cascavel	35.1	3.4
Curitiba	30.9	2.4
Foz do iguaçu	35.1	3.4
Guaratuba	33.0	7.5
Ipanema	33.0	7.5
Londrina	33.9	7.2
Maringá	33.9	7.2
Pinhais	30.9	2.4
Ponta Grossa	32.0	2.1
Toledo	34.9	2.4

Table 1 – Summer and winter temperatures in the cities of Paraná – Brazil

Source: ASHRAE, 2022.

As a source of heat in winter there are geothermal heat pumps. The word "geothermal" according to Egg & Howard comes from the Greek "geo" (earth) and "thermos" (heat) and is applied to the use of heat from the ground (Ward, 2011).

Specifically, Santos *et al.* (2016) developed a study of geothermal temperatures at 2 meters from the surface of the ground was carried out where the temperatures shown in Table 2 were chosen (higher temperature in summer and lower temperature in winter).

Place/City	T_{summer} (°C)	T_{winter} (°C)
Cascavel	22.9	16.0
Curitiba	22.1	18.1
Foz do iguaçu	23.0	17.7
Guaratuba	22.9	18.2
Ipanema	23.0	18.3
Londrina	24.0	16.2
Maringá	23.0	17.9
Pinhais	20.9	17.0
Ponta Grossa	21.1	18.0
Toledo	23.0	17.7

Table 2 – Geothermal temperatures

Source: Santos *et al.*, 2016.

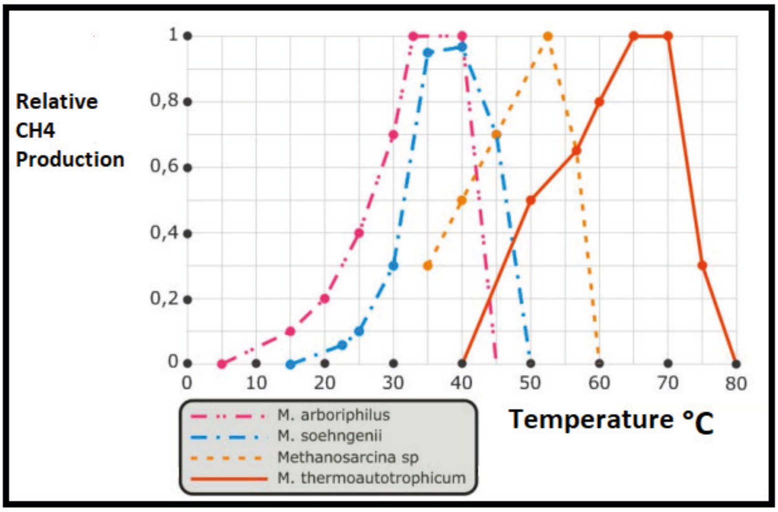
In comparison with air, the geothermal source can be interesting to be the hot source of a heat pump. While in winter the minimum temperatures in the south of Brazil vary from 2.1 to 7.5°C, the geothermal ones in the same cities vary from 16 to 18.3°C.

MATERIALS AND METHODS

The first step was to generate a hybrid project. As it is a geothermal heat pump, in addition to heating the sludge, it also takes advantage of the possibility of using this spare cold to cool the dairy cows in the summer. The rectal temperature interferes with milk production. An increase of 1.5°C in the rectal temperature generates a reduction of 0.322 kg/h of milk. The scheme shown in Figure1 provides the option to simultaneously heat the sludge and help in the better thermal sensation of the cows (Wheelock, 2018).

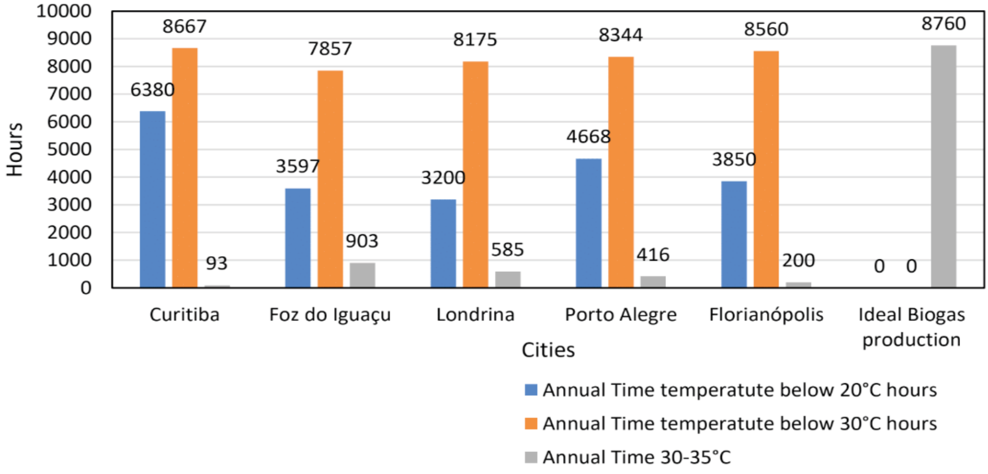
According to the diagram shown in Figure 2, there are two geothermal coils for changing the evaporator and condenser.

