

## Article

# Geothermal Heat Pumps for Slurry Cooling and Farm Heating: Impact and Carbon Footprint Reduction in Pig Farms

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**Abstract:** The pig farm sector has been developing rapidly over recent decades, leading to an increase in the production of slurry and associated environmental impacts. Breeding farms require the maintenance of adequate indoor thermal environments, resulting in high energy demands that are frequently met by fossil fuels and electricity. Farm heating systems and the storage of slurry constitute considerable sources of polluting gases. There is thus a need to highlight the advantages that new green heating solutions can offer to reduce the global environmental impact of pig farming. This research presents an overview of alternative pig farm slurry technology, using geothermal heat pumps, which reduces the harmful effects of slurry and improves the energy behavior of farms. The results reflect the environmental benefits of this solution in terms of reducing carbon and hydric footprints. Reducing the temperature of slurry with the geothermal heat pump of the system also reduces the annual amount of greenhouse gases and ammonia emissions, and, via the heat pump, slurry heat is used for installation heating. Annual emissions of CO<sub>2</sub>e could be reduced by more than half, and ammonia emissions could also experience a significant reduction if the slurry technology is installed. Additional advantages confirm the positive impact that the expansion of this renewable technology could have on the global pig farm sector.

**Keywords:** slurry cooling; geothermal heat pump; greenhouse gas emissions; carbon and hydric footprints



**Citation:** Blázquez, C.S.; Borge-Diez, D.; Nieto, I.M.; Maté-González, M.Á.; Martín, A.F.; González-Aguilera, D. Geothermal Heat Pumps for Slurry Cooling and Farm Heating: Impact and Carbon Footprint Reduction in Pig Farms. *Sustainability* **2022**, *14*, 5792. <https://doi.org/10.3390/su14105792>

Academic Editor: Alessandro Franco

Received: 25 March 2022

Accepted: 6 May 2022

Published: 10 May 2022

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## 1. Introduction

The increase in the global population is inevitably leading to higher global animal production levels. The livestock sector is considered to contribute more than 50% of the general agricultural gross domestic product, supporting the livelihoods of around 1.3 billion people in developing countries [1,2]. As a result, not only are agricultural needs increasing, but the consumption of farm animals is increasing, too. Parallel with this increase, an intensification in livestock farming has been observed, including increases in the numbers of production units and animal densities as well as associated technologies, such as vaccinations and concentrated feeds, the latter requiring improved feed infrastructures [3]. Thus, the farming sector is responsible for the occupation of 30% of the earth's terrestrial surface and 75% of this total is associated with livestock production [4,5]. The number of animals reared for human consumption has been increasing worldwide in recent years, from almost  $4.9 \times 10^9$  in 2013 to  $5.1 \times 10^9$  in 2017, according to FAOSTAT [6]. Ninety-three percent of all animal production is concentrated in four classes of livestock: cattle, sheep,

goats, and pigs. Within this framework, Europe was responsible for the production of around 19% of the total pig population ( $1.9 \times 10^8$ ) in 2017—a value that has remained practically constant over the last few years.

#### *Pig Production and Associated Impacts*

The pig sector has undergone successful development and seen high demand, resulting in a sustained increase in production in recent years. In January 2020, there were about 677.6 million pigs worldwide, China being the foremost producer, supplying more than half of the global pig population. This country is the leading pork producer worldwide, producing about 55 million metric tons of pork each year. As of 2020, the level of pig meat production in China was 38,000 thousand tones, which accounts for 51.52% of the world's production of pig meat. The other countries in the top five (the United States of America, Brazil, the Russian Federation, and Vietnam) account for the rest of the world's total production of pig meat. In the case of the European Union, the pig sector represents the largest livestock category, before bovines. By 2018, almost three-quarters of the EU's pigs were produced in six EU Member States: Spain (20.8%), Germany (17.8%), France (9.3%), Denmark (8.5%), the Netherlands (8.1%), and Poland (7.4%) [7]. Moreover, global pig production was expected to increase by 4% in 2021 due to the recovery of production in countries affected by African Swine Fever (ASF) and those impacted by COVID-19. In the case of China, a 9% increase was estimated, as producers there adopted an aggressive strategy to take advantage of high pork prices. Regarding the European Union, production is marginally growing in relation to stable herd levels and an increase in productivity. In Germany, the discovery of ASF in the wild boar population is not expected to directly impact production, but export restrictions will probably result in higher German pork supplies in a saturated EU market. This fact, together with the weak domestic demand and considerably slowing demand from China, is likely to control prices in the next few years. In the case of Brazil, production is expected to grow by nearly 4% because of the rebounding consumption of domestic pork and resilient export demands.

The generation of gaseous pollution is linked to animal production. Although it is commonly accepted that ruminants are the principal drivers of agriculture-related global warming (enteric fermentation), several recent reviews of the scientific evidence have confirmed that the production of monogastric animals also requires special attention. In this regard, pork is the most consumed meat worldwide, its production being responsible for more than 9% of global livestock emissions [8,9]. Gaseous effluents associated with pig farms lead to numerous environmental problems that affect the atmosphere, neighborhood populations, and pig-keepers' health. Pig farming waste is included in so-called slurry: the liquefied, doughy, or semi-liquid manure with a significant ammoniac odor consisting of a mixture of excrement, washing water, and the remains of feed and fodder. The composition of pig slurry can be highly heterogeneous from one farm to another depending on different factors: the type of animals (breed, age, etc.), the type of farm (bait, piglets, breeding sows, etc.), and the type of feed or drinking water management [10]. Slurry from pig farms is a type of waste with a high water content (around 90%), an organic matter content between 50% and 75% (dry matter), a high content of total nitrogen (2–4 g/kg), a high concentration of phosphorus (0.7–1 g/kg), magnesium (0.2–0.3 g/kg) and potassium (0.9–1.4 g/kg), and an appreciable content of metals, such as copper, iron, manganese, and zinc. This composition makes slurry potentially a source of energy that can be harnessed.

On the other hand, these residues also present odorous compounds, such as hydrogen sulfide, volatile fatty acids, and phenolic compounds. Depending on the growth phase of pigs, slurry production varies from 23.5 to 41.1 l/animal day during weaning to 10–16 l/animal day during maternity to 3.5–9.7 l/animal day during fattening [11,12]. These large amounts of slurry cause the emission of pollutants, such as ammonia ( $\text{NH}_3$ ), and recognized GHGs, such as methane ( $\text{CH}_4$ ), carbon dioxide ( $\text{CO}_2$ ), and nitrous oxide ( $\text{N}_2\text{O}$ ). Ammonia and nitrous oxide are emitted during all the stages of manure management, whereas carbon dioxide comes from both manure processing and animal respiration

and methane derives from both the enteric fermentation of animals and the management of manure [13].

