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Published Version:
Strpic Kristina, Barbaresi A., Tinti F., Bovo M., Benni S., Torreggiani D., et al. (2020). Application of ground heat exchangers in cow barns to enhance milk cooling and water heating and storage. ENERGY AND BUILDINGS, 224(1 October 2020), 1-17 [10.1016/j.enbuild.2020.110213].

Availability:
This version is available at: https://hdl.handle.net/11585/773987 since: 2020-10-09

Published:

DOI: http://doi.org/10.1016/j.enbuild.2020.110213

Application of ground heat exchangers in cow barns to enhance milk cooling and water heating and storage

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ABSTRACT

This paper presents an innovative ground heat exchanger with double-circuit, GeoUWT (Geothermal Underground Water Tanks), and the required preconditions for installing this kind of configuration in the livestock sector. Dedicated Thermal Response Test was conducted on the test site to represent barn conditions and to estimate the heat exchange capacity of the GeoUWT in a realistic case study performance. This dynamic simulation of geothermal heat exchange between the process fluids on the barn - precooling of the produced milk and warming required amount of water - proved enhanced potential compared to existing systems of direct heat exchange. The additional value is an innovative solution for underground water storage at fixed target temperature.

Keywords: underground thermal energy storage, renewable energy, ground heat exchanger, direct thermal exchange, precision livestock farming, rural buildings

1. INTRODUCTION

1.1 Energy and water demand in the dairy cattle sector

Energy consumptions are projected to significantly increase in all energy-consuming sectors in the future decades [1]. This growing demand can be satisfied either by boosting the energy supply, including low-carbon energy sources, or with a better management and reduction of the demand [2]. Sustainable and low greenhouse gas emission solutions and energy efficiency could help in solving both sides of the energy demand problem. Agri-food is a very complex energy-consuming sector since it is based on several feedstocks and manifold production steps. Therefore, understanding the total energy content of final agricultural products and possible applications of renewable energy solutions is currently challenging. Besides, agriculture and livestock farming are the major energy consuming sectors and they are responsible together for 34% energy embedded in food-production in Europe [3], [4]. The energy involved in final food production does not account only for direct energy uses, such as fuel for the machinery or powering the devices, but it includes also indirect energy flows, such as the energy needed to produce and transport fertilisers, to operate irrigation systems, to feed and to guarantee the animal welfare [5]. According to OECD [6], in the OECD area, 68% of the direct energy consumed in agricultural sector origins from fossil fuels whereas only 4% comes from renewable energy sources entailing an immediate change oriented to energy efficiency and sustainability.

Within this context, the dairy cattle farming sector is characterized by relevant energy demand but at the same time could hold several opportunities of enhancement for increase its energy efficiency. More in detail, in intensive livestock farms, dairy cattle barn usually includes zones for cow resting, feeding and milking, besides service rooms for milk storage, technical plants, offices and other minor services for workers (e.g. restrooms, changing room). Energy requirements for the permanent equipment are mainly due to milk refrigeration, milking operations, artificial lighting, forced ventilation, manure removal. The animal welfare turns out to be an important aspect for both production quantity and milk quality, but at the same time, requires specific indoor parameter ranges. The optimal habitat for a dairy cow is between -5°C and 25°C [7], ranges from 50% to 80% of relative humidity [8] and needs adequate air exchange [9]. These parameters are usually summarized by the Temperature-Humidity Index (*THI*), a widespread measure in the farming context, indicating the real climatic impact perceived by the cows. It can be expressed as follows [10]:

$$THI = T_{db} + 0.36 \cdot T_{dp} + 41.2 \qquad (1)$$

where T_{db} represents the dry bulb temperature [°C] and T_{dp} the dew point temperature [°C].

In the barn, the suitable conditions for the cows are generally obtained through a properly designed building envelope, which should be predominantly open in warmer climatic region in order to enhance heat dispersion in the hot season, while allowing enough protection from the cold winds. In the warmer season, in order to mitigate the heat stress, which represents a serious threat to cow's welfare and milk production [11], energy for microclimate control is needed. In fact, heat stress affects cows' behavior [12], milk production, milk quality [13] and conception rate [14]. The technical solutions mostly adopted in open barns make use of manifold systems, such as moving shading screens and fans combined with water soakers. Instead, in the colder period, in the Mediterranean area, the energy for barn heating concerns the production of hot water to clean and disinfect the milking system and the tanks. Moreover, a slight warming of the drinking water is advisable, especially in the cold days, in order to stimulate water intake so to improve milk production. The scientific literature [15] indicates, as optimal, a warmed water with temperature around 18°C. In the most of Italian cow barns, the drinking water is directly provided by the well, usually having temperature lower than 18°C especially in the cooler season. To avoid decrease of milk production, several barns started to introduce electrical heating system to rise the temperature in the drinking troughs.

The main electricity usages, obtained by the monitoring of a sample of dairy farms in Italy [16], are represented by milk harvesting (23% of total yearly electricity consumption), milk refrigeration (19%) and water heating (15%). Water pumping, including irrigation, covers 13% of the demand; ventilation and misting absorb the 5%, while 4% is required for lighting and 4% for brushing. Manure removal calls for a fraction of the 5% of energy assessed for slurry management, while the remaining percentage is mainly related to field operations. Energy saving in dairy cattle barns represents, currently, an unavoidable design target. In particular, the dairy facilities can reuse energy of highly consuming milk cooling process to warm up the drinking water for cows.

Besides energy issues, a few concerns about the environmental impacts of livestock production have grown especially in the last two decades. Livestock productions have been acknowledged as intensive consumers of freshwater resources: beyond the usage for growing feed crops or forages, also drinking, cleaning and processing animal products call for significant water volumes [17]. Drinking represents a significant component of blue water usage by dairy farms, since cows have a drinking water requirement (WR) up to 130 liters of water every day, in 10-15 visits to the drinker [18]. The consumption of water depends on dry matter percentage of the ration, milk yield and environmental temperature. Robinson et al. [19] surveyed average usages, in free stall dairy barns, ranging from 113.6 l/day to 196.0 l/day per cow, from August 2013 through December 2014, over 12 selected farms. VanderZaag et al [20] measured the use of pumped water over a full year on a small dairy farm in Ontario with 34 lactating cows and 39 non-lactating animals. 82% of annual average water use was drinking water and 18% was used for the milking system cleaning. When *THI* was below 50, water use ranged from 4.3 to 4.8 l/kg of milk, and it increased to a maximum of 6.7 l/kg at a *THI* of 68, being 5.35 l/kg of milk the annual average water use.