The second step of the project was to define the size of the type of property system, where it is necessary to calculate for 60 days of manure curing in the biodigester. Considering that a



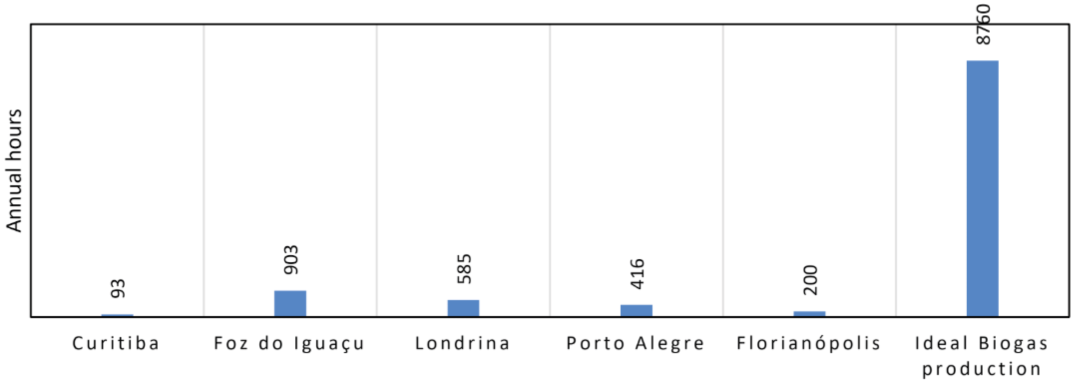
Graphic 1 – Effects of temperature on relative methane production activities in methanogenic bacteria

Fonte: Bicalho, 2007.



Graphic 2 – Hours vs Temperature South Brazil main cities

Fonte: ASHRAE, 2022.



Graphic 3 – Annual time 30-35ºC hours

Fonte: ASHRAE, 2022.

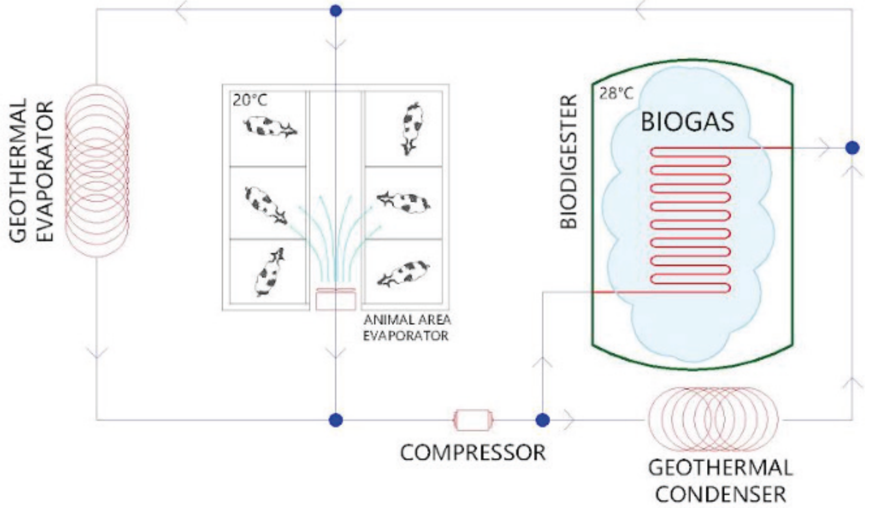
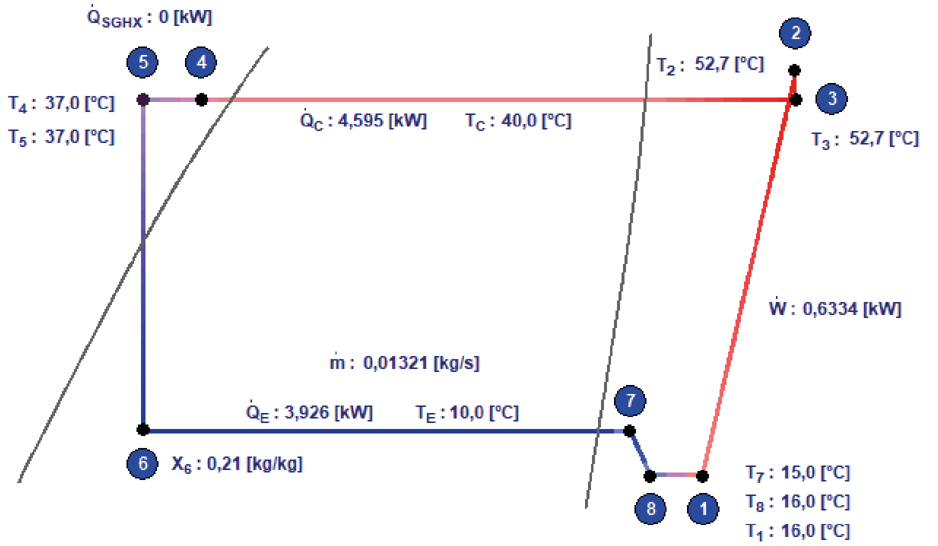


