Energy 234 (2021) 121258

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Investigating the potential of the slurry technology for sustainable pig farm heating

Cristina Sáez Blázquez [a, *], David Borge-Diez [b], Ignacio Martín Nieto [a], Miguel Ángel Maté-González [c], Arturo Farfán Martín [a], Diego González-Aguilera [a]

[a] Department of Cartographic and Land Engineering, University of Salamanca, Higher Polytechnic School of Avila, Hornos Caleros 50, 05003, Avila, Spain
[b] Department of Electric, System and Automatic Engineering, Universidad de León, León, Spain
[c] Department of Topographic and Cartography Engineering, Higher Technical School of Engineers in Topography, Geodesy and Cartography, Technical University of Madrid, Mercator 2, 28031, Madrid, Spain

ARTICLE INFO

Article history:
Received 3 August 2020
Received in revised form
12 April 2021
Accepted 14 June 2021
Available online 16 June 2021

Keywords:
Farms
Slurry technology
Ground source heat pump systems
Greenhouse gases emissions
Operational costs
Initial investment

ABSTRACT

Sustainable energy development in the farming sector is an essential strategy to respond the combined challenge of achieving a reliable and affordable solution but including mitigation and adaptation to climate change. Intensive breeding farms require maintaining an adequate indoor thermal environment that results in high energy demands, usually covered by fossil fuels and electricity. This paper addresses the application of the combined slurry technology for a particular pig farm that currently uses a diesel boiler to supply the piglet heating energy needs. The study also considers different options based on closed ground source heat pump systems. After the design of the slurry alternative and the geothermal ones, notable advantages are detected compared to the existing diesel system. Results show that the implementation of the slurry technology implies an important reduction of the operational costs, which, in turn, involves short amortization periods for this system in relation to the diesel one. Greenhouse gases emissions are also highly reduced in the slurry alternative based on the low electricity use of the heat pump. The environmental side is reinforced by the reduction of polluting substances such as methane of ammonia derived from the descent of temperature of the slurry.

1. Introduction

Energy consumption is a global concern that leads the world to look for new sources and alternatives that contribute to more efficient practices. Considering the energetic resources available and their geolocation besides the controversial energy markets (especially for those of fossil fuels), it is mandatory for the today's society the optimization of the energy consumption in the different sectors. In this context, the *"Clean Energy for All Europeans"* package from the European Commission includes a series of measures aimed at increasing the energy efficiency, promoting renewable energy, and providing a framework for energy policy in the European Union. The Commission's proposal establishes a 30% energy efficiency target for 2030 at the EU level [1,2]. Finally, the revised Energy Efficiency Directive set a binding 32.5% target for 2030 with a clause for an upward revision by 2023 [3].

Within the wide range of productive activities that need to incorporate efficient measures, agriculture and livestock production has recently received attention because of its considerable economic and environmental impacts [4–6]. According to the Eurostat database, the European Union energy consumption by agriculture made up 2.8% of the final energy consumption in 2014 [7]. However, this value is probably underestimated since it only considers the direct energy uses related to electricity and fuel consumption [8]. The proportion of direct energy used from the total primary energy consumption in agriculture in the EU is estimated at 61% and largely varies for the specific activity [9]. In the context of pig productivity, the conditions of the inside room are essential and highly influence the correct animal's growth. Nursery pigs are susceptible to low temperatures and hence, a significant proportion of the global costs associated with pig farming is for heating to achieve a comfortable temperature [10]. In intensive breeding farms, for maintaining an adequate thermal environment, fossil fuels and electricity are the principal energy sources usually adopted. In this sense, there are therefore, two main issues that

---

* Corresponding author.
E-mail address: u107596@usal.es (C.S. Blázquez).

https://doi.org/10.1016/j.energy.2021.121258

must be addressed: the dependency on fossil energies and their related costs as well as the greenhouse gas emissions [11].

In this way, interventions on animal housing are required with the aim of reducing the energy demand and increasing the efficiency of the climatization systems. Strategies are then focused on the use of alternative energy sources as the renewable ones. In this regard, geothermal heat pump systems represent a potential improvement both in energy consumption and indoor air quality. These systems are commonly classified into Ground Source Heat Pump (GSHP) and Groundwater Heat Pump (GWHP) systems. The first one is based on a closed water loop consisting on several borehole heat exchangers. In the second case, the system operates on an open water loop circuit, extracting groundwater from a well and re-injecting it into another well after the corresponding heat exchange [12]. Both cases represent a potential exploitation of a heat source (the ground or the groundwater) whose temperature remains constant temperature all year round. These systems are also able to operate both in heating or cooling modes, resulting in high energy efficiency and low operational costs [13].

Farming sector is also an ideal candidate for geothermal energy because farms frequently have enough space to host the well field. Geothermal heat pumps are traditionally associated to heating/cooling purposes in residential, commercial, and public buildings; however, their use in animal farms has been recently investigated by some authors [14–18]. Generally, they all agree in the positive effects that the implementation of shallow geothermal systems means in terms of economic savings and reduction of greenhouse gases emissions. Geothermal heating is capable of ensuring the animal welfare but also enabling an improved quality environment. Animal houses contain different air pollutants such as carbon dioxide or ammonia and geothermal solutions have shown to be effective from an economic point of view [19,20]. In this sense, the European Council Directive [21] aims to prevent the pollution of surface water and groundwater by promoting the implementation of good farming practices. The incorporation of any renewable alternative as the geothermal ones have meant an ideal tool to reduce the mentioned negative impacts.

Despite the above, low temperature geothermal solutions are rarely adopted in farms and there is still the necessity of spreading the possibilities of these systems. The use of heat pumps for technological processes in farming is not enough investigated and there are some peculiarities when these systems are used on a live-stock breeding farm [22]:

- Resting place for piglets needs to be heated during all the year, not only in the cold period.
- Geothermal heat pumps require working in the temperature range of 22–36 °C instead of 20–22 °C as for the building sector.

Thus, this sector opens the way to innovative strategies, which, combining the traditional geothermal pattern with new alternatives, improve the indoor air quality conditions as well as the animal wellbeing. The objectives of this research are then to evaluate a new geothermal concept currently adopted in piglet farms. This strategy aims to supply the heating demand but also to contribute to the reduction of the polluting animal waste. Throughout this work, an extensive analysis of this solution will be performed to finally highlight its advantages in terms of energy and economic savings and efficiency. The designed slurry system will be finally compared to different closed-loop geothermal solutions and the existing energy source of the farm.

2. Materials and methods

2.1. Background to slurry technology

Pressures on the pig industry to reduce emissions of ammonia and odour from slurry have increased in the last years due to the evolution of the regulation in the field. The principal objective of exiting regulation is to reduce risks to the environment and human and animal health.