More in detail, Meyer et al. [21], based on the data of 60 German Holstein cows, calculated WR as a function of milk production (*MP*), average ambient temperature (*AAT*), animal weight (*AW*) and sodium intake (*SI*), according to the following formula:

$$WR = -26.120 + 1.516 \cdot AAT + 1.299 \cdot MP + 0.058 \cdot AW + 0.406 \cdot SI \qquad (2)$$

where: WR is expressed in [kg/day], AAT in [°C], MP in [kg/day], AW in [kg] and SI in [g/day].

Thus, just for example, a cow weighting 750 kg, producing 35 kg of milk/day, with an average temperature of 35°C and 50 g/day of sodium intake, will require about 136 kg/day of water.

1.2 Smart energy applications for barns

Energy efficiency strategies, including smart systems for optimal energy use and innovative renewable energy systems, are crucial for the sustainable progress of the livestock farming sector. In fact, energy efficiency and renewable energy solutions, such as lighting bulbs replacement, cleaning and maintenance programs of refrigerators and pumps, use of anaerobic digesters for electricity production and placement of photovoltaic panels over the roof have become a common standard both in the industrial livestock farming facilities and in family-run farms [22]–[25]. Among the most innovative energy solutions, implementation of geothermal systems and utilization of heat waste including use of heat pumps was considered, in recent years, in several national and international projects in the agricultural sector, all of them emphasizing the importance of respecting the specific needs. During the mapping project of dairy farms in Sweden (2012 -2013), a study about integration of heat pumps was conducted and part of the Swedish contribution to IEA HPP Annex 35 [26] dealing with implementation of industrial heat pumps. The study has investigated the possibility of implementing a heat pump on a case study farm (Arla dairy in Götene, Sweden) for water heating (55-80°C) using the heat recovery from the chiller's condenser (30°C) [27]. Moreover, a recent study [28] has showed the possibility of using the ground to store the low temperature heat coming from the wastewater, cooling units and compressed air at the NÖM dairy plant, to provide heating and cooling for the old military camp "Martinek-Kaserne" and finally, in return, to feed the cooling supply for the dairy plant.

The use of ground as heat-bank, so to overcome the mismatch between availability and needs, is called Underground Thermal Energy Storage (UTES) and can be used for both long and short-term purposes [29] and leads to an improvement in the use of renewable sources [30]. Most common types of UTES are confined aquifers [31], Borehole Heat Exchangers (BHEs) [32] and caverns [33]. Recently, Underground Water Tanks (UWT) have been hypothesized for purposes of UTES, too [34]. By using UWT, the heat capacity of the water medium gives the possibility to consider planned and controlled charge/discharge cycles. Conventional UWT storages are large reinforced concrete structures, mostly connected with solar collectors [35]. Recently, Kappler et al. [36] investigated the possibility of using UWT for tempering climate conditions, thus substituting heat exchangers. Moreover, several studies debate the potential of submersing the BHEs in groundwater and surface water, primarily because of the benefits of induced convection phenomena and additional capacity for heat exchange [37].

Gustafsson and Westerlund [38] presented a research about the effects of thermally induced convective heat flow on the groundwater filled BHEs. Even in cases where groundwater flow is limited or absent, convection terms occur and lead to an increase of the heat transfer with respect to grouted BHEs. As a result, borehole thermal resistance is lower, and the system proves to be more efficient. In Istria Region

(Croatia), helical heat exchangers (HHE) were installed in concrete UWT, buried 2m deep in two projects, one in Labin and one in Buzet [39], [40]. Preliminary results showed general feasibility of this configuration, but further studies are still needed for system optimization. Recently, Focaccia and Tinti [41] developed a laboratory prototype of an innovative configuration of BHE inserted in a protective casing filled with water. The research, analysing both thermocouple and visual records, has shown that natural convection movements are triggered in the water inside the UWT, due to the thermal activation of the BHE.

1.3 Aim of the study

Following the encouraging results of the application of shallow geothermal system in the agrifood facilities [42], [43], this paper presents a pre-feasibility study for an efficient application of UWT as UTES in the livestock sector, with focus on the cow barns needs. Specifically, the aim of this work is to study the theoretical feasibility of an integrated system able to pre-cool the produced milk and warm up the water used for cows' needs (drinking and soaking) by means an innovative shallow geothermal system. The principle of this work is that, by means of free heat exchange enhanced by the HHE placed inside a UWT, the system will warm up the water and cool down the milk at every milking operated in the barn. Moreover, the water contained in the UWT will be kept at proper temperature for cow drinking during the day avoiding the installation of water pre-heaters.

It is worth to note that most of the cow barns in Italy are equipped with milking parlour allowing the total milk collection in about four hours every day. To reduce the energy consumption for milk cooling, very few barns have installed systems for free heat exchange between water and milk. As better explained in the following Sections, an effective heat exchange requires a volume of water comparable to the cow barn daily need and should be performed during the milking operation time (four hours). To avoid water waste, the barns should be equipped with reservoir able to keep the daily volume of water that often represents an economical unsustainability. Due to its geometry, the system proposed here, besides the heat exchange enhancing, can keep the water at a proper temperature for the time needed by cows during the day.

The study considers the use of a recent new UWT concept, with HHE inserted, based on the geometry of the RAUGEO Helix®. The new system (hereinafter GeoUWT) was recently tested in a real scale experiment in the LAGIRN Lab of University of Bologna [44] and has showed a combined potential of efficient cooling, energy storage and contemporary heating of casing water for non-potable uses.

The study is based on a real case study barn located in Emilia-Romagna Region (Italy). The missing data on energy and water needs are derived from the historical data collected in other cow barns of the Emilia-Romagna Region having similar characteristics to that considered here. The input data, related to the GeoUWT system, are derived from the experimental investigations conducted in Bologna in the years 2018-2019 on the GeoUWT prototype. The results of the test have been applied to the present study, to evaluate the efficiency of the system in providing milk cooling and contemporary heating of water for livestock necessities. The great amount of required water in a barn and the need of achieving target temperatures for drinking and cleaning are thus combined with the necessity of milk refrigeration to optimize energy usage. The operating scheme of the system proposed here is summarized in Figure 1. The system is composed of three main parts: the barn, the milk refrigerator and the geothermal field "GeoUWT". The details of the various elements will be described in the following Section.