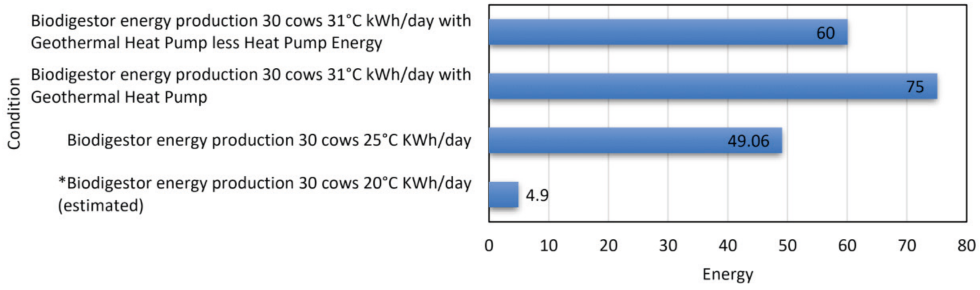
Figure 1 – Project

Source: Own authorship, 2023.



Graphic 4 – Software simulation coolpack

Source: Coolpack 1.50, 2023.



Graphic 5 – kW/day condition

Source: Own authorship, 2023.

cow produces an average of 50 kg of manure (manure, urine and water) per day and that the rural producer has 30 animals, daily waste is 1,500 kg (1.3 m^3); totaling, in 60 days, 90-110 m^3, which should be the size of the tank. The dung heap is dimensioned in the same way.

The third step is to measure a thermal load. In this case, the specific heat and thermal conductivity of dairy cattle manure is around 3.606 kJ $kg^{-1}°C^{-1}$. A maximum thermal load of the product (considering 24 hours for thermal equilibrium, with an active compressor for 18 hours) of 976.66 kcal/h was considered. The transmission load of the linings and other losses was assumed to be 2,400 kcal/h, generating a worst case total thermal load of 3,376.6 kcal/h (Nayyeri *et al.*, 2009).

The fourth step was dimensioning the heat pump system. he condensing unit was selected to work with propane as a refrigerant gas due to its low GWP (Global Warming Potential) index. The GWP of propane in the AR -05 is only 3. The characteristics shown in Table 3 were considered (Neto *et al.*, 2019):

Characteristics; Unit	Value
Thermal Load (W)	3,926
Refrigerant Gas	R-290 propane
Evaporation Temperature (°C)	+10
Condensation temperature(°C)	+40
Superheat/Subcooling (k)	5/3
Isentropic efficiency	0,80
Unuseful superheat (k)	1
Condensation Type	Water Cooled

Table 3 – Characteristics

Source: Neto et al., 2019.

The evaporation temperature of 10°C is feasible in terms of geothermal applications, since there is a hot source above 17°C. In order to keep the sludge between 28 to 35°C, a condensation temperature of 40°C is also feasible.