The most relevant source of ammonia in pig production is the decomposition of urea, excreted in urine. Different factors influence this process such as the concentration of urea in urine and the slurry temperature and ph. In addition, the volatilisation of ammonia is influenced by the ambient ammonia concentration, the dry matter contents of the slurry and the air speed. In this sense, ammonia emissions can be reduced at source by the implementation of different technologies that could allow to increase the number of swine on an existing farm or to obtain an environmental authorization.

The basis of the mentioned technologies is the cooling of slurry in storage, which indeed reduces emissions, but also enables the use of the heat extracted to heat the livestock housing. The system also uses heat pumps to transfer the heat from one site to another, avoiding the conventional heat sources such as oil and gas. Cooling together with heat recovery was identified as *"Best Available Technique"* (BAT) in the Reference Document for the Intensive Rearing of Poultry or Pigs in 2017 [23], and has been successfully implemented in Finland since 2004, and on more than 300 farms in Denmark. It is also possible to find this kind of installations is the Netherlands, North America, or China.

However, this practise is no classified as BAT when the heat reuse is not possible. Furthermore, it requires to be installed in housing systems where slurry is frequently removed, that is to say, cooling is not effective for large volumes of slurry.

Regarding the economic point of view, several European installers anticipate that the investment on these systems can be recouped in less than five years (from savings in energy costs).

2.2. Working principle

The principal fundamental of the slurry technology is described in Fig. 1. As shown in this Fig. 1, slurry is collected in the farm through holey concrete sheets so that the thermal energy of it is transferred to the working fluid of the heat exchangers. This fluid

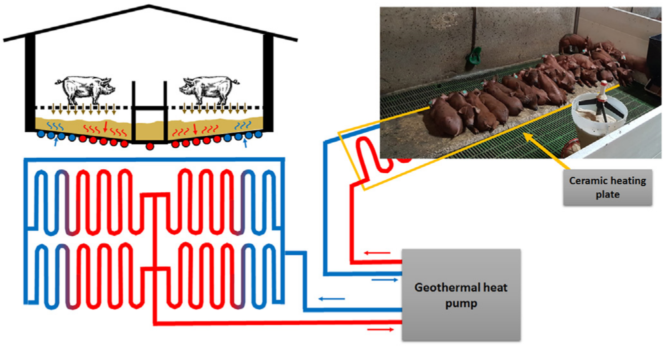

Fig. 1. General working principle of the slurry technology.

enters then in the heat pump, and, as in a conventional geothermal system, the outlet fluid increases its temperature to heat the ceramic heating plate where the piglets are resting.

As mentioned in the above, the system is constituted by a heat pump that moves thermal energy against the thermal gradient with the same principles as the refrigeration cycle. The principle of operation is shown in Fig. 2.

In *point 1* of Fig. 1, low temperature water is pumped around a closed-loop cooling circuit returning to the evaporator. Here, heat is used to raise the temperature of a liquid refrigerant which evaporates (*point 2*). The temperature of this refrigerant depends on the type of product and the specific applications.

The higher-temperature gas in then compressed (*point 3*), also increasing its temperature due to the increase of pressure from 3 to 25 bar. The high-pressure gas passes through the condenser, where it is cooled by transferring heat to water moving around the heating circuit (*point 4*). At this point, the refrigerant is liquid again. The pressurised refrigerant is then passed on through the expansion valve (*point 5*), where its temperature and pressure are reduced and returns to the evaporator.

Finally, the heating circuit described at *point 6* can be used directly to heat livestock accommodation or to supply a heat store. This last heat could be used for different purposes such as domestic use or hot water for heating.

2.2.1. Slurry cooling circuit

The slurry cooling system represented on the left part of Fig. 1 is the responsible for reducing the ammonia emissions. This circuit is commonly installed in or on the floor of under-slat or other relatively long-term slurry storage. However, it can be also installed in the floor of slurry channels. The slurry cooling system is constituted by Low Density Polyethylene (LDPE) pipes of different diameters (usually 18 mm) fixed to the floor at 350–400 mm spacing, plumbed in parallel (Fig. 3A) or following a slinky pattern (Fig. 3B).

If temperatures of less than 0 °C are expected to cool the slurry, glycol or other types of antifreeze must be added to the contents of the closed-loop cooling circuit. However, temperatures of below 5 °C are not recommendable to avoid the reduction of the heat pump performance. Cooling water can also circulate through a floating heat exchanger, using arrays of plastic of metal fins. In each channel, fins are connected in series, an in parallel between channels, achieving a uniform cooling effect in all the cooling elements over the totality of the slurry surface. The cooling system is essential to reduce the ammonia emissions and to maintain a proper air quality, contributing to comply with the environmental permit limits. Beyond the environmental aspect, the system also allows the reduction of the energy consumption running cooling fans.

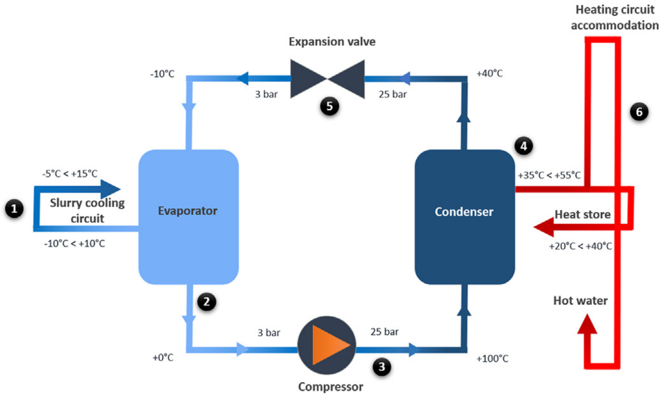

Fig. 2. Diagram of the heat pump operation to recover heat from slurry and generate hot water.

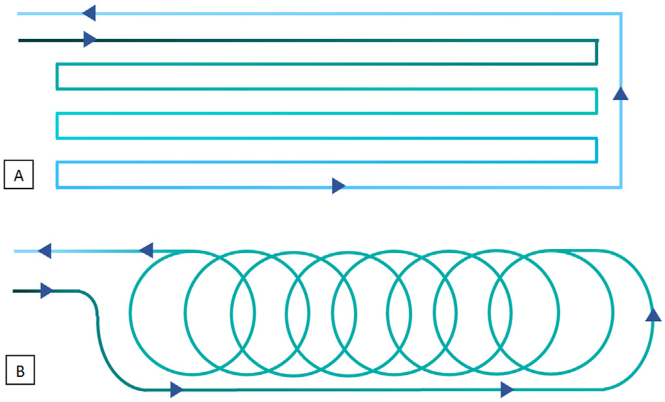

Fig. 3. Slurry cooling circuits, A. parallel pipe network, B. Slinky pipe network.

Slurry temperature plays an essential role in odour emission, affecting the characteristics and concentration of odour emissions from slurry. So that a reduction of 10 °C in the slurry temperature has been proved to reduce odour emissions by 75% [24]. Besides the ammonia, CH_4 is also reduced from the slurry emissions.