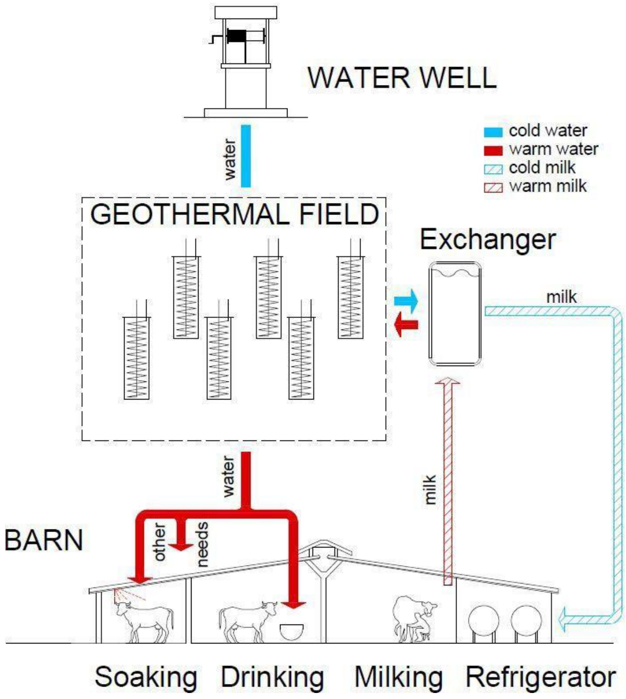


Figure 1. Simplified operating scheme showing the three parts of the system: the cow barn, the milk refrigerator and the geothermal field “GeoUWT”.

2. MATERIALS AND METHODS

The scheme of the research is presented in Figure 2, indicating the different subsections of Section 2 where each aspect is dealt with, and how the various phases are interrelated with each other.

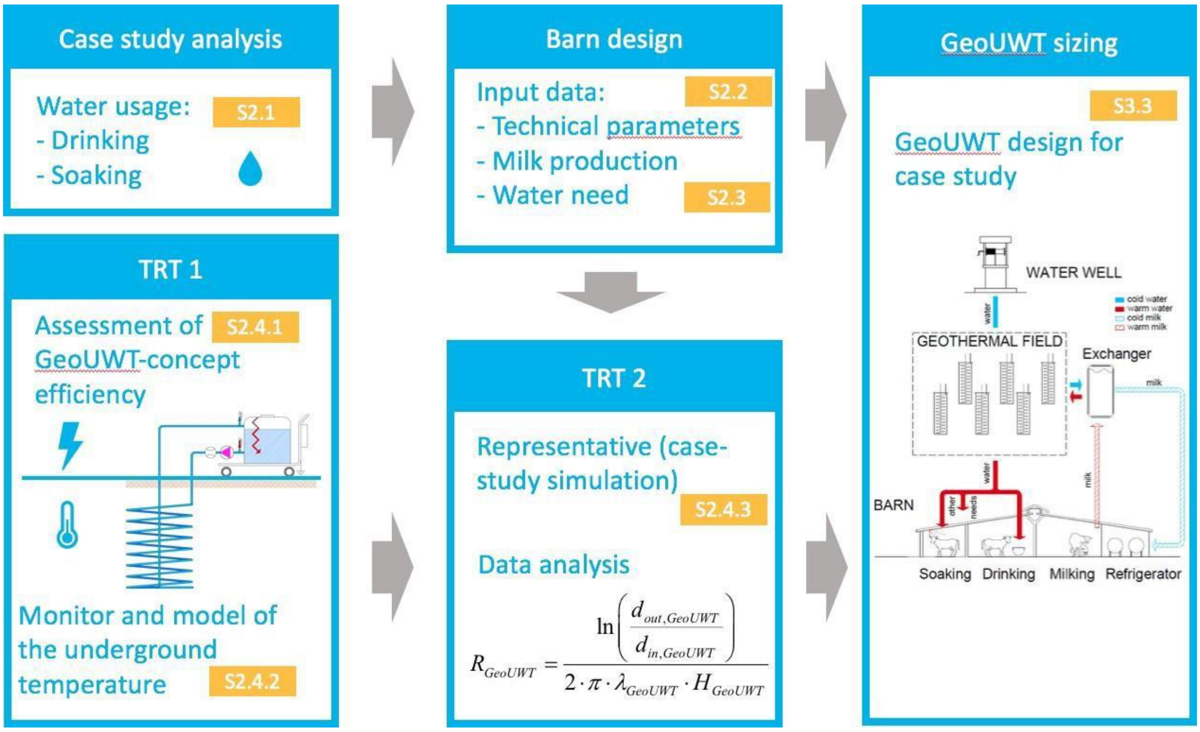


Figure 2. Scheme reporting a graphical explanation of the research process. The yellow rectangles refer to the subsections of this paper, identified by S.

2.1 Description of the case study

The farm "Montagnini" was selected as case study in the present work. The farm has two main facilities hosting the cows: a new modern barn for the lactating cows and the older stable hosting dried cows and heifers and containing the milking parlour of the farm. The new barn is located in the Emilia-Romagna Region (in the North of Italy), in a plain countryside about 25 km north of Bologna (WGS84 coordinates 44°42'59.2"N 11°27'04.9"E, 17 m a.s.l.). 270 lactating cows were reared in the barn, which has rectangular plan layout with dimension of 42.22×80.30m. The longitudinal axis (i.e. the longer dimension) is SW-NE-oriented with -20° azimuth angle (see Figure 3).