Concern over the negative impacts of these kinds of farms across Europe is not new but different international protocols, European Directives and national regulations that aim to reduce associated risks have appeared in recent years. Thus, NH<sub>3</sub> emissions are controlled under the EU National Emissions Directive [14] coming from the Gothenburg Protocol [15]. Furthermore, CH<sub>4</sub> and N<sub>2</sub>O emissions produced in livestock farming are regulated by the Kyoto Protocol under the United Nations Framework Convention on Climate Change [16]. Additional Directives can be found within the water framework for the management of different substances, such as nitrates or phosphorus [17,18]. The Industrial Emissions Directive [19] also sets a series of common rules for licensing different industrial activities with the aim of the environmental protection. One of the sectors contemplated in this Directive is intensive livestock farming, which makes it necessary to have an operating license describing the environmental performance of any farm.

In line with the previously mentioned regulations, livestock must be oriented towards a strategy resulting in more sustainable systems and strategies, contributing to the achievement of the objectives. The application of alternative technologies, referring to the application of novel processes and techniques to manage the animal production, is essential to achieve environmental sustainability in livestock farming [20]. As presented before, the increase in the number of pigs leads to an inherent increase in the generation of slurry, and so the need of management solutions to this type of waste is mandatory. In this sense, the introduction of renewable energy sources is directly related to the reduction in the energy demand and the increase in the heating/cooling system efficiency. As presented in this research, Geothermal Heat Pumps (GHP) are one of the systems with a higher potential to reduce energy consumption and also improve both indoor air quality in pig farms and reduce the associated pollution. Exploiting geothermal resources results in low operational costs and a high energy efficiency [21–23]. Its implementation in animal farms has already been investigated by different authors, who conclude that the performance of a GHP system allows a reduction in energy consumption by up to 46% and the CO<sub>2</sub> emissions linked to farm heating [24–26].

The problem to address through this work is clearly the management of slurry waste in the pig sector and, in turn, the high energy consumption associated with the conventional heating systems of the farms. While renewable technologies, such as GHP, constitute an appropriate solution for lowering the impact of the heating/cooling farm systems, they do not solve the slurry management. The aim of this research is to perform an extensive analysis of a recent geothermal strategy that combines the covering the pig farm energy demand and reducing the impact of slurry environmental and propose a novel system that improves the whole slurry management cycle. This solution, generally known as “slurry technology”, could play a vital role in the near future for ensuring the continuity of the pig sector. As shown in the following sections, this work seeks to evaluate the slurry technology from both an energy and environmental points of view, in order to emphasize the advantages of this strategy.

## 2. Theoretical Background

### 2.1. Environmental Impacts of Pig Farms

As already mentioned, the livestock sector is one of the principal consumers of natural resources, with a significant influence on the global climate, soil, air and water quality, biodiversity, land occupation, terrestrial eco-toxicity, and ozone layer depletion. Beyond slurry generation, the environmental impacts of pig farms derive from the notable energy requirements to maintain thermal indoor conditions and also from high water consumption [27]. In this way, pig farming activity is responsible for the generation of a large number of noxious gases derived from the high energy demand, which is closely linked to maintaining adequate environmental conditions for the animals inside. Controlling the

environment improves the welfare of animals and contributes to achieving the production objectives of the farm. In a farm, energy is mainly used for:

- Heating the first stage weaners and farrowing accommodation;
- Fans and ventilation systems;
- Lighting;
- Feeding, washing, slurry agitation, etc.

From all the items listed above, heating the farm space, especially the resting places of nursery pigs, requires the highest energy consumption. The term farrowing house is used to refer to those pig rooms in which a temperature of at least 24 °C is needed when the first piglet is born. After 48 h, this temperature can be reduced to 20 °C. First-stage weaners require environments at temperatures of 28–29 °C during the first week, which can be gradually decreased. Heating systems of intensive breeding farms use fossil fuels (e.g., kerosene, Natural Gas (NG) or Liquefied Petrol Gases (LPG)) and electricity to maintain an adequate thermal environment. These systems increase dependency on fossil energies, related costs and GHG emissions [28].

## 2.2. Slurry Environmental Impact

In the past few decades, the livestock revolution has involved a growth in meat consumption but also an increase in waste and associated environmental pollution [29]. Pigs' diets are often too rich in nutrients such as minerals and protein and only a small amount of them is absorbed by the animal. Consequently, slurry is rich in nitrogen, phosphorus, magnesium and potassium, which gives it a very interesting quality as a fertilizer, since these elements are the essential nutrients for plants [30]. For this reason, a direct application of the slurry to the soil has been and still is the main way of managing this waste. However, this has inherent environmental risks such as GHG emissions or exceeding the concentration of nitrogen and/or phosphorus in the soil, which can encourage eutrophication. Because of the above, the use of slurry in the soil is regulated, limited to 170 the kg of N that can be added per agricultural hectare in a year [31]. When this limit is reached, the surplus must be transported to other areas, causing increased transport costs and environmental impacts.

In different territories, such as Spain, which encompasses a multitude of agricultural landscapes and soils, an unequal productive capacity, strongly derived from an irregular distribution of rainfall both in time and space, with a habitual water deficit in many basins and the phenomena of soil erosion, makes slurry management and agricultural use difficult. The production of many crops depends exclusively on rainfall, and so when rainfall is low, slurry cannot be used on crops because it would salinize the land. However, it is also common to find that in irrigated areas or areas with high rainfall, slurry causes problems such as water contamination. In addition, the agricultural application of slurry in crops irrigated with phreatic water seems to reduce the salinization of soil due to organic matter's retention of sodium, whose excess causes serious imbalances in a plant's physiology. Another environmental problem caused by slurry management is ammonia emissions. In fact, the largest source of NH<sub>3</sub> emissions in Europe is the agricultural and livestock sector, which contribute around 90% of the year total emissions [32]. Around 64% of these emissions come from manure and slurry in their different management phases, usually three: accommodation for animals, the storage of manure and slurry and application in the field.