2.2.2. Heat recovery system

Heat water leaves the condenser of the heat pump at a temperature of between 35 and 50 °C. Moving this heat over long distances would require relatively large volumes of water to be moved through insulated pipework, which is, in fact, unproductive. In this way, it is recommendable to use this heat close to the source.

Low-grade heat can be accumulated in heat stores to be then used to preheat high temperature water supplies such as domestic heating or underfloor heating systems. In the farming context, stored heat gained from cooling slurry during the day can be used at nigh to heat weaner housing and farrowing. If this is the case, concrete floor is used to minimise the temperature variation through the day.

Underfloor heating presents important benefits, both in terms of economy and accurate delivery of heat in the area where it is needed. Comparing the costs saved by this system with the more traditional heating technologies, the heat pump installation means a significant improvement to reduce future energy costs and provide additional source of income through the system design life.

2.3. Farming under study

The case under study considers a pig farming located in the region of Toledo (Spain). In the following Fig. 4 it is possible to observe a general view of the farm and its exact location.

The aforementioned farm included in this research is constituted by 1500 breeding places and 2500 of transition (from weaning to 23 kg). Piglets housing uses a heating plate made of a ceramic material where heat is homogeneously distributed. As shown in Fig. 5, the ceramic plate is integrated in a small-mess grille that allows the proper slurry filtration.

The current heating system used to heat the nests and floor plates of piglets is a diesel boiler whose consumption is 5.000 L per month in the coldest season.

3. Practical process

This section includes all the technical calculations required to finally design the heating system presented in this research. In this

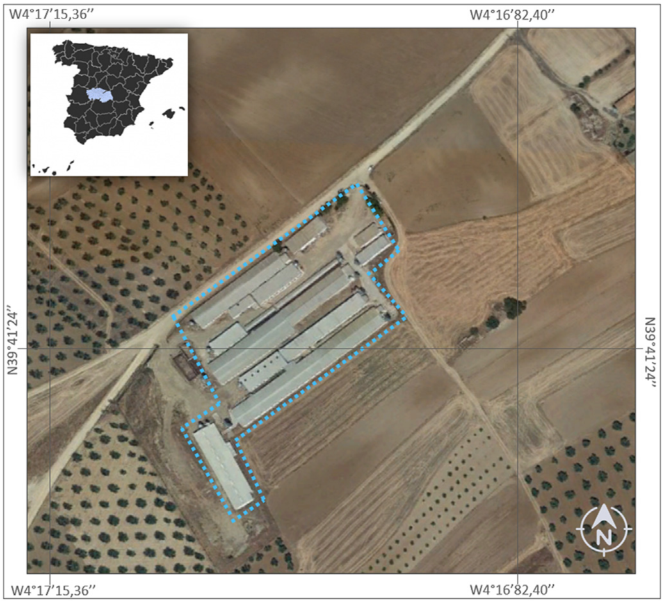

Fig. 4. Location of the farm under study.

Fig. 5. Piglets resting place in the farm considered in this research.

way, from the heating energy needs of the farm, each of the elements of the installation will also be defined in the following subsections.

3.1. Farm energy needs

The initial step of the calculation process is to define the annual energy demand of the farm to cover the heating needs of the piglets. From the information obtained in the pig farm about the use of 5000 L of diesel in the coldest month and considering the annual temperatures where it is located, the annual use of diesel has been estimated as 33,235 l/year (also taking into account that the performance of a diesel boiler is of around 85%).

Once determined the use of diesel, it is required to calculate the initial Coefficient of Performance (COP) of the heat pump that is planned to be installed in the system. In this regard, according to the EU Standard Law 813/2013 [25], which establishes the relation between the COP of the heat pump and the temperature of the inlet working fluid, the COP of the heat pump would be of 5.8 (considering that the temperature of the slurry is of around 20 °C). This relation, for the heat pump selected, can be observed in Fig. 6.

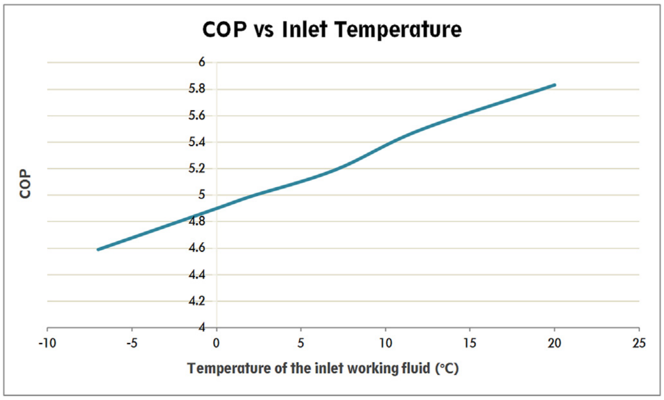

Fig. 6. Relation COP of the system and temperature of the inlet working fluid.

The previous Fig. 6 indicates that, for the temperature conditions of the slurry, the COP of the heat pump reaches a considerable high value (higher than the common geothermal heating systems). Based on this COP, the power of the heat pump required in the installation may be reduced and therefore lower than in the traditional geothermal heat pumps systems. All this will mean, in turn, a reduction of the heat pump investment but also of the operational costs associated to the slurry system working.

Furthermore, since the Net Calorific Value (NCV) of diesel is 10.28 kWh/l [26], the annual energy contribution of this fuel would be of 341,655.80 kWh/year. Given that the COP of the system is 5.8, the heat pumps energy needs would be 58,906.17 kWh/year, meaning that (for a working period of 2400 h/year), the heat pump power must be of at least 24.54 kW. A commercial geothermal heat pump of 32.4 kW has been selected with the aim of overestimating the obtained value and dealing with possible future energy demand issues.

3.2. Design of the buried heat exchanger

This subsection aims to define the total length of the heat exchanger constituting the system. The calculation of this parameter is conditioned by a series of factors as the following Eq. (1) shows [27].

$$L_H = \frac{Q_H \cdot \frac{COP_H - 1}{COP_H}\left(R_P + R_S . F_H\right)}{T_L - T_{MIN}} \tag{1}$$

where:

L_H = Heat exchanger length (m)
Q_H = Energy needs (kWh)
COP_H = Heat pump coefficient of performance in heating mode.
R_P = Pipe resistance to heat flow (K/Wm)
R_S = Heat exchanger thermal resistance (mK/W)
F_H = Usage factor.
T_L = Slurry minimum temperature (°C)
T_{MIN} = Working fluid minimum inlet temperature (°C)

In this way, all these factors must be previously determined to finally calculate the global length of the heat exchanger required in the geothermal system.