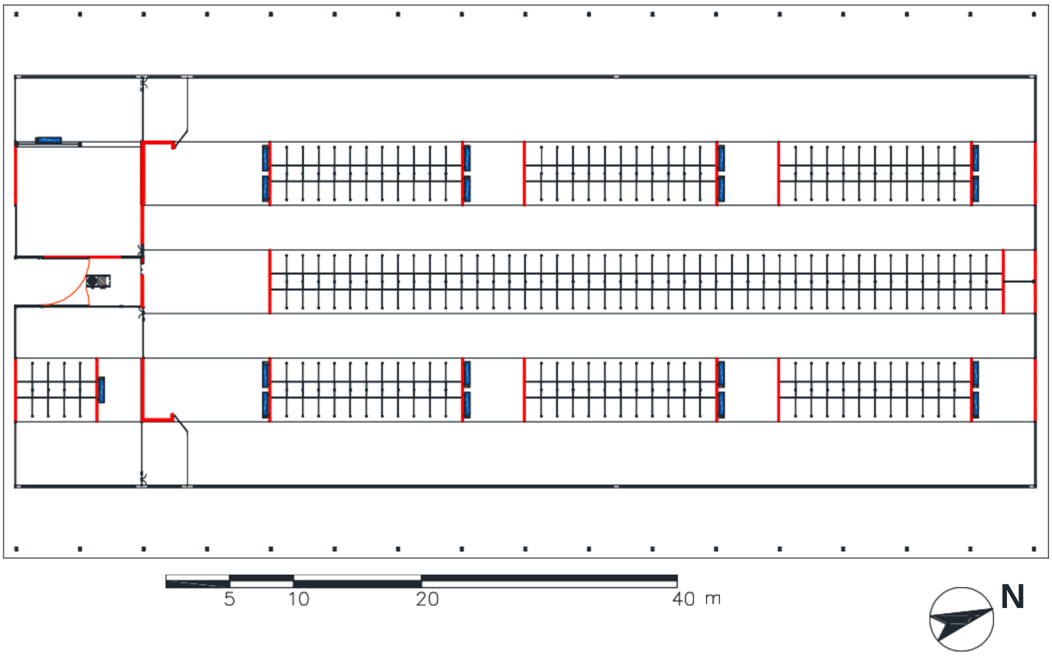


Figure 3. Plan view of the case study barn.

The inner part of the barn represents the resting area where, closing fences along the symmetry axis allows to subdivide the herd into two groups, as both the resulting parts of the barn can be independent. The elevation of the building creates a symmetrical double pitched roof with no internal column, with ridge along the longitudinal direction. It has 33% slope, height at eaves of 4.00m and ridge height of 12.15m, with continuous ridge opening (see Figure 4). The long sides of the building are open, to enhance natural ventilation for both displacement effect and stack effect.

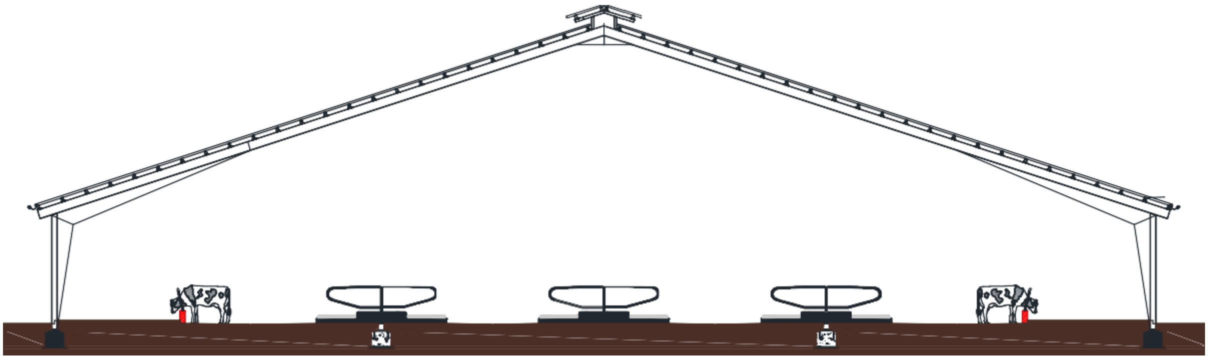


Figure 4. Transverse cross-section of the case study barn.

Indoor thermo-hygrometric conditions are controlled also through forced ventilation, by means of high-volume low speed (HVLS) fans with horizontal blades, activated by a temperature-humidity sensor situated close to the barn centre. Further cooling benefit is achieved through low-pressure, large-droplet water soaker lines installed above the feeding lanes. This sprinkler system completely wets the cows by soaking the hair coat and it proved to reduce the body temperature and improve the dry matter intake, the conception rates and live calf birth rate [45].

A pipeline is thus installed next to the feeding area (see Figure 5) and mounted with low pressure 180° nozzles with spray pattern with a radius of max. 2.50m, which is suitable to avoid wetting the cubicles bedding. Spraying is activated when *THI* measured in the barn is over a specific threshold. It is important to remark that usually, in the barns, water is delivered independently on the presence of animals under the soaker lines, as no sensor of presence is installed.

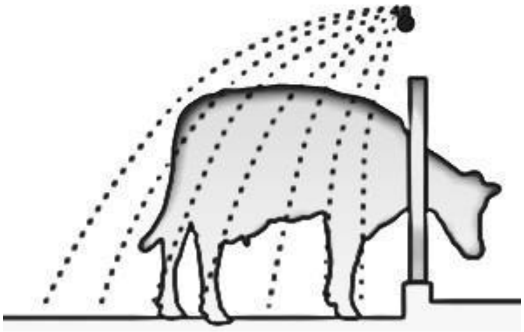


Figure 5. Scheme of a large-droplet water soaker line installed above the feeding barrier with the function of watering the cow during feeding.

In addition to the study case farm, the research group has studied several dairy cattle barns in the Bologna countryside allowing to collect a wide data set on sprinkler systems in order to gather information and assess the water consumptions for each cow. Specifically, the research group studied a sprinkler system widespread in commercial and experimental dairy barns identical in terms of brand and model to the case study system. This system is located in a barn in an area close to the case study therefore with similar environmental conditions. In this barn, the sprinkler system covers a total area with 77 cows, divided into three sectors of 21 (sector 1), 27 (sector 2) and 29 (sector 3) cows respectively. The three sectors are independently controlled since three temperature and humidity sensors are present. As previously said these systems are activated only by *THI* values regardless the presence of the cows under the sprinklers. Specifically, for *THI* values over 75 the water is supplied. The central unit of the system globally returned over 236 000 records steps in a 2-year period. For each record, *THI* and water consumptions (in litres) are included.

Year 2017 has been taken as reference for this study. The *THI* overtook the threshold of 75 in May 17th for the first time, and September 13th the last time, therefore a period of 120 days has been investigated. Figure 6 shows the average water consumption for each cow in the three sectors. The graph remarks the high variability of the water supply during the whole period and among the sectors. A further period from 1st to 30th July (period of 30 days) representative of the month with the highest number of soaker activations was analysed. For this second period, characterized by fewer oscillations, the data coming from the three sectors are gathered and the water consumption trend is exhibited in Figure 7.