Slurry generates major problems in terms of emissions and to reduce transport costs, it is left in rafts for storage and moisture reduction. This generates emissions of ammonia, causing NO<sub>x</sub> contamination in the air. Furthermore, sometimes anaerobic conditions are produced, generating methane, causing a reduction in organic matter and bad odors. In summary, slurry management causes the emission of atmospheric pollutants directly linked to potentially harmful effects for soil, the atmosphere, water, animals, human beings, and plants. All these effects are summarized in Table 1 [33].

**Table 1.** Principal effects derived from an unappropriated management of slurry.

Medium	Effects
Soil	Land occupation Episodes of anaerobiosis Phytotoxicity Nutritional imbalances Metal bioaccumulation Salinization
Atmosphere	Unpleasant smells Dispersion of pathogens Greenhouse gases emissions Rotting of organic matter Emissions of NH <sub>3</sub> , H <sub>2</sub> S and CH <sub>4</sub> under anaerobic conditions
Water	Eutrophication of rivers, lakes, and reservoirs Turbidity that hinders photosynthesis Anaerobic processes at the bottom of watercourses Deterioration of the water quality Spread of pathogens
Animals and humans	Diseases derived from water consumption and contaminated plants Methemoglobin and gastric disorders
Plants	Weed development Metal bioaccumulation Physiological drought due to salinization

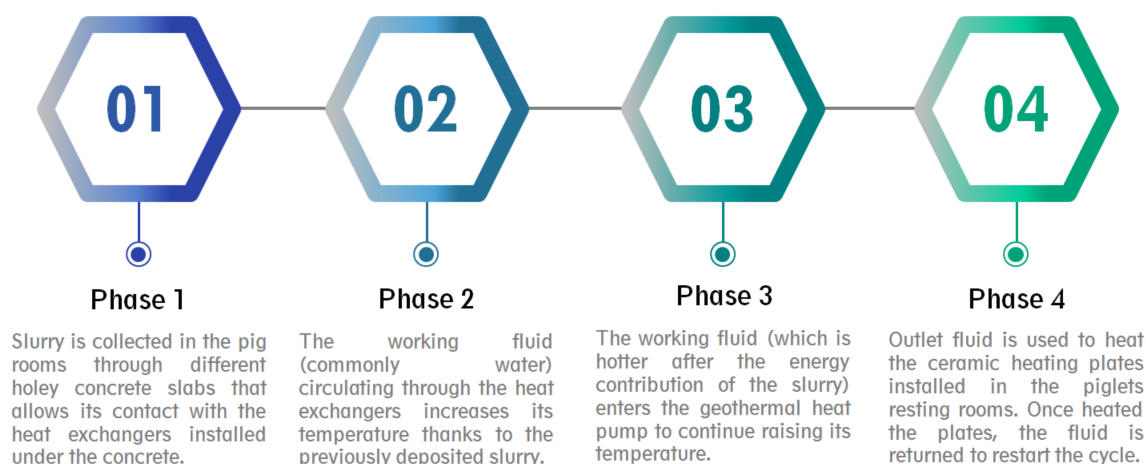
### 2.3. Slurry Technology

To tackle the previously described issues related to slurry management, production levels should be maintained within the maximum capacity of the ecosystem. Therefore, the pig farm sector is in a difficult position since it also needs to guarantee high production levels while reducing its environmental impact. On this matter, different mitigation strategies can be adopted, such as improving the efficiency of recovering nutrients and energy from slurry in pig production (including breeding and animal health), using low-emission systems or the implementation of alternative technologies.

The proposed GHP slurry management technology is based on the use of GHP and farm slurry to cover the energy requirements while reducing the negative impact of the slurry. This solution proposes the use of horizontal geothermal collectors, in a linear or spiral circuit configuration, to capture the heat of pig slurry in the beds of farms, with the aim of heating the farm through the use of a GHP. Thus, the fundamental principal of this technology is the collection of the slurry in a farm through holey concrete sheets, so that the thermal energy of it is transferred to the working fluid of the heat exchangers. This fluid is then received in the heat pump, where, as in a common geothermal installation, the temperature of the outlet fluid is increased and used to heat the ceramic heating plate in which the piglets are resting. The simplified processes that are included in the slurry technology are described in the following figure, Figure 1.

The implementation of the mentioned system ensures a double solution for covering the energy needs of the farm but also for the management of slurry. In this way, this technology brings significant advantages to pig farms:

- The reduction in the farm energy costs for heating, which frequently represent up to 80% of the global costs;
- Lowering the carbon footprint;
- Environmental sustainability, up to 70% of emissions inside the warehouses where the slurry housings are cooled;
- Improvement of air quality and animal welfare;
- Enhancements in corporate social responsibility, because of better environmental conditions for those working on farm facilities;
- Contributes to the development of quality seals in products derived from pork produced in those farms that apply this technology.