3.2.1. Slurry maximum and minimum temperatures

The general heat exchange will be conditioned by the difference of temperature between the slurry and the fluid that circulates through the heat exchangers. Thus, first of all, maximum and minimum temperatures of the slurry during the year are calculated by using Eqs. (2) and (3) [27].

$$\boldsymbol{T_L} = T_m - A_S \cdot e^{\left(-X_S\sqrt{\frac{\pi}{365\cdot\alpha}}\right)} \tag{2}$$

$$\boldsymbol{T_H} = T_m + A_S \cdot e^{\left(-X_S\sqrt{\frac{\pi}{365\cdot\alpha}}\right)} \tag{3}$$

where:

T_L = Slurry minimum temperature (°C).
T_H = Slurry maximum temperature (°C)
T_m = Slurry mean temperature (°C)
A_S = Daily mean temperature (°C)
X_S = Heat exchanger installation depth (cm)
α = Thermal diffusivity of the ground (cm^2s)

The following Table 1 includes the specific parameters of the system and the final T_L and T_H results after applying Eqs. (2) and (3).

The next step is to calculate the outlet temperature of the working fluid in the heat pump, and, using that value, its minimum inlet temperature. Whit that aim, Eqs. (4) and (5) have been implemented [27] and results are included in Table 2.

$$\boldsymbol{T_O} = T_i - \frac{2,400 \cdot P_C \cdot \frac{COP_H - 1}{COP_H}}{C_P(Q/3,600)} \tag{4}$$

$$\boldsymbol{T_{MIN}} = \frac{1}{2}(T_i + T_O) \tag{5}$$

where:

T_O = Outlet heat pump temperature (°C)
T_i = Inlet heat pump temperature (°C)
P_c = Heat pump power in heating mode (kW)
COP_H = Heat pump coefficient of performance in heating mode.
C_P = Working fluid specific heat (J/KgK)
Q = Flow rate (l/h)

3.2.2. Pipe resistance to heat flow

For the proper design of the heat exchanger, it is also necessary to know the resistance of the pipe to the heat flow. Thus, through Equation (6), this parameter has been calculated and can be observed in Table 3.

$$R_P = \frac{1}{2\cdot\pi\cdot K_P} \cdot ln\left(\frac{D_0}{D_1}\right) \tag{6}$$

where:

R_P = Pipe resistance to heat flow (K/Wm)
D_0 = Pipe external diameter (m)
D_1 = Pipe internal diameter (m)
K_P = Pipe thermal conductivity (W/mK)

3.2.3. Heat exchanger thermal resistance

The thermal resistance of the heat exchanger depends on the kind of pipe, the slurry, the configuration of the buried heat exchanger and the system working period. For horizontal heat exchangers (as the one of the system suggested in this work), the procedure consists of calculating the factor for each single heat exchanger through the following Eq. (7).

$$R_S = 1\Big/4\pi k E_i\left(-r^2\Big/(4\alpha t)\right) \tag{7}$$

where:

R_S = Pipe resistance to heat flow (K/Wm)
k = Ground thermal conductivity (W/mK)
E_i = Exponential integral function [29]
r = Heat exchanger radius (m)
t = Heat exchanger usage time (s)

Eq. (7) must be applied to calculate R_S for all the distances among pipes (distance of each pipe to others including the image pipes symmetrically arranged regarding the surface). These distances are obtained from the following Eq. (8).

$$L = \left(B^2 + D^2\right)^{1/2} \tag{8}$$

Each of the terms of the above Eq. (8) are graphically described in Fig. 7.

By applying both Eqs. (7) and (8), the distances among pipes and the corresponding single values of R_S are included in Table 4. It is worth mentioning that for the parameter k of Eq. (7), the thermal conductivity of the concrete (material covering the pipes) has been used [28].

Thus, R_S of all the buried pipes must be added for then subtracting the values of the image pipes. The final R_S of the geothermal heat exchanger will derive from dividing the previous value by the total number of pipes (without considering the image pipes). From the information of Table 4 R_S takes the value of 0.394 mK/W.

3.2.4. Usage factor

F_H represents the fraction of time in which the heat pump is operating and, therefore, the seasonal working period of the system. It is a quite influential factor since it defines the amount of heat that the system will exchange with the ground during the heating mode. Since in the system of this work, the heat pump has been designed to be working 2400 h/year, F_H is obtained from dividing the mentioned working period by the number of total hours of a year, obtaining the value of 0.270.

3.2.5. Final system design

From all the parameters previously calculated, the total length of the buried heat exchanger is obtained applying Eq. (1). The following Table 5 compiles the values of the calculated parameters and final L_H for the system of this research.

Considering the above heat exchanger total length and given that the separation among pipes is 0.5 m, an estimated area of

Table 1
Determination of the minimum and maximum temperatures of the slurry.

Temperatures of the slurry	
T_m (°C)	20
A_S (°C)	14.9
X_S (cm)	50
α (cm^2s)	0.00087[a]
T_L (°C)	**10.67**
T_H (°C)	**29.33**

[a] Thermal diffusivity of the concrete (material covering the heat exchangers) [28].

Table 2
Outlet and minimum inlet temperature of the working fluid in the heat pump.

Working fluid temperatures	
T_i (°C)	12
P_C (kW)	32.4
COP_H	5.8
C_P	4185
Q (l/h)	7100
T_O (°C)	**4.21**
T_{MIN} (°C)	**8.11**

Table 3
Calculation of the pipe resistance to heat flow.

Pipe resistance to heat flow	
D_0 (m)	0.036
D_1 (m)	0.032
K_P (W/mK)	0.41
R_P (K/Wm)	**0.046**