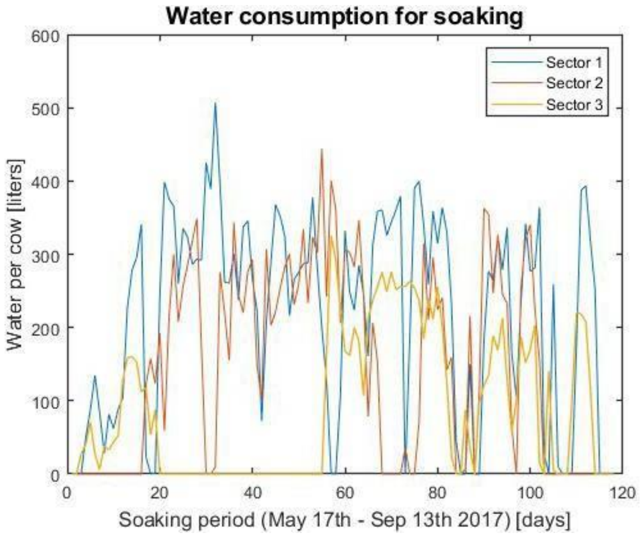


Figure 6. Water consumption of soaker system per cow during the period of activation (from 17th May to 13th September) for the three sectors.

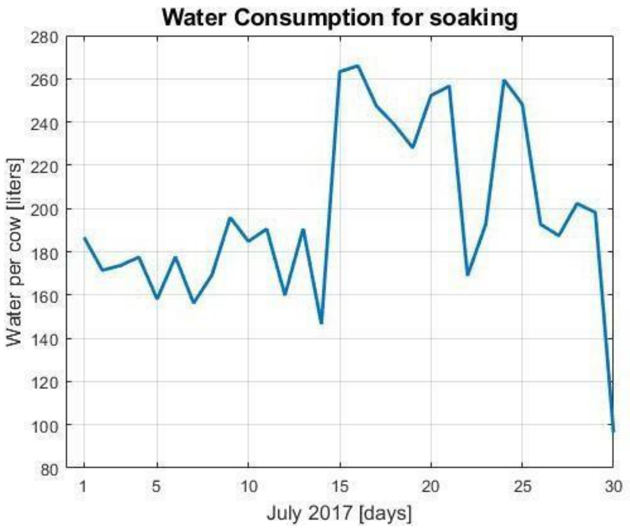


Figure 7. Water consumption of soakers in the period with highest number of activations (1st July – 30th July) for estimating average water demand per cow.

As reference values, from the analysis of the recorded data, we obtain an average water consumption of about 137 litres per cow per day in the 120-day period of activation of the soakers, and 198 litres per cow per day in the 30-day period representative of the month of the year with highest number of soakers activation.

The milking system is represented by a recent 2×15 herringbone milking parlour hosted in the older barn located 27 m South-West from the new barn described above. Herd milk yield is recorded daily. Data about milk production, energy demand for milk refrigeration, target temperatures of hot water for cleaning and of drinking water were collected during on-site surveys and interviews with the farmer, carried out in December 2018. Data about water usage for cooling through water soakers were recorded by the electronic central unit controlling the forced ventilation and the watering system of the barn. Based on data collected on-site in *Montagnini* barn, daily average milk production per cow is around 35 kg. Drinking water intake trend corresponds to milk production as cows' need for water intake increases after the production sessions. According to a sample of farmers interviewed, since there is no precise measurement of the water consumption for drinking purpose in the farm, an average daily water consumption of 200 l per cow was considered, value consistent with scientific literature. Table 1 reports the timing of daily phases in the *Montagnini* barn.

Table 1 Daily phases in the *Montagnini barn.*

5.00-7.00	1st milking session
5.30-8.00	1st milk pre-cooling
6.00-9.00	1st peak of drinking water demand
14.00-16.00	Peak of water soaking
18.00-20.00	Milk refrigeration
17.00-19.00	2nd milking session
17.30-20.00	2nd milk pre-cooling
18.00-21.00	2nd peak of drinking water demand

Technical preconditions for application of GeoUWT concept on the described theoretical model of typical cow barn in Emilia-Romagna Region were investigated. The final aim was to present solutions in form of required number of GeoUWTs. Key parameters for this aim were chosen and analysed in order to ensure a certain flexibility of adjustment according to different possible barn dimensions.

2.2 Main technical parameters and relations

Some of the target parameters and relations analysed in this research are presented hereinafter. Energy and water needs were derived from historical data of typical barns in the Region while GeoUWT energy capacity specifications were defined from a dedicated Thermal Response Test (TRT) performed for simulating the typical barn operation (see Section 2.4.3).

Required number of GeoUWTs is defined as the total thermal energy required for milk precooling and the specific heat exchanged by one GeoUWT, according to TRT results:

$$n_{GeoUWT} = \frac{\sum En}{En_{GeoUWT}} \qquad (3)$$

Where:

n_{GeoUWT} is the number of GeoUWT (-);

En is the required thermal energy (J);

En_{GeoUWT} is the thermal energy exchanged by one GeoUWT (J).

The total required thermal energy is a function of the milk (mass) produced in one session and the temperature difference between starting temperature and target temperature:

$$En = c_{milk} \cdot M_{milk} \cdot \Delta T_{milk} \tag{4}$$

Where:

c_{milk} is the milk heat capacity (J/kg·K);

M_{milk} is the total milk mass in the storage tank after one milking session (kg);

ΔT_{milk} is the temperature difference between starting ($T_{milk,start}$) and target ($T_{milk,\ target}$) milk temperature (K).

Therefore, it was possible to calculate the number of cows supplied by one single GeoUWT as:

$$n_{cows,GeoUWT} = \frac{n_{cows}}{n_{GeoUWT}} \tag{5}$$

Where:

$n_{cows},_{GeoUWT}$ is the number of cows for single GeoUWT (-);

n_{cows} is the total number of cows (-).