**Figure 1.** Description of the different phases that are part of the slurry technology.

### 3. Proposal and Case Study

#### 3.1. Heat Pumps for Slurry Management

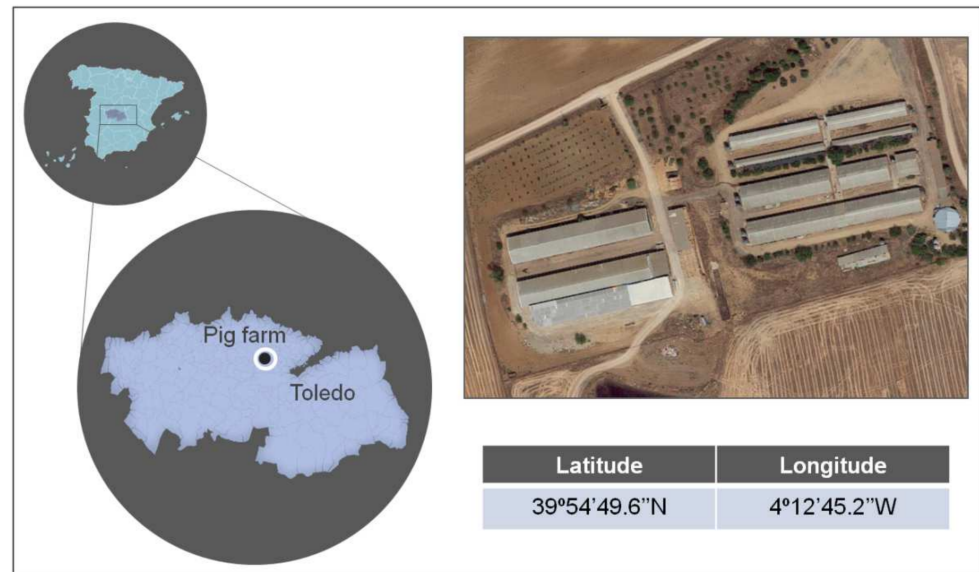
The high volume of slurry generated in the pig farm sector and the demanding regulations involve different associated problems that require the slurry to be managed in an environmentally friendly way. Moreover, the treatment must be economically competitive. Direct application to the soil is frequently preceded by the storage of the slurry in evaporation ponds to reduce its volume, to achieve a reduction in transport costs. This storage reduces the presence of pathogens and a certain degree of mineralization. However, GHG emissions to the atmosphere, such as ammonia and organic compounds, are still present, generating unpleasant odors. Alternative solutions include performing previous physical or physical-chemical separation operations where two phases are obtained: a phase is obtained diluted with suspended matter, and another is concentrated in solids. These processes are not efficient enough from both the economic and the energy points of view. In the rural sector, anaerobic digestion is an important economic alternative, specifically as a renewable energy source for electricity production. Animal manure has become an important raw material, but it is often associated with low methane yields. The anaerobic co-digestion of manure with other substrates has been applied as a cost-effective alternative to improve process efficiency [34]. Other techniques, such as struvite precipitation, are used for the recovery of nutrients from waters rich in phosphates and ammonium, as is the case of slurry, or from the effluents of slurry treatment. This alternative has been evaluated at a laboratory and pilot scale but is not implemented at an industrial level. Other numerous examples of slurry management are found in the use of anaerobic reactors such as Upflow Anaerobic Sludge Blanket (UASB) or the design of recovery systems to control the precipitation of different polluting compounds [35–37].

Nowadays, there is no effective solution that has proved definitive or advantageous for the treatment of slurry and this topic requires extensive research. The proposed combination of GHP for slurry management is an innovative way to combine slurry management and the integration of RE in a single system. This schema involves the reduction in the environmental impact of the farm heating plant but also a considerable reduction in the slurry pollutant potential. With the aim of underlining the environmental advantages of the discussed technology, this research includes the design of the slurry system for a real case study and the definition of the principal working parameters, as shown in the following sections.

#### 3.2. Case Study

The case study farm considered in this research is located in the Spanish region of Toledo. This case study was selected based on the typical parameters of pig farms and the

proposed system and methodology analysis can be extended to any other facility worldwide. Figure 2 shows the location of the farm and a simplified view of its distribution.



**Figure 2.** Location of the pig farm considered in this case study.

The pig farm is a private livestock unit specifically dedicated to raising pigs for commercial purposes. The property has an approximate area of 2.16 ha used to produce pigs and food warehouses. The distribution of the farm is as follows:

- 600 sows;
- 1400 transition piglets;
- 700 breeding places.

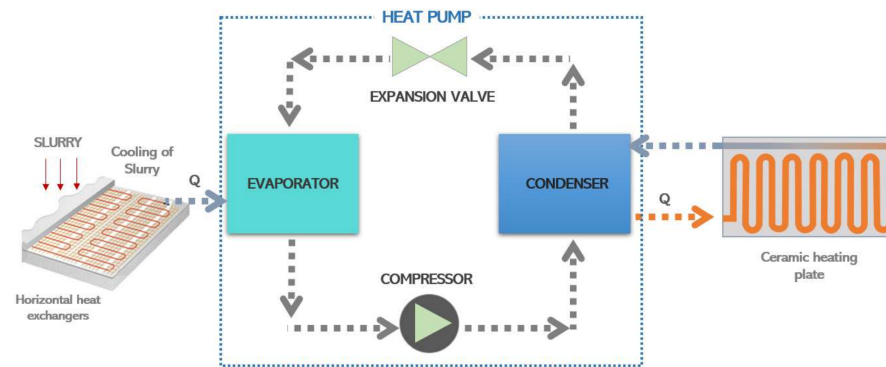
The heating system used in the farm is constituted by electric heaters with a monthly energy cost of around EUR 3000 in the periods with the highest energy demand.

### 3.3. System Configuration

For the design of the slurry technology system, it is necessary to define the annual energy demand of the pig farm for covering the current heating needs. From the monthly energy costs in the coldest period (EUR 3000/month) and estimating the distribution of these costs during the whole year, the annual electricity use was estimated as 182,310.38 kWh/year (considering a standard electricity rate in Spain for the period of EUR 0.1147 kW/h).

The second step is to determine the required GHP power that will drive the slurry system. The Coefficient of Performance (COP) of the heat pump was calculated for the operating temperatures of the circuit. Considering that the temperature of the slurry integrated in the farm heating system will be around 20 °C, the heat pump COP can be deduced from the EU Standard Law 813/2013 [38] that covers the temperature of the inlet working fluid and the mentioned COP. Through the selection of a preliminary commercial heat pump and, according to its operating parameters, the COP of the system designed will be of 5.39. The schema of the GHP operation is presented in the following figure, Figure 3.

From the previously calculated COP and for an annual working period of 2400 h, the heat pump power obtained is of 13.10 kW and a commercial heat pump of 17 kW was selected for the calculations. The heat pump power was slightly overestimated to face the possible variations of the energy requirements.



**Figure 3.** Operation schema of the GHP system.

The heat exchanger for the slurry system was calculated using Equation (1) [39]:

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

where  $L_H$  is the heat exchanger length (m),  $Q_H$  represents the energy needs (kWh),  $COP_H$  is the heat pump coefficient of performance in heating mode,  $R_P$  is the pipe resistance to heat flow (mK/W),  $R_S$  is the heat exchanger thermal resistance (mK/W),  $F_H$  is the usage factor,  $T_L$  is the slurry minimum temperature ( $^{\circ}\text{C}$ ) and  $T_{MIN}$  refers to the working fluid minimum inlet temperature ( $^{\circ}\text{C}$ ).

When applying Equation (1) and obtaining the aforementioned heat exchanger length, it is necessary to define a series of influential parameters, as described below.