The COP (coefficient of performance in W/W) was determined, COP = 6.2 W/Win(cooling COP), the COP for Heating is 7.255 W/Win, and the hybrid (cooling and heating simultaneous)COP is 13,45 W/Win. In this case, the compressor has an electrical supply demand of 0.63 kW. It is important to emphasize that the thermal load was dimensioned for a compression regime of 18 hours a day, but it is necessary the cold water and condensation pumps. The flow in a regime of ΔT of 6 K is approximately 650 l/h and manometric head of 10 mca. The electric power of the pumps is 0.125 HP each. In this case, with the two pumps and the refrigeration system working 18 hours a day, an energy consumption of 14.7 kWh daily is obtained. Considering other sources such as electronics expansion valve power and smaller components such as solenoid valves, the value has been rounded up to 15 kWh/day (Coolpack, 2023).

ANALYSIS AND DISCUSSION

In the field under the temperature conditions of Castro (city with very similar characteristics and close to Curitiba), a 600 kg cow with an average production of 30 kg of milk per day consuming 39.13 kg/day of feed, produced an average of 100 kg of methane per year (Ferreira, 2011).

Considering the calorific value of biogas situated between 5,000 to 7,000 kcal/m^3, even reaching 12,000 kcal/m^3 if carbon dioxide is removed from the mixture, containing 60% methane produces 5.97 kWh, 30 cows produce per day 49.06 kW.

In tests under an average ambient temperature of 25 °C, as shown in Table 4, a variation of the sludge from 25 °C to 31 °C, generated in a period of 96 hours an increase of 1.53 times in gas production. Applying this study in the simulation condition in the city of Castro, it would be possible to generate approximately 75 kWh/day using heat pumps keeping the sludge at 31°C (Silva *et al.*, 2012).

Characteristics; Unit	25°C	31°C
Biogas annual prodution kg/Cow	100	153
Energy by day kWh 30 Cows	49.06	75
Energy Geothermal Heat Pump by day		15

Table 4 – Characteristics simulation

Source: Silva *et al.*, 2012.

As shown in Graphic 5, even with the electric energy of the geothermal heat pump active, there are advantages in the production of biogas, since there is an increase counting with the energy of the geothermal heat pump from 60 to 75 kWh for 30 cows, that is, 1.25 times.

Something important is that even the summer in the south of Brazil is mild. A city like Castro (largest milk producer in Brazil) has 6,380 annual hours below 20°C, which means that the geothermal heat pump will be on practically all year round, above 30°C is only 93 hours. At the same time, the metabolism of dairy cows is extremely high. This means that this project also foresees the use of the cold source to support the acclimatization of the cows (Assembleia PR, 2023).

It is important to emphasize that animals subjected to thermal stress end up having reduced performance. The combination of temperature and relative humidity of the air makes up a variable called THI (Temperature Humidity Index). The animal begins to suffer thermal stress when this index exceeds the value of 72. Even with a temperature of 23°C, if the relative humidity is greater than 80%, there is already thermal stress (Silpa, 2021), as shown in Table 5.

In general, evaporative systems are used to generate comfort for the cows, but this action, despite improving the temperature, ends up generating an increase in relative humidity and increasing the proliferation of fungi in the compost barn. Evaporating at 10°C, it is possible to generate cold water at 15°C. Using an area of 10 m^2 per cow with a ceiling height of 5 m, the volume of the resting place for the cows would be 1,500 m^3. Using 20 air changes per hour in an evaporative system, the flow would be 30,000 m^3/h. In a condition of 30°C with a relative humidity of 50%, the stress index would be 78. Using an evaporative system with an evaporative hive (pad) yield of 80%, the conditions shown in Table 6 are obtained.

	P1	P2
Dry Bulb (°C)	**30.00**	**23.44**
Wet Bulb (°C)	**21.80**	**21.80**
Dew Point (°C)	**18.07**	**20.79**
Enthalpy (kJ/Kg)	**68.16**	**68.60**
Spec. Vol. (m^3/Kg)	**0.9796**	**0.9627**
Density (Kg/m^3)	**1.0208**	**1.0388**
RH (%)	**50.00**	**87.22**
Abs. Humidity (g/Kg)	**14.8623**	**17.7004**
Air Flow rate (CMM)	**500.00**	**500.00**

Table 6 - Conditions

Source: ASHRAE, 2023.