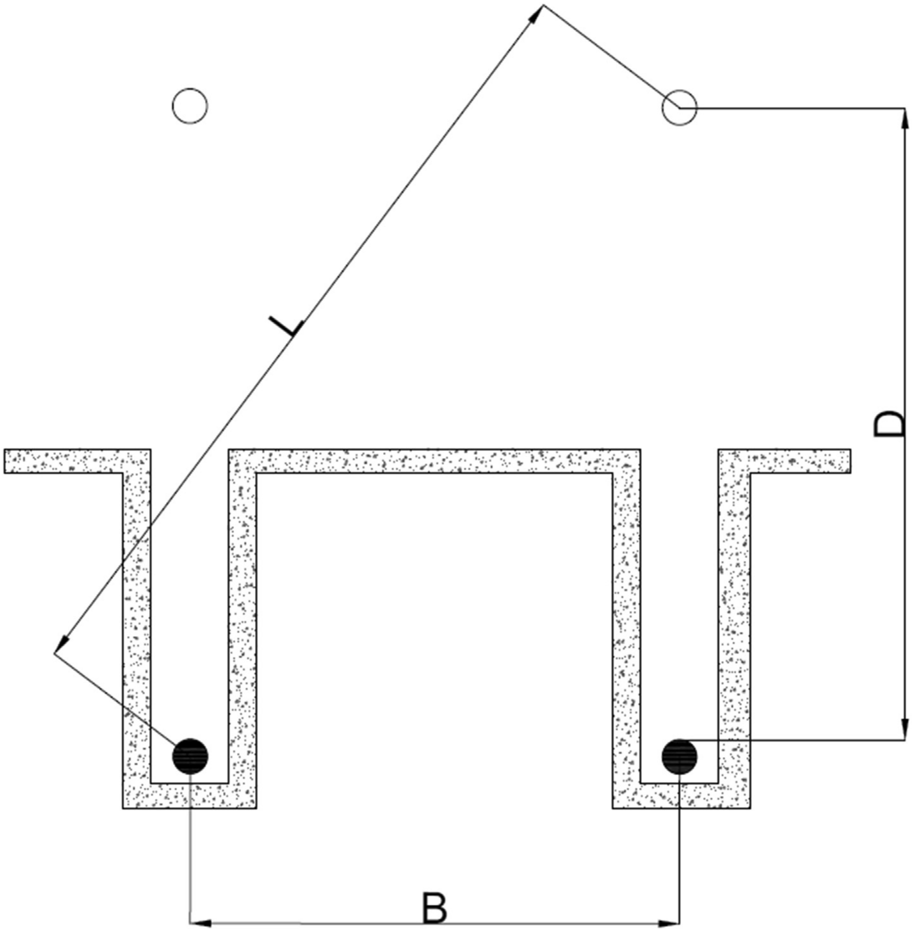

Fig. 7. Scheme of the buried horizontal pipes.

1915.26 m^2 is needed for the installation of the piping system and the corresponding reinforced concrete cover. In this sense, it is also necessary to determine the amount of slurry that will be feeding the heating system during the year. With that aim, Table 6 includes the annual and daily volume of slurry produced in the farm of study.

Since the area of the thermal circuit (before calculated) is 1915.26 m^2, the system could maintain a layer of 27.90 cm of active slurry during the whole year.

Table 4
Calculation of R_S according to the distances of each pipe.

	Distance (m)	R_S
Pipe 1 to 1	0.016	0.42
Pipe 1 to 2	0.5	0.014
Pipe 1 to 3 (image pipe)	1	0.019
Pipe 1 to 4 (image pipe)	1.12	0.021
Pipe 2 to 1	0.5	0.014
Pipe 2 to 2	0.016	0.42
Pipe 2 to 3 (image pipe)	1.12	0.021
Pipe 2 to 4 (image pipe)	1	0.019

3.3. Overall system evaluation

This subsection addresses the global evaluation of the system here proposed from an economic and environmental point of view.

3.3.1. Economic analysis

Once calculated the technical parameters of the suggested system, it is convenient to determine the initial investment required in the installation as well as the operational costs associated to its regular use. For the calculation of the first factor (initial investment), three main components have been considered: (i) the geothermal heat pump, (ii) heat exchangers and (iii) the reinforced concrete cover. The total initial investment value and the price of each single component are included in the following Table 7. It must be clarified that although the geothermal heat pump is, in itself, provided with a circulation pumping system, additional recirculation pumps have been included in the installation to guarantee the continuous operation of the circuit. In this sense, for the design of these pumps, the pressure drop and the flow rate must be known. Flow rate is given by the regime of the geothermal heat pump and the total pressure drop has been estimated considering the unitary pressure drop of the PE-100 heat exchangers (17.7 m per 100 m of pipe) [27]. Thus, the circuit is designed in 7 loops provided with 6 recirculation pumps of 1.5 kW of nominal power.

The remaining economic indication rests on the regular costs associated to the operation of the system. These costs will be mainly attributed to the electricity use of the geothermal heat pumps and circulation pumps and are shown in Table 8.

3.3.2. Environmental impact

The evaluation of the environmental impact is here approached by considering the greenhouse gases emissions associated to the operation of the geothermal heat pumps and the recirculation pumping system. In this way, Table 9 includes the annual CO_2 emissions of the system.

Beyond the calculation of the greenhouse gases emissions, it is important to remember the environmental advantages of reducing the temperature of the slurry in the technology of the system. These advantages are mainly related to the descent of emissions of ammonia and CH_4. As mentioned before, the mean temperature of the slurry will be of around 20 °C, achieving a minimum value of 10.73 °C. This means that, in the most favourable conditions, the active slurry will decrease its temperature in approximately 10 °C. As stated in some research, the rates of CH_4 and ammonia emissions descend around 80% per 10 °C of slurry temperature decrease (0.15 gh/kg at 10 °C to 0.75 gh/kg at 20 °C) [36].

Table 6
Estimation of the annual and daily slurry produced in the farm under study.

	Number of places	Annual slurry [m^3][a]	Daily slurry [m^3]
Breeding pigs	1500	3225	8.84
Transition pigs	2500	3075	8.42
Total	**4000**	**6300**	**17.26**

[a] Considering that each breeding and transition pig produces around 2.15 m^3 and 1.23 m^3 of slurry per year respectively [30].

Table 7
Global initial investment of the system described in this research.

	Unitary price	Units	Total price
Heat pump system	16,245.00 €/u	1 u	16,245.00 €
Geothermal heat exchangers	1 €/m	3830.52 m	3830.52 €
Reinforced concrete cover	16.26 €/m^2	1915.26 m^2	31,142.13
Recirculation pumps	911.00 €/u	6 u	5466.00 €
Working fluid	4.08 €/l	770.07 l	3141.89 €
Total initial investment [€]			**59,825.54 €**

*Prices are based on the commercial catalogues of “Vaillant”, “ALB”, “Grundfos” for the geothermal components and the Standard Law UNE-EN 13163:2013+A2:2017 for the concrete cover [31–34].

4. Discussion

With the aim of providing a complete analysis of the installation addressed in this work, a traditional Ground Source Heat Pump (GSHP) system has also been contemplated to cover the heating needs of the farm. In this way, the slurry technology will be finally compared to the common geothermal system and the diesel installation currently used in the farm.

4.1. Ground source heat pump system

For the design of the shallow geothermal system, the software GES-CAL has been implemented. This software, developed by research from the TIDOP Research Group (University of Salamanca) allows defining the most appropriate geothermal design depending on the particular conditions of the system [37]. For its use, it is required to know the energy demand (already calculated in subsection 3.1. Farm energy needs) and the thermal conductivity of the ground in the surrounding area. According to the Geological

Table 5
Determination of the total length (L_H) for the buried heat exchanger of the system.

Heat exchanger total length	
Q_H (kW)	32.4
COP_H	5.8
R_P (K/Wm)	0.046
R_S (mK/W)	0.394
F_H	0.270
T_L (°C)	10.67
T_{MIN} (°C)	8.11
L_H(m)	**3830.52**

Table 8
Operational costs associated to the use of the suggested system.

	Electricity use [kWh/year]	Price per kWh [€][a]	Total [€]
Heat pumps	58,906.17	0.1476	8694.55
Recirculation pumps	21,600.00	0.1476	3188.16
System maintenance	–	–	120.00
Annual operational cost [€]			**12,002.71**

[a] The electricity price per kWh has been estimated as an average of the electricity rate in Spain for the off-peak and peak hours.