The total drinking water required for the cows, in the present case study is extracted from a nearby groundwater well. It can be related to the stored water inside the GeoUWT by the following equation:

$$V_{w,day} = V_{w,GeoUWT} \cdot n_{s,day} \cdot n_{GeoUWT} \tag{6}$$

Where:

$V_{w,day}$ is the volume of water extracted from the well for daily supply (l);

$V_{w,GeoUWT}$ is the volume of water kept in a GeoUWT (l);

$n_{s,day}$ is the number of milk sessions per day (-).

2.3 Input data for the theoretical system design

Considering the optimal conditions for milk storage and transport, it is possible to get an insight about required energy demand (*En*) for milk refrigeration after the milking process, in case without the milk precooling system (Table 2). Production quantities and corresponding water intake are assumed according to the data collected from *Montagnini* farm and mentioned Holsteins' calculation for water requirements (approximately 150 l/cow daily). Regarding milk thermophysical properties, the production temperature is 40°C, the storage temperature is 4°C and the milk specific heat capacity is 3.93 kJ/(kg·K). Two milking sessions per day, $n_{s,day}$, were taken into consideration.

Table 2. Energy demand for milk refrigerating process without the precooling (ΔT = 36°C)

n_{cows}	1	10	300	270 (*Montagnini*)	**300 (theoretical model)**
M_{milk} / day (kg)	35	350	10 500	8 000	**10 000**
M_{milk} / session (kg)	17.5	175.0	5 250.0	4 000.0	**5 000.0**
V_w / day (l)	150	1 500	45 000	54 000	**45 000**
V_w / session (l)	74	750	22 500	27 000	**22 500**
En / day (kWh)	1.37	137.00	411.00	314.40	**393.00**
En / session (kWh)	0.685	68.500	205.500	157.200	**196.200**

With respect to the daily water needs, several scenarios were created (based on the theoretical model from the table 2), considering the different seasonal water demand per cow and case with installation of the sprinkle-cooling system in summer season. Winter scenario **1a** covers the case of average daily water consumption per cow, while **1b** considers possible increase in water consumption because of increased milk production due to optimal living conditions and drinking water temperature (18°C). Summer scenario **1c** considers the case of barn without installed cooling system, with the respect of noticed increase of water demand per cow in summer season from the case study data. Scenario **1d** covers the case of the barn with the installed cooling system in form of water sprinkles activated at certain ambient condition. The complete analysis can be found in Annex 1, whose input information are presented in Table 3.

Table 3. Input data

Input parameter	Value	Unit
c_{milk}	3.93	kJ/(kg·K)
$T_{milk,start}$	40	°C
$T_{milk,target}$	4	°C
M_{milk} /day	10 000	kg
M_{milk} /session	5 000	kg
n_{cows}	300	/
$\mathrm{n}_{\mathrm{s,day}}$	2	/
Drinking water / day		
Scenario *1a*	150	l
Scenario *1b, 1c, 1d*	200	l
Drinking water / session	100	l
Scenario *1a*	75	l
Scenario *1b, 1c, 1d*	100	l
Sprinkler water / day (summer)		
Scenario *1d*	200	l
Sprinkler water / session (summer)		
Scenario *1d*	100	l

The study case farm has been considered as a suitable application for the UTES technology in the form of GeoUWT, which is supposed to be used to match the energy demand for milk cooling with the needs of water heating in double-circuit process. For this purpose, a scheme of the GeoUWT installation is reported in Figure 8.

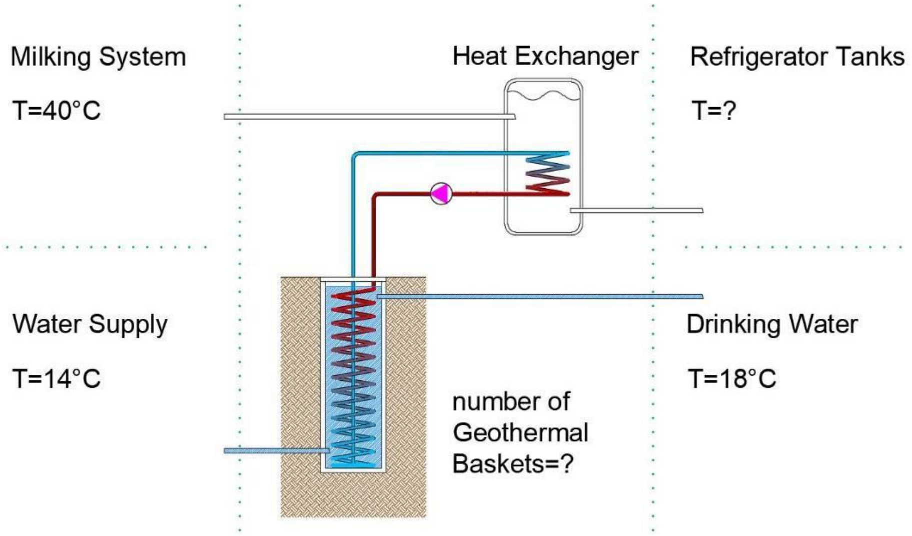


Figure 8. Scheme of the GeoUWT inside the process water and milk cooling circuits of the cow barn.

2.4 Design methods for the GeoUWT system applied to the cow barn

The procedure adopted to design the GeoUWT for the specific cow barn application is divided in three parts:

1. The validation of GeoUWT concept, by realisation of an experimental setup at University of Bologna labs;
2. The modelling of underground temperature, varying with seasonality;
3. The description of the dedicated TRT realised and the mathematical model for data analysis.