With this condition, a sensitive load of 58.65 kW is removed, while a latent load of 62.48 kW is added, but the stress index of the animals will drop from 78 to 73. With the use of the geothermal heat pump at 15°C chilled water temperature, that is, below the dew temperature of the air outlet condition, there will be an increase in cooling of 3.93 kW. This will generate an increase in capacity of almost 7% (in relation to this evaporative system) and generate a decrease in the temperature of 0.46°C, reducing the relative humidity by almost 5%, generating a new stress index of 71, with this index is possible to reduce from medium stress to mild stress.

It is important to remember that the benefit of the geothermal heat pumps in the biodigester go much further, since in the temperature difference of 20 to 30°C the production of biogas can be multiplied almost 10 times. Additionally, the use of cold water in

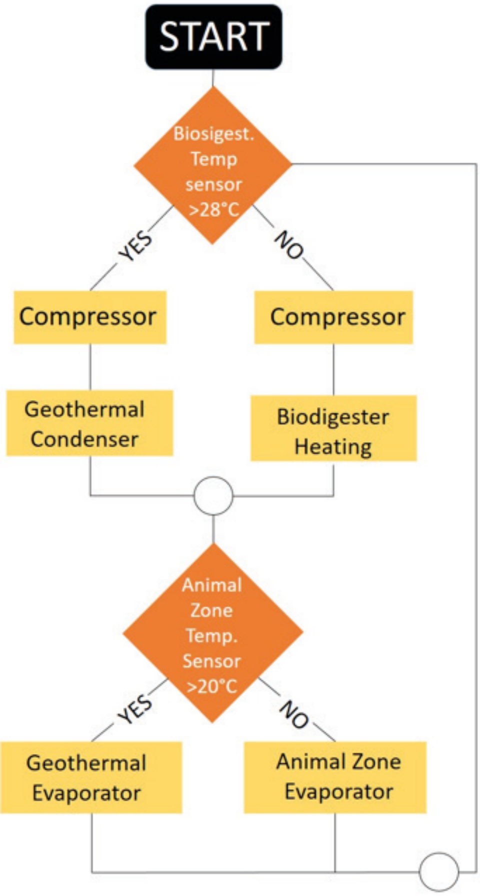


Figure 2 – Diagram

Source: Own authorship, 2023.

		Relative Humidity (%)								
		10	20	30	40	50	60	70	80	90
Tempe-rature (ºC)	22	65	66	66	67	68	69	69	70	71
	23	66	67	67	68	69	70	71	72	73
	24	67	68	69	70	71	71	72	73	74
	25	68	69	70	71	72	73	74	75	76
	26	69	70	71	72	73	74	75	77	78
	27	69	71	72	73	74	76	77	78	79
	28	70	72	73	74	76	77	78	80	81
	29	71	73	74	76	77	78	80	81	83
	30	72	74	75	76	78	80	81	83	84
	31	73	75	76	78	80	81	83	85	86
	32	74	76	77	79	81	83	84	86	88
	33	75	77	79	80	82	84	86	88	90

Table 5 – Temperature vs Relative Humidity of the air, to generate thermal comfort animal.

Source: Souza, 2017.

this case would be a recovery of heat. On hot days, cold water becomes the priority, and the system can send hot water instead of heating the sludge to the earth.

CONCLUSION

The cows produce more milk in temperate climates such as Europe, while low temperatures make it difficult to produce biogas. To improve both conditions, geothermal heat pumps can be a viable option to support both work fronts, increasing the temperature of the sludge and being a source to simultaneously improve the comfort of the cows and increase the production of milk and biogas (Hill, 2015).

Biogas is a renewable raw material that can even be used to produce hydrogen by decomposing biomethane. The International Energy Agency (IEA) points out that green hydrogen is the fuel of the future (Swartbooi, 2022; IEA, 2023).

The report concludes that clean hydrogen is currently enjoying unprecedented political and commercial momentum, with numerous policies and projects around the world expanding rapidly, so green hydrogen is a promising commodity (Bairrão, 2023).

According to EERE (Energy Efficiency and Renewable Energy), ground source heat pumps are more energy efficient than usual cooling systems and can help ease the load on the electricity grid, especially during peak demand in summer. In addition, they can help reduce carbon emissions thanks to their high efficiency. Using this technology in favor of the production of biogas or even green hydrogen, can be a viable solution to generate a more sustainable world (Energy, 2023).

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