- Temperature ranges and temperature profiles

The minimum and maximum temperatures of the slurry highly condition the performance of the heat exchange that takes place in the system. Therefore, these temperatures are established according to Equations (2) and (3).

$$T_L = T_m - A_s \cdot e^{(-X_S \sqrt{\frac{\pi}{365 \cdot \alpha}})} \quad (2)$$

$$T_H = T_m + A_s \cdot e^{(-X_S \sqrt{\frac{\pi}{365 \cdot \alpha}})} \quad (3)$$

where  $T_L$  and  $T_H$  are the slurry minimum and maximum temperatures, respectively ( $^{\circ}\text{C}$ ),  $T_m$  is the slurry mean temperature ( $^{\circ}\text{C}$ ),  $A_s$  is the daily mean temperature ( $^{\circ}\text{C}$ ),  $X_S$  is the heat exchanger installation depth (cm) and, finally,  $\alpha$  is the thermal diffusivity of the ground ( $\text{cm}^2\text{s}$ ).

Once the above parameters were defined, the outlet temperature of the working fluid  $T_O$  (in the heat pump) and its minimum inlet temperatures  $T_{MIN}$  were calculated using Equations (4) and (5).

$$T_O = T_i - \frac{2400 \cdot P_c \cdot \frac{COP_H - 1}{COP_H}}{C_p (Q/3600)} \quad (4)$$

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

where  $T_O$  and  $T_i$  are the outlet and inlet heat pumps temperatures ( $^{\circ}\text{C}$ ), respectively,  $P_c$  is the power of the heat pump in heating mode (kW),  $COP_H$  is the heat pump coefficient of performance in heating mode,  $C_p$  is the specific heat of the fluid ( $\text{J}/\text{K}_g\text{K}$ ) and  $Q$  is the flow rate (L/h).

- Heat flow and thermal resistances

Firstly, the resistance of the pipe to the heat flow can be obtained from the expression of Equation (6). In this sense, it is also necessary to define the thermal resistance of the heat

exchanger that, for the horizontal configuration implemented in this study case, can be estimated according to Equation (7).

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

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

where  $R_P$  is the pipe resistance to heat flow (K/Wm),  $D_0$  and  $D_1$  are the pipe's external and internal diameters (m),  $K_P$  is the pipe's thermal conductivity (W/mK),  $R_S$  is the heat exchanger thermal resistance (K/Wm),  $k$  is the ground thermal conductivity (W/mK) (in this case, the concrete that covers the pipes),  $E_i$  is the exponential integral function [40],  $r$  is the heat exchanger radius (m), and, finally,  $t$  is the heat exchanger usage time (s).

The previous factor  $R_S$  of Equation (7) must be obtained for all the distances among pipes (including the image pipes symmetrically arranged regarding the surface). In this way, the  $R_S$  value is calculated from the addition of the single values corresponding to the buried pipes and the subtraction of the values of the image pipes. Finally, the global heat exchanger thermal resistance derives from dividing the previous calculated value by the total number of pipes and without considering the pipe images.

- Global configuration

Before applying Equation (1) to obtain the total length of the heat exchanger integrated in the present system, the last factor to be defined here is the usage factor  $F_H$ . This mainly refers to the fraction of time in which the heat pump is operating and, since the heat pump here considered is planned to be working 2400 h/year,  $F_H$  is directly obtained from dividing this period by the number of hours of a year.

Based on all the explained above, the following table, Table 2, presents the values of all the parameters previously described and the final heat exchanger length obtained for the system under study.

**Table 2.** Configuration of the slurry system included in the study.

System General Conditions	
$Q_H$ (kW)	17
$COP_H$	5.39
$F_H$	0.27
Slurry configuration	
$T_m$ (K)	293
$A_S$ (K)	289
$X_S$ (m)	0.4
$\alpha$ (m <sup>2</sup> /s)	$8.7 \cdot 10^{-8}$
$T_L$ (K)	283
$T_H$ (K)	303
Heat pump working fluid	
$T_i$ (K)	286
$C_P$ (J/kgK)	4185
$Q$ (m <sup>3</sup> /s)	$7.36 \cdot 10^{-4}$
$T_O$ (K)	275
$T_{MIN}$ (m)	280
Heat exchanger parameters	
$D_0$ (m)	$3.6 \cdot 10^{-2}$
$D_1$ (m)	$3.2 \cdot 10^{-2}$
$K_P$ (W/mK)	$4.1 \cdot 10^{-1}$
$R_P$ (K/Wm)	$4.6 \cdot 10^{-2}$
$R_S$ (K/Wm)	$3.9 \cdot 10^{-1}$
Total heat exchanger length	
$L_H$ (m)	2428

### 3.4. Slurry Management Proposal

The large volume of slurry generated in the pig farm sector and the demanding regulations oblige us to look for environmentally friendly management and economically competitive measures.

In the case under study, the global annual amount of slurry generated in the farm is presented in the following table, Table 3. As shown and considering the current number of animals, the total generation of slurry is about 4727 m<sup>3</sup> per year.

**Table 3.** Total slurry generated in the pig farm under study [41].

Type of Cattle	Annual Slurry Per Cattle (m <sup>3</sup> )	Total Annual Slurry (m <sup>3</sup> )
Sows	2.50	1500
Breeding pigs	2.15	1505
Transition pigs	1.23	1722

Considering the total length of the heat exchanger required (Table 2) and the optimal pipe distance, the area covered by the installation is about 1214 m<sup>2</sup> and considering the monthly slurry production rate, the slurry average thickness will be 0.33 m over the year.

### 3.5. Gaseous Emissions

In this subsection, the GHG emissions for the current configuration of the farm and the ones of the proposed slurry solution are estimated. The evaluation of the gaseous emissions associated with the farm is based on existing literature in similar climatological and animal conditions, with pigs fed with a mixture of cereals and protein concentrate [42]. As a first step, the emissions of the slurry coming from the fattening pig production unit, without any previous treatment, were calculated and are presented in Table 4. Calculations are based on the frequent emission rates of a pig farm unit: CH<sub>4</sub>—1.8 g/m<sup>3</sup>/h; N<sub>2</sub>O—0.003 g/m<sup>2</sup>/h; CO<sub>2</sub>—0.89 g/m<sup>2</sup>/h; NH<sub>3</sub>—1.45 kg/pig·year—sows; 0.28 kg/pig·year—transition piglets; 3 kg/pig·year—breeding pigs [42–44].