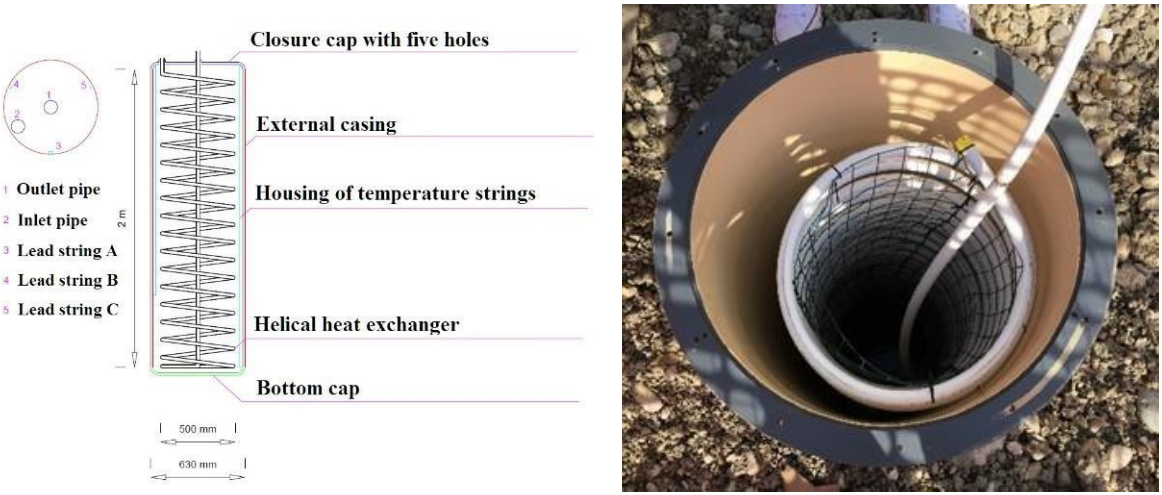
2.4.1 Experimental setup

Firstly, the efficiency of GeoUWT on long term stimulation was verified by performing a long term thermal response test on two HHEs: the first one was buried in the ground, 2.0 m deep, and the second one was installed inside a UWT, positioned at 4.0 m of distance, together forming the GeoUWT [44]. The reason for selecting a helical configuration lies in the fact that it provides higher heat transfer per meter of unit comparing to conventional BHEs [46]. The conventional HHE and the GeoUWT were installed in the area of the Laboratory of the School of Engineering and Architecture, in April 2018. The annulus of the GeoUWT was filled with distilled water as thermoconductive fluid with the possibility to replace its whole volume. The HHE pipes were also filled with distilled water. To avoid the infiltration of groundwater and chemical elements inside the GeoUWT, but also to avoid leakage of the fluid from the tank, bottom of the casing was sealed. In the final configuration, casing walls were in contact with the ground to ensure the heat exchange, mechanical strength, elasticity and low thermal resistance. Detailed description of the test site and installation procedures were provided by Tinti et al. [44]. For the sake of relevant comparison, both HHEs consist of the same configuration. Table 4 reports the main properties of both HHEs and UWT, while Figure 9 presents the scheme of the GeoUWT.

Table 4. Main characteristics of the helical heat exchanger HHE and the underground water tank UWT of the experimental campaign

Helical heat exchangers HHE properties	
Material	PE-Xa
External diameter	25.0 mm
Thickness	2.3 mm

Internal diameter	20.4 mm
Length	40.0 m
Vertical length of the cylinder	2.0 m
Diameter of the cylinder	500.0 mm
Number of coils	26
Spacing between coils	80.0 mm
Weight	7.5 kg
Fluid volume	13.07 l
Underground water tank UWT properties	
Material	PVC
Material of the bottom	PE
Material of the closure cap	PE
External diameter	630.0 mm
Thickness	16.0 mm
Internal diameter	614.0 mm
Fluid volume (with installed HHE):	572.0 l



(a) (b)

Figure 9. The GeoUWT: (a) experimental configuration and (b) picture of the prototype installation [43].

Extensive field thermal response test (TRT) and related monitoring campaign were performed for several months in both summer and winter seasons, to conduct power and efficiency analysis and comparison between the two HHEs subjected to heat injection in the ground (thus cooling a hypothetical end user).

TRT was performed by using a lightweight machine (named M-TRT), with three individual heaters of 500 W, a sufficient power for relevant measurement on described HHEs [47] since even larger helical configurations are estimated to achieve between 400 W and 700 W [48]. Standard TRT analysis on vertical heat exchangers has the objective of estimating ground thermal conductivity and borehole thermal resistance [49]. In the case of HHEs and in particular GeoUWT, due to the particular geometry, the very shallow configuration (2 m) and the high impact of weather conditions during the test, this approach is hardly feasible, and results of thermal resistance would be affected by high degree of incertitude [50]. Therefore, for the purposes of contrasting the performances of the two HHEs, authors have chosen to perform long TRT, at different power steps, to compare the exploited heat dissipation capacity of the two configurations in different weather and power conditions. More information about specifics of the M-TRT machine can be found in [51]. Multiple power-step TRT was conducted simultaneously on both HHEs in summer (28.05.2018 - 18.06.2018) and winter season (27.01.2019 - 17.02.2019).

Power analysis were conducted on both HHEs, by measuring the inlet and outlet temperatures, $T_{f,in}$ and $T_{f,out}$, for time steps of 15 seconds, and then using Equation 7:

$$P = q_f \cdot \Delta T_{HHE} \cdot \rho_f c_f \tag{7}$$

Where:

q_f is the constant flow injected in each HHE (0.15 l/s);

ρ_f is the circulating fluid density (1000 kg/m^3);

c_f is the circulating fluid heat capacity (4.19 kg/(J·K));

ΔT_{HHE} is the temperature difference ($T_{f,in}$ - $T_{f,out}$) of the circulating fluid inside the HHE at each time step (K);

$T_{f,in}$ is the inlet temperature of circulating fluid (°C);

$T_{f,out}$ is the outlet temperature of circulating fluid (°C).

2.4.2 Modelling underground temperature

The underground temperature down to 2 m depth varies with seasonality. Therefore, a temperature model occurs, to define the temperature boundary condition around the GeoUWT.

In order to do so, the test site was equipped with temperature strings in different zones of the area, able to measure both the undisturbed ground and water temperature and the heat wave due to the TRT work. Five temperature strings were placed to measure the temperature of the ground and fluid in the annulus of GeoUWT at different layers – each 0.4 m of the depth. Three of them were installed inside the UWT to measure the temperature of the fluid (A, B, C strings), one was installed between the HHEs (D string) inside a dedicated pipe, and the last (E string) was installed in the centre of the conventional HHE buried in the ground (see Figure 10).