Table 9
Annual CO_2 emissions of the system due to the electricity use of the heat pumps and recirculation pumps [35].

	Electricity use [kWh/year]	CO_2 emissions per kWh [kg]	Total [kg]
Heat pumps	58,906.17	0.296	21,029.50
Recirculation pumps	21,600.00	0.296	7711.20
Annual CO_2 emissions [kg]			**28,740.70**

and Mining Institute of Spain (IGME), the area where the farm is located is mainly constituted by granite formations of medium to coarse grain [38]. The thermal conductivity of these materials is typically 2.8 W/Mk [28], so this will be the value used in when calculating the system in GES-CAL.

Once introduced all the information about the geothermal system, GES-CAL software provides different configuration in function on the heat exchanger selected. Results derived from the use of this tool can be observed in Table 10.

4.2. Existing diesel installation

From the information provided by the farm about the use of diesel for heating purposes in the coldest month, the distribution of fuel use per month has been estimated (in function on the ambient temperatures in the area) and is shown in Fig. 8. The global annual fuel use in the farm is then of 39,100 l of diesel.

From the above value of annual fuel use, the total annual CO_2 emissions are directly obtained from the emission factor of this fuel (2.868 $kgCO_2/l$) [39] and reaches the value of 112,138.80 kg-CO_2/year.

Regarding the economic point of view, considering a standard price of the diesel for heating of 0.764 €/l (real price in the month of January 2020 in Spain), the annual operational costs would be of 29,872.40 €.

4.3. Comparative analysis

Analysing all the previous results, the slurry technology presents important advantages regarding the traditional geothermal installations and especially the current farm heating system. The most remarkable differences are found when comparing the slurry system to the existing diesel one. In the following Fig. 9, it is possible to easily observe the principal benefits of the system proposed here: reduction 60% of operational costs, 74% of CO_2 emissions and 80% of CH_4 and NH_3 emissions.

Comparing now all the solutions presented in this research in the context of the operational costs associated to each system, it is considered appropriate to evaluate the costs accumulated during the whole lifetime of the installations (30 years). This aspect is graphically presented in Fig. 10, in which it is possible to deduce the enormous differences among the slurry and geothermal systems and the diesel one. In this sense and, on the basis of the existing diesel installation, the accumulated costs are 60% lower for the slurry system, and in the range of 45–55% for the geothermal solutions.

It is convenient to mention that, for the feasibility analysis performed in the previous Fig. 10, accumulated costs are expressed considering the Consumer Price Index (CPI) with an average annual discount rate of 1.8%. According to the Spanish Institute for National Statistics [40], CPI index has experienced a variable behaviour in the last 40 years, so the mentioned value of 1.8% has been established taking into account a conservative and regular approach for the period of useful life of the systems (30 years). The use of this type of economic indicator is essential for a realistic analysis during the mentioned lifetime period.

Considering also the initial investment required in each system, the following Fig. 11 shows both the initial investment (blue colour) and the operational costs (green colour) associated to each of the analysed solutions. This Fig. 11 also includes the amortization period of the investment of each system according to the economic analysis graphically performed.

As can be deduced from the previous Fig. 11, the lowest initial investment and operational costs are associated to the slurry technology. Because of this fact, the investment for the slurry system would be amortized in only 4 years (taking into account the differences between its operational costs and the ones of the current diesel system). The remaining geothermal installations involve

Table 10
Results obtained in GES-CAL software for each of the heat exchanger designs.

	Vertical Double-U	Vertical Single-U	Horizontal	Helical
Technical design	Number of boreholes = 8 Total drilling length = 988 m	Number of boreholes = 9 Total drilling length = 1184 m	Pipe length = 6355.82 m Ground area = 794.48 m^2	Number of boreholes = 12 Total drilling length = 310 m
Economic evaluation	Initial investment = 82,755.19 € Annual operational costs = 13,587.09 €	Initial investment = 90,361.88 € Annual operational costs = 13,703.55 €	Initial investment = 206,794.88 € Annual operational costs = 16,653.74 €	Initial investment = 195,458.65 € Annual operational costs = 13,769.82 €
Environmental analysis	Annual CO_2 emissions = 26,987.49 kg	Annual CO_2 emissions = 27,200.61 kg	Annual CO_2 emissions = 33,096.93 kg	Annual CO_2 emissions = 27,413.20 kg

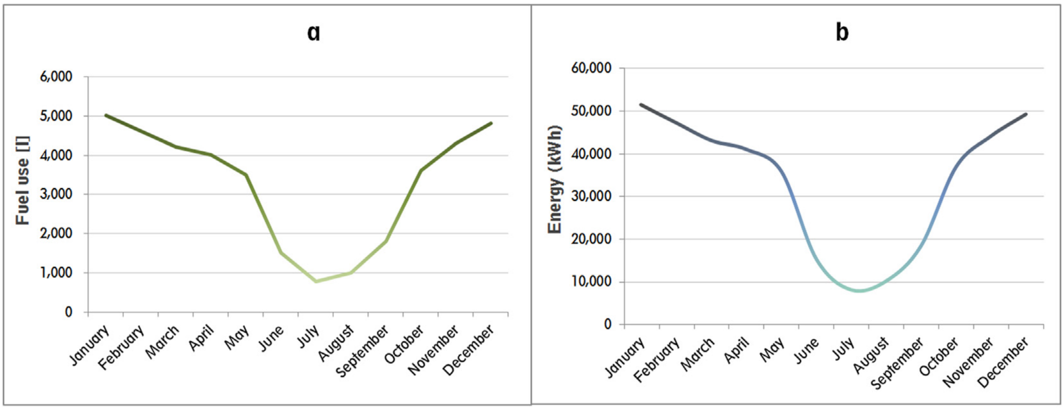

Fig. 8. Distribution of fuel use for heating during the year in the farm under study, (a). fuel use (l), (b). energy (kWh).

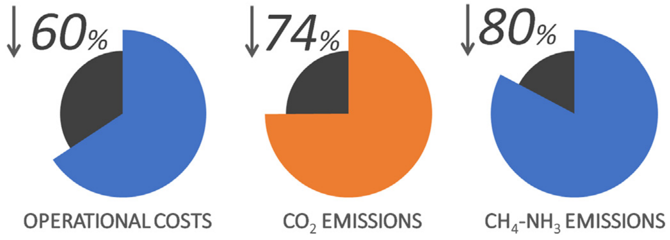

Fig. 9. Principal advantages of the slurry technology in relation to the existing diesel installation.