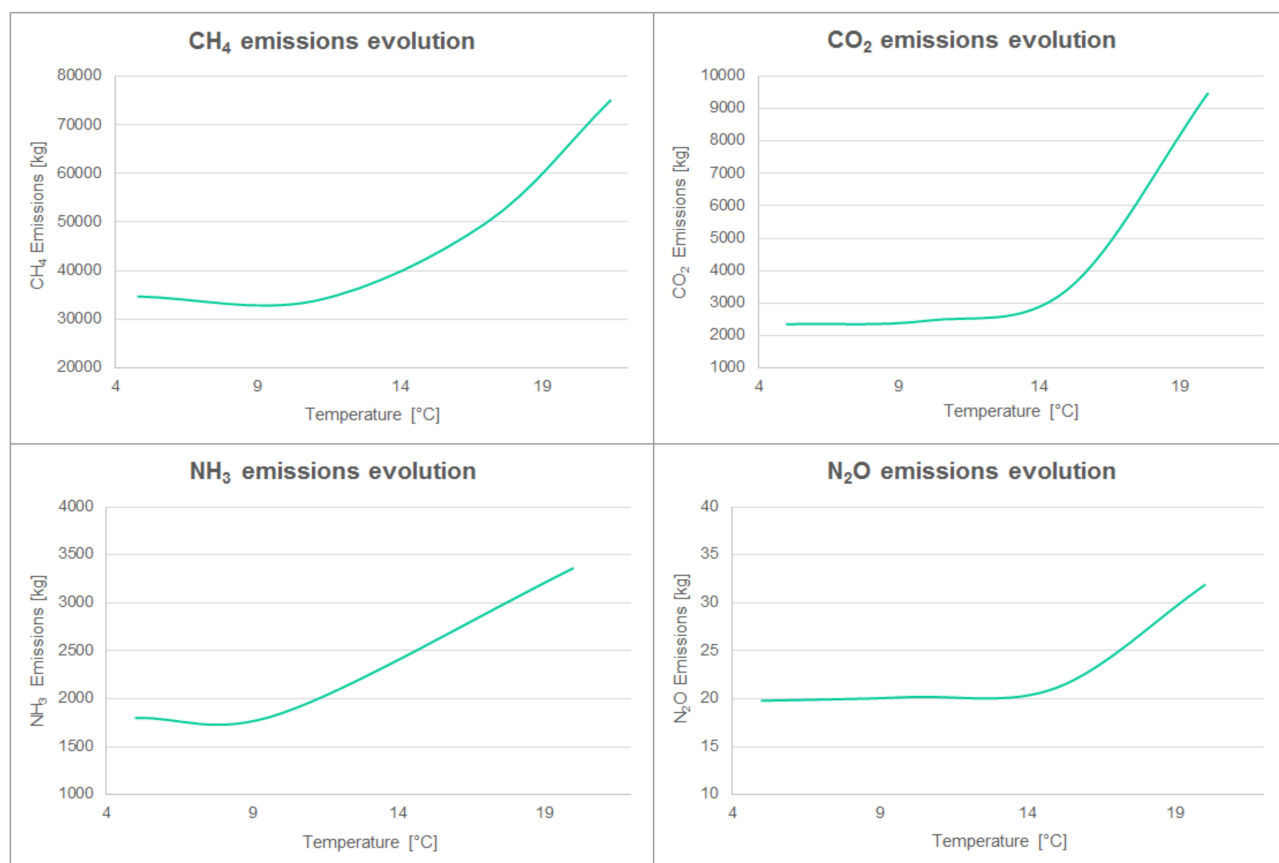
**Table 4.** Annual gaseous emissions derived from the slurry generated in the pig farm of the study.

	CH <sub>4</sub> (kg)	N <sub>2</sub> O (kg)	CO <sub>2</sub> (kg)	NH <sub>3</sub> (kg)
Mean value per year	74,535	32	9465	3362

CO<sub>2</sub> emissions derived from the use of the electric heating system used in the farm must be also considered and will be included in the global comparison of Section 4. The associated principal advantage of the system is the slurry cooling up to 0 °C, considering that 5 °C is recommended in order to achieve a good GHP efficiency. This involves the reduction in ammonia and GHG emissions, contributing to compliance with environmental regulations and limits and to maintain good air quality in housing and also reducing global energy consumption.

- CH<sub>4</sub> emissions

CH<sub>4</sub> is one of the most important GHG produced in the agricultural sector; as reported in the existing literature, CH<sub>4</sub> emissions from livestock houses and manure stores are significantly reduced when slurry is cooled to 10 °C. From this temperature level, methane emissions remain almost constant or even slightly higher [45–47]. According to the emissions estimated for the pig farm (Table 4), slurry cooling up to 5 °C involves the reduction in methane emissions, as shown in Figure 4.



**Figure 4.** Evolution of the different gaseous emissions with the slurry temperature.

- CO<sub>2</sub> emissions

In the case of CO<sub>2</sub>, cooling mitigation strategies applied in existing pig farms show that the reduction is especially remarkable in the temperature range of 20–15 °C. From this value, as shown in Figure 4, the trend is similar to the one of the methane emissions, remaining almost constant until the 5 °C of temperature achieved in the slurry system [48].

- NH<sub>3</sub> emissions

The protein metabolized in the animal is excreted in urine in the form of urea, which in the slurry originates ammonia nitrogen. Ammonia is in equilibrium between a water-soluble ionic form (NH<sub>4</sub><sup>+</sup>) and a gaseous form, ammonia (NH<sub>3</sub>), which is colorless, strong smelling, and lighter than air. In order to reduce emissions of ammonia into the atmosphere of a pig farm, Best Available Techniques (BAT) guides recommend the implementation of different actions, including the cooling of the slurry surface, which causes a reduction of about 45% of the NH<sub>3</sub> emissions when slurry is cooled to 10 °C [49]. In the case of the present study, applying the slurry methodology, the reduction in NH<sub>3</sub> emissions in the pig farm can be observed in Figure 4.

- N<sub>2</sub>O emissions

Nitrous oxide produced by treating animal manure slurry is another important source of GHGs. Previous experimental results have shown the effect of the slurry temperature on the global emissions of N<sub>2</sub>O [50] and concluded that an increase in temperature could accelerate N<sub>2</sub>O production in the temperature range of 15–35 °C, while reductions in emissions are practically non-existent at lower temperature values (Figure 4).

It is worth mentioning that the range of temperatures used in Figure 4 (4–20 °C) covers the temperature interval that pig slurry usually reaches. The maximum value shown here

means the reference temperature at which slurry, which has a temperature similar to that of pigs, is found as the average temperature on farms after manure.

Considering the objective temperature of 5 °C, and as shown in Figure 4, the annual gaseous emissions corresponding to the management of the slurry with the proposed technology are described in Table 5. The calculations are based on the frequent emission rates of a pig farm unit: CH<sub>4</sub>—1.8 g/m<sup>3</sup>/h; N<sub>2</sub>O—0.003 g/m<sup>2</sup>/h; CO<sub>2</sub>—0.89 g/m<sup>2</sup>/h; NH<sub>3</sub>—1.45 kg/pig·year—sows; 0.28 kg/pig·year—transition piglets; 3 kg/pig·year—breeding pigs) [42–44].

**Table 5.** Annual gaseous emissions derived from the slurry (at the temperature of 5 °C), implementing the solution here presented.

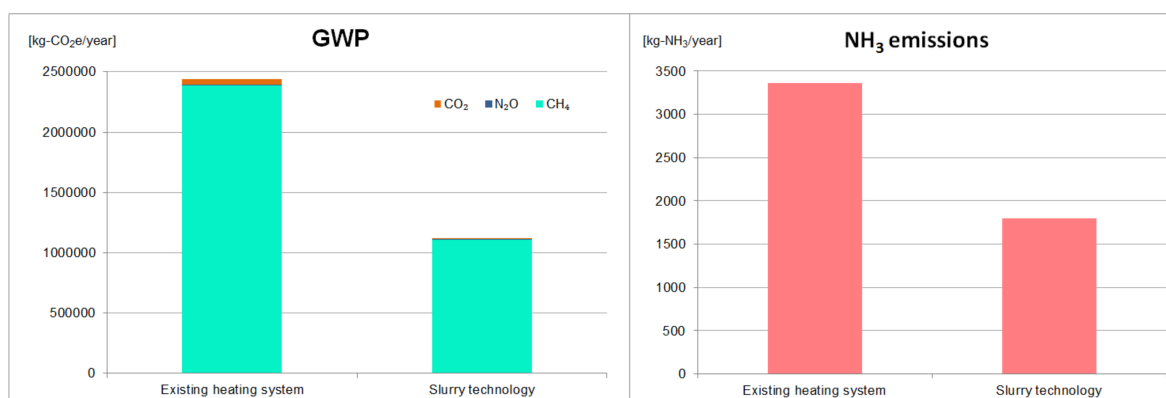
	CH <sub>4</sub> (kg)	N <sub>2</sub> O (kg)	CO <sub>2</sub> (kg)	NH <sub>3</sub> (kg)
Mean value per year	34,681	20	2353	1800

## 4. Discussion

### 4.1. Reduction in Carbon and Hydric Footprints

As stated in the previous section, the principal advantage of the proposed system is the reduction in the slurry temperature and, hence, achieving a reduction in GHG and ammonia emissions. Global Warming Potential (GWP) allows one to define the quantity of energy that the emissions of 1 ton of a gas will absorb over a certain period, relative to the emissions of 1 ton of CO<sub>2</sub>. This indicator is used for comparing the warming impact of the gases. The global warming potential over 100 years (GWP<sub>100</sub>) can be estimated by converting CH<sub>4</sub> and N<sub>2</sub>O to CO<sub>2</sub>e using different conversion factors. Methane is estimated to have a GWP of 28–36 over 100 years, and nitrogen oxide has one 265–298 times that of the carbon dioxide for the same 100-year timescale. Since CO<sub>2</sub> is the gas used as a reference, it has an associated GWP of 1 regardless of the time period used [51].

Beyond the environmental impact of slurry management, the differences between the existing heating system of the farm and the technology considered in this research derive from the electricity use associated with each of them. The existing heating pig farm system has an annual energy demand of 182,310.38 kWh supplied by electric heaters. Using the proposed slurry management technology, the GHP would only require 33.823.82 kWh/year. Considering the CO<sub>2</sub> emission factor of the electricity supplied by the local company (0.20 kg-CO<sub>2</sub>/kWh), the annual emissions associated with each assumption were calculated and are included in the below comparison (Figure 5) [52].



**Figure 5.** Ammonia (NH<sub>3</sub>) emissions and GWP of each of existing heating system and the slurry technology.

Using the aforementioned GWP index that includes the GHG emissions from the slurry management and from the heating system, the comparison of the warming impact

associated with the emission of GHGs in the existing heating installation and the one proposed here can be observed in Figure 5.

Figure 5 shows that the annual GWP associated with the heating system existing in the farm is more than double that estimated in the proposed new slurry management system installation. In this graphic, it is shown that the GWP is mainly produced due to the emissions of CH<sub>4</sub> derived from slurry management, and, regarding the ammonia emissions, the reduction in the slurry temperature in the suggested technology also involves a significant diminution, up to double, of these emissions in relation to the traditional systems used in the pig farm.

In addition to reducing these gas emissions, the cooling of the slurry achieved in using the proposed GHP system described in this research also helps reduce the frequency of slurry emptying and cleaning, achieving a diminution in water consumption. For the farm under study, the use of water currently required was estimated and is presented in Table 6. The calculations are based on the following conversion factors: sows—12.80 l/pig/day; breeding pigs—0.51 l/pig/day; and transition pigs—0.62 l/pig/day [53].

**Table 6.** Average water consumption according to the type of pig.

Type of Cattle	Water Consumption (m <sup>3</sup> /day)
Sows	7.68
Breeding pigs	0.357
Transition pigs	0.868

As shown in Table 6, the daily water consumption of the pig farm used for cleaning the pits is of about 0.89 m<sup>3</sup>/day, a quantity that could be significantly reduced by implementing the alternative slurry system. The holey concrete slabs installed in the heating installation allow continuous slurry removal without the need to use such a high amount of water, contributing to the reduction in the global hydric footprint.