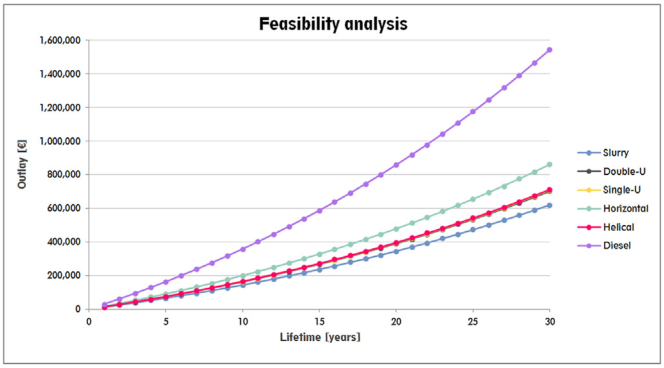

Fig. 10. Accumulated costs of each solution during the established lifetime.

amortization periods of 5 years (double-U), 6 years (single-U), 11 years (helical) and 13 years (horizontal). It is also worth mentioning that, the operational costs associated to each solution and, included in this Fig. 11, are expressed according to a NPV with a discount rate of 1.8%.

The final comparative analysis is related to the environmental impact. Comparing the CO_2 emissions, all the geothermal solutions and the slurry one present a similar annual emission rate. The diesel installation has however, the highest CO_2 emissions rate. All the mentioned above is graphically described in Fig. 12.

Within the environmental context, it is also necessary to highlight the positive impact of the slurry technology derived from the reduction of temperature of the slurry. As seen before, this descent involves, in turn, a significant reduction of the global CH_4 and NH_3 emissions.

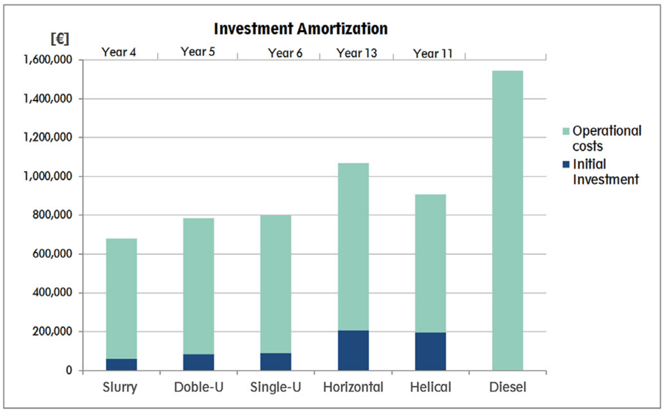

Fig. 11. Operational costs, initial investment and investment amortization period of each system.

5. Conclusions

The work presented here aims to be a crucial contribution towards the international scientific community, for the operators in the farming areas in the sense of facilitating the decision making when selecting one or another energy system. The technical approaches performed in a piglet farm in the centre of Spain, shows relevant advantages of the slurry technology and several geothermal solutions compared to a traditional diesel fuelled heating system. Results show that the specific heating needs of the animals can be satisfied by implementing these renewable technologies, being a promising option for the substitution of the fossil systems. As far as the strategy for the optimised use of slurry is concerned, the following statements are deduced from the installation here designed:

- The slurry technology involves significant improvements in relation to the existing diesel system of the farm. By implementing the slurry alternative, the operational costs could be reduced up to 60%. Given the differences between the costs of both systems, the initial investment required by the slurry installation (around 60,000 €), could be amortized in only four years. The environmental advantages are also notable, being the CO_2 and CH_4 emissions reduced to 74% and 80%, respectively.
- The conventional geothermal systems considered in the study constitute a recommendable option to replace the diesel

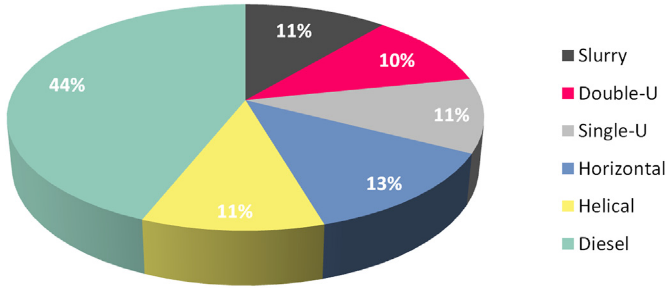

Fig. 12. CO_2 emissions associated to each of the systems considered in this work.

installation, both from the economic and environmental points of view.

- Focusing on the most optimal geothermal solution (vertical double-U or single-U), the initial investment is higher than the one of the slurry technology, what could make the user to select this last option. Regarding the operational costs and the emissions of CO_2, these are practically the same for the geothermal and the slurry systems.
- Beyond all the positive impacts of the slurry system, the reduction of the slurry temperature also constitutes a significant point when considering this option. In general terms, CH_4 and NH_3 emissions can be reduced up to 80% if these systems are implemented in the farms.

Based on all the above, the slurry technology has proved to be an excellent solution to cover the heating demand of a pig farm. Vertical GSHP systems are also recommendable because of the economic and environmental benefits obtained compared to the traditional fossil installations. This study thus, confirms the potential of the geothermal energy and the combined slurry system to mitigate climate change but also to optimize the heating system, contributing to important economic savings for the farm operator.

In addition, the expected long-term impact of the discussed methodology involves a global strategy to improve the national pig sector in the sense of making it more efficient and less vulnerable in the future. Beyond the direct economic and environmental advantages (presented before), the slurry technology is expected to contribute to different significant issues: (i) improvement of the animal health by the enhancement of the air quality and environment conditions; (ii) increase of the productivity of sow farms and the number of piglets produced thanks to the improvement of the animal's quality of life; (iii) promotion of the energy self-sufficiency of farms; (iv) improved perception of the pig farm in the international meat industry market with the consequent advancement in the global positioning; (v) opening to new possibilities of business and general increase of the farm sales derived from the improved farm conception.

Direct and indirect positive aspects of the combined slurry system indicate the importance of delving into this kind of sustainable technologies. In this sense, future author's research will be aimed at finding new possibilities of implementing the discussed system and inquiring into the associated advantages briefly addressed in this work.

Credit author statement

Cristina Sáez Blázquez: Investigation, Methodology, Writing – original draft, Reviewing and Editing, David Borge-Diez: Formal analysis, Validation and Supervision, Ignacio Martín Nieto: Data curation and Methodology, Miguel Ángel Maté González: Investigation, Resources and Formal analysis, Arturo Farfán Martín: Supervision, Diego González-Aguilera: Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Authors would like to thank the Department of Cartographic and Land Engineering of the Higher Polytechnic School of Avila, University of Salamanca, for allowing us to use their facilities and their collaboration during the experimental phase of this research. Authors also want to thank the veterinary staff of the farm, Jorge Plumé García, for providing the specific information about the annual energy use.