#### 4.2. Additional Advantages

In addition to the already-mentioned advantages of the slurry technology, these systems, based on capturing the heat from slurry, have the following benefits for the pig farm:

- **Animal welfare:** The reduction in polluting gases inside the pig's housings directly contributes to the improvement of the air quality and animals' breathing but also the working conditions of the farm operators. All this results in the diminution of the animal environmental stress and the enhancement of the productivity of sow farms and the number of piglets produced.
- **Energy savings:** Beyond the environmental benefits, the energy and economic benefits are also relevant. The implementation of GHPs with high COPs allows for reducing the operational costs by up to 60% in comparison to the conventional farm heating systems. Additionally, the relative affordable initial investment associated with this alternative solution could be amortized in a period of approximately five years, depending on the specific conditions of the farm. The recent electrical cost increase improves the economic and financial performance of the solution.
- **Environmental sustainability:** The reduction in the carbon and hydric footprints and the associated low energy dependence of the slurry system contributes to the achievement of a more sustainable environment in the livestock sector.
- **Control of the slurry management:** The use of the slurry in these installations is useful for heating purposes but also facilitates its management, especially in those cases with insufficient land for use as an agricultural fertilizer.
- **Sustainable development of the pig farming sector:** The implementation of this kind of renewable technology has proven to improve the foreign positioning of local livestock products through the declaration of nearly zero emissions in their production.

## 5. Conclusions

This research constitutes a novel and important contribution for achieving a more sustainable livestock sector. The definition and design of the slurry approach on a real pig farm under study highlighted the environmental benefits associated with this solution. The results provide clear evidence of how this technology could contribute to reduce the GWP and the ammonia emissions associated with traditional pig farms. The high amount of methane emissions, together with the carbon dioxide, nitrous oxide and ammonia produced by slurry management and derived from heating the pig's housing, is reduced by almost half with the proposed approach. The reduction in the carbon footprint is also complemented by a reduction in the water required for cleaning the pits. In Europe, the meat and dairy supply chains emitted 360 Mt CO<sub>2</sub>e or 80% of all agricultural CH<sub>4</sub> and N<sub>2</sub>O emissions in 2018 [54]. A reduction of at least 40% of these emissions would be expected using the technology presented in this paper, with which around 21.6 Mt CO<sub>2</sub>e would be emitted, and an important contribution would be made to the development of the emission-reduction plans of the E.U. According to the calculations of the real case studied in this work, the following statements are presented:

- The GWP expressed in terms of kg-CO<sub>2</sub>e is mainly produced by the emissions of the methane from slurry. More than 74,000 kg of methane is annually emitted by the studied farm; meanwhile, the implementation of the slurry system would mean a reduction in this value to around 34,600 kg.
- N<sub>2</sub>O emissions, although significantly lower, represent a serious environmental impact that is reduced to 19.8 kg in the slurry approach (compared to 31.9 kg when using the existing heating system).
- The amount of NH<sub>3</sub> produced by the existing farm (3362 kg) was reduced to 1800 kg, a considerable reduction, especially taking into account the harmful effects of this compound.
- CO<sub>2</sub> emissions were reduced through slurry cooling but also thanks to the incorporation of the GHP included in the system. In this way, the total carbon dioxide produced by the farm using its current methods is 46,000 kg/year; this value would be 9000 kg/year with the proposed solution.
- The cooling of slurry to the temperature of 5 °C is easily viable with the heat pump system of the slurry technology, achieving the mentioned reductions in GHG and ammonia emissions. In addition, it has been found that at lower temperatures, slurry emissions remain almost constant, and the extreme cooling could even reduce the efficiency of the heat pump.

In conclusion, this study confirms the importance of applying efficient slurry management techniques and farm heating systems to tackle the environmental impact of pork production and proposes a novel GHP system. Beyond the environmental impact, the slurry solution has proven to be an effective technique for reducing the operational costs of farms and to improve the quality of life of animals. It is also remarkable that the implementation of this system usually boosts the production and commercialization of local products. The results of this research will provide clear benefits to the pig production sector, which will be able to know and understand the advantages of implementing this type of system for economic savings and environmental improvement, but also enhance the conception of the company in the eyes of the potential end user.

In this sense, we recommend carrying out an in-depth study of the generation of slurry from farms, as well as their energy needs, in a precise way to establish the optimal design of the heat exchanger field that allows the coordination of the supply of active slurry with the energy contributions towards the animals. Coordinating these two factors is the key to the proper functioning of this technology.

**Author Contributions:** Conceptualization, C.S.B. and D.B.-D.; methodology, C.S.B., I.M.N. and D.B.-D.; validation, D.G.-A. and A.F.M.; formal analysis, C.S.B., I.M.N., M.Á.M.-G. and D.B.-D.; investigation, M.Á.M.-G.; resources, M.Á.M.-G.; data curation, C.S.B.; writing—original draft preparation, C.S.B.; writing—review and editing, C.S.B., I.M.N., M.Á.M.-G. and D.B.-D.; supervision, D.G.-A. and A.F.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The 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. The authors also want to thank the veterinary staff of the farm, Jorge Plumé García, for providing the specific information about the farm energy use.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Nomenclature

### Acronyms

ASF	African Swine Fever
BAT	Best Available Techniques
COP	Coefficient of Performance
GHG	Greenhouse Gases
GHP	Geothermal Heat Pumps
GWP	Global Warming Potential
GWP <sub>100</sub>	Global Warming Potential over 100 years
LPG	Liquefied Petroleum Gas
NG	Natural Gas

### Formulae

AS	Daily mean temperature (°C)
CO <sub>2e</sub>	Equivalent Carbon Dioxide
COP <sub>H</sub>	Heat pump coefficient of performance in heating mode
D <sub>0</sub>	Pipe external and internal diameter (m)
D <sub>1</sub>	Pipe internal diameter (m)
E <sub>i</sub>	Exponential integral function
F <sub>H</sub>	Utilization (usage) factor
k	Ground thermal conductivity (W/mK)
L <sub>H</sub>	Heat exchanger length (m)
P <sub>c</sub>	Heat pump power in heating mode (kW)
Q	Flow rate (L/h)
Q <sub>H</sub>	Energy needs (kWh)
r	Heat exchanger radius (m)
R <sub>P</sub>	Pipe thermal resistance (mK/W)
R <sub>S</sub>	Heat exchanger thermal resistance (mK/W)
t	Heat exchanger usage time (s)
T <sub>i</sub>	Inlet heat pump temperature (°C)
T <sub>L</sub>	Slurry minimum temperature (°C)
T <sub>m</sub>	Slurry mean temperature (°C)
T <sub>MIN</sub>	Working fluid minimum inlet temperature (°C)
T <sub>O</sub>	Outlet heat pump temperature (°C)
X <sub>S</sub>	Heat exchanger installation depth (cm)
α	Ground thermal diffusivity (cm <sup>2</sup> /s)

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