References

[1] European Commission. Communication from the commission to the European parliament, the Council, the European economic and social committee, the committee of the regions and the European investment bank. Clean energy for all Europeans. COM; 2016a.
[2] European Commission. Commission staff working document impact assessment. Accompanying the document. Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on Energy Efficiency. SWD (2016) 405 final. 2016.
[3] The European Parliament and the Council of the European Union. Directive (EU) 2018/2002 of the European parliament and of the Council of 11 December 2018 amending directive 2012/27/EU on energy efficiency. 2018.
[4] Barber EM, Classen H, Thacker P. Energy use in the production and housing of poultry and swine-an overview. Can J Anim Sci 1989;69:7–21.
[5] Corré W, Schröder JJ, Verhagen A. Energy use in conventional and organic farming systems. In: Proceedings of the international fertiliser society; 2003. p. 24.
[6] Kythreotou N, Florides G, Tassou SA. A proposed methodology for the calculation of direct consumption of fossil fuels and electricity for livestock breeding, and its application to Cyprus. Energy 2012;40:226–35.
[7] Agri-environmental indicator - energy use. Eurostat, Statistics Explained. 2017.
[8] Gołaszewski J, De Visser C, Brodzínski Z, Myhan R, Olba-Ziety E, et al. State of the art of energy efficiency in agriculture, Project Deliverable 2.1. Energy Efficiency in Agriculture (AGREE) Project; 2012.
[9] Meyer-Aurich A, Berg W, Kraatz S, Jubaer H, Mellmann J, et al. Priorities for energy efficiency measures in Agriculture,Project deliverable 3.2. Energy Efficiency in Agriculture (AGREE) Project; 2013.
[10] Hessel E, Zurhake C, Van Den Weghe H. Heating and cooling performance of an under floor earth tube air tempering system in a mechanical ventilated farrowing house. In: Proceedings of the XVIIth world congress of the international commission of agricultural and biosystems engineering (CIGR), Québec, Canada; 2010.
[11] Rojas-Downing M Melissa, et al. Climate change and livestock: impacts, adaptation, and mitigation. Clim Risk Manag 2017;16:145–63.
[12] Kavanaugh Stephen P. Design of geothermal systems for commercial and institutional buildings. Ground-Source Heat Pumps 1997.
[13] Hadi Farabi-Asl, Fujii Hikari, Kosukegawa Hiroyuki. Cooling tests, numerical modelling and economic analysis of semi-open loop ground source heat pump system. Geothermics 2018;71:34–45.
[14] Andrievs Ilsters, Ziemelis Imants, Kristutis Igors. Possibilities of heat pump usage for heating piglet resting places. Engineering for Rural Development 2009;28:29. Jelgava.
[15] Wang MZ, et al. Economic performance study on the application of ground source heat pump system in swine farms in Beijing China. AASRI Procedia 2012;2:8–13.
[16] Borge-Diez David, et al. Geothermal source heat pumps under energy services companies finance scheme to increase energy efficiency and production in stockbreeding facilities. Energy 2015;88:821–36.
[17] Islam Md Manirul, et al. Evaluation of a ground source geothermal heat pump to save energy and reduce CO_2 and noxious gas emissions in a pig house. Energy Build 2016;111:446–54.
[18] Alberti Luca, et al. Geothermal heat pumps for sustainable farm climatization and field irrigation. Agric Water Manag 2018;195:187–200.
[19] Pulat E, Coskun S, Unlu K, Yamankaradeniz N. Experimental study of horizontal ground source heat pump performance for mild climate in Turkey. Energy 2009;34:1284–95.
[20] Yang W, Shi M, Liu G, Chen Z. A two-region simulation model of verticalU-tube ground heat exchanger and its experimental verification. Appl Energy 2009;86:2005–12.

[21] Consiglio delle comunità europee. Direttiva cee 91/676. 1991.
[22] Andrievs Ilsters, Ziemelis Imants, Kristutis Igors. Possibilities of hea tpump usage for heating piglet resting places." Engineering for Rural Development. Jelgava 2009;28:29.
[23] Santonja Germán Giner, Georgitzikis Konstantinos, Maria Scalet Bianca, Montobbio Paolo, Roudier Serge, Delgado Sancho Luis. Best available techniques (BAT) reference document for the intensive rearing of poultry or pigs. JCR Science for policy report. European Comission; 2017.
[24] Huegle Th U, Andree H. Odor emissions from cattle and swine slurry. In: ASABE Paper 014098; 2001.
[25] Diario Oficial de la Unión Europea. REGLAMENTO (UE) Nº 813/2013 DE LA COMISIÓN de 2 de agosto de 2013 por el que se desarrolla la Directiva 2009/125/CE del Parlamento Europeo y del Consejo respecto de los requisitos de diseño ecológico aplicables a los aparatos de calefacción y a los calefactores combinados. 2013.
[26] Instituto para la Diversificación y Ahorro de la Energía (IDAE), Guía Técnica: diseño de centrales de calor eficientes. Ahorro y Eficiencia Energética en Climatización 2010.
[27] Instituto para la Diversificación y Ahorro de la Energía (IDAE). Guía Técnica: diseño de sistemas de intercambio geotérmico de circuito cerrado. Ahorro y Eficiencia Energética en Climatización 2012. ISBN: 978-84-96680-60-9.
[28] Prontuario de soluciones constructivas. Código Técnico de la Edificación (CTE). Instituto de Ciencias de la Construcción Eduardo Torroja e Instituto de la Construcción de Castilla y León; 2007.
[29] Carslaw HS, Jaeger JC. Conduction of heat in solids. Oxford): Clarendon; 1959.
[30] Real Decreto 324/2000, de 3 de marzo, por el que se establecen normas básicas de ordenación de las explotaciones porcinas. Ministerio de la Presidencia, Relaciones con las Cortes y Memoria Democrática; 2000.
[31] ALB SISTEMAS, Tarifa de precios, Sistema de Geotermia. 2020. https://www.alb.es/.
[32] Vaillant, Catálogo tarifa, bomba de calor. 2020. https://vaillant.com/.
[33] Grundos, Catálogo de productos, CM 5–12. 2020. https://grundfos.com/.
[34] UNE-EN 13163:2013+A2, 2017. Thermal insulation products for buildings - factory made expanded polystyrene (EPS) products – Specification. 2017.
[35] European Environment Agency. National emissions reported to the UNFCCC and to the EU greenhouse gas monitoring mechanism. CO_2 emission intensity; 2020.
[36] Sommer SG, Petersen SO, Sørensen P, Poulsen HD, Møller HB. Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. Nutrient Cycl Agroecosyst 2007;78(1):27–36.
[37] Cristina Sáez Blázquez, Ignacio Martín Nieto, Rocío Mora, Arturo Farfán Martín, Diego González-Aguilera. GES-CAL: a new computer program for the design of closed-loop geothermal energy systems. Geothermics 2020;87:101852.
[38] Instituto Geológico y Minero de España (IGME). Mapa y memoria explicativa de la Hoja 657-SONSECA. Mapa Geológico de España a escala 1: 50 000. 1992.
[39] Factores de emisión, registro de huella de carbono, compensación y proyectos de absorción de dióxido de carbono. Ministerio para la Transición Ecológica y el Reto Demográfico; 2020.
[40] INE. Spanish Institute for National Statistics; 2021. https://www.ine.es/.