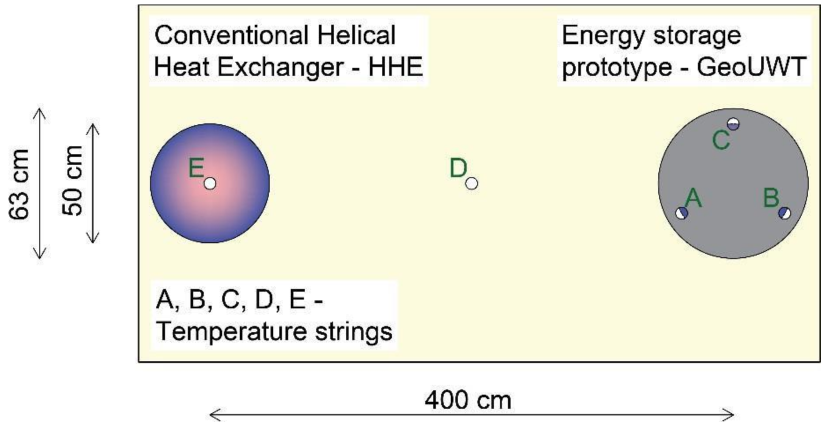


Figure 10. Layout of the test site with the positions of the temperature strings

The monitoring of the temperature distribution in the ground was conducted from October 2018 and is currently ongoing. The registration and record of the measurements taken with the sensors were performed by using the Long-Range Radio Technology. Accuracy and precision of the temperature sensors are 0.01°C and +/- 0.03°C, more details about the technology can be found in [52]. In the further representation of results, index t_1 represents the deepest layer of monitoring (2.0 m) and t_5 is the shallowest (0.4 m) below the surface level. Recorded data were used in combination with the data of ambient drifts for the local area (Table 5) in order to create an approximation of the annual model of undisturbed temperature distribution. Due to the prolonged heat injection during TRTs performed during January and February 2019, it is possible to observe influence of induced heat wave on the ground temperature so recorded temperatures in that period are not relevant for the annual model. Moreover, together with an unusual trend of air temperature in Bologna during the spring period of 2019 (March–May), which was not following usual annual waveform distribution, it resulted in a discrepancy from the model. For that reason, recorded data of October-December 2018 were chosen for fitting the temperature distribution. To describe the temperature distribution of the underground, the Hillel's correlation in Equation 8 was chosen [53]:

$$T_g(d,t) = T_m + A_{o,s} \cdot e^{\left(-\frac{d}{\Psi_p}\right)} \cdot \sin\left(2\cdot\pi\cdot\frac{t}{p} - \frac{d}{\Psi_p} - \frac{2\cdot\pi}{3}\right) \qquad (8)$$

Where:

T_g is the temperature of the ground, function of depth and time (°C);

T_m is the annual average external temperature (°C);

$A_{o,s}$ is the external temperature wave amplitude (°C);

d is the depth (m);

p is the period (days);

t is the time (days);

Dumping depth $\Psi_p=\sqrt{(2\,\alpha_{eff}/\omega)}$ is the depth at which the annual temperature amplitude of the ground decreases to $1/e$ of surface air temperature amplitude and ω is a period for the sine function, $\omega=2\pi/p$; α_{eff} is the effective ground thermal diffusivity (m^2/day). Climate data of the test site in Bologna are presented in Table 5.

Table 5. Climate data for the test site (Bologna, Italy)

T_m	15.5 °C
$A_{o,s}$	13.0 °C
p	365 days

2.4.3 Dedicated TRT and data analysis for cow barn case study

Although traditional TRT was conducted, it was clear that the potential of GeoUWT system could be much higher, when performing a double circuit, with total or partial replace of the fluid in the GeoUWT annulus, when needed. This can provide extra potential for heat exchange and storage and keep the surrounding soil indefinitely below the complete thermal saturation state. A secondary functional usage of the extracted fluid would give an additional value to this concept, better adapting to the cow barn case study.

For the specific case study of the cow barn, a dedicated TRT should last for the time of heat extraction from the milk (approximately two hours) and should respect the following assumptions:

- Milk temperature after milking ($T_{milk,start}$): 40°C;
- Milk target temperature for storage ($T_{milk,target}$): 4°C;
- Water temperature ($T_{GeoUWT,start}$): 14°C (constant, taken from a well at 50 m depth in confined aquifer);
- Optimum temperature of drinking water for cows ($T_{GeoUWT,target}$): 18°C.

In order to use the experimental results of the dedicated TRT, to assess the potential use of GeoUWT for the cow barn, a thermal model of the system has been created, thus calculating the total heat exchanged and the peak thermal power after operation period, as well as the necessary time to reach the tank water temperature needs. Being the heat injection time relatively short, and the GeoUWT walls low thermal conductive, ground thermal modification due to the TRT work has not been considered. Equations used in the thermal model are presented below. Particularly, the heat transfer rate between the circulating fluid and the tank water (Equation 9) has been compared with the heat transfer rate inside the HHE circuit (See equation 7), to get proportions usable for estimating temperature behaviour for different temperature starting levels.

$$P = 2 \cdot \pi \cdot \lambda_{HHE} \cdot L_{HHE} \cdot \frac{(T_{HHE} - T_{GeoUWT})}{\ln\left(\frac{d_{out,HHE}}{d_{in,HHE}}\right)} \qquad (9)$$

where:

- P is the heat rate calculated for the time step (W);
- $d_{out,HHE}$ is the external ~~radius~~ diameter of pipe of the HHE (0.0250 m);
- $d_{in,HHE}$ is the internal ~~radius~~ diameter of the pipe of the HHE (0.0204 m);
- λ_{HHE} is the pipe thermal conductivity (0.41 W/(m·K));
- L_{HHE} is the total length of the HHE (40 m);

- T_{HHE} is the average temperature of the circulating fluid inside the HHE in the time step (°C);

- T_{GeoUWT} is the average temperature of the water inside the GeoUWT in the time step (°C).

A logarithmic regression on average water temperature measured in the tank has been performed (Equation 10).

$$T_{GeoUWT,i} = a \cdot \ln(t_i) + b \qquad (10)$$

The coefficients *a* and *b* have been used to reconstruct the tank water temperature behaviour, subjected to different external conditions, causing different initial undisturbed values.

On the other hand, for each time step the power value *P* and the correspondent ΔT_{HHE} have been calculated by proportion with the behaviour of representative TRT in the time step.

For each time step, the new outlet and inlet water temperatures are calculated as follows:

$$\begin{cases} T_{f,out,i} = \dfrac{P_i \cdot \ln\left(\dfrac{d_{out,HHE}}{d_{in,HHE}}\right)}{2\pi\lambda_{HHE} \cdot L} + T_{GeoUWT,i} - \dfrac{\Delta T_{HHE,i}}{2} \\ T_{f,in,i} = \Delta T_{HHE,i} + T_{f,out,i} \end{cases} \qquad (11)$$

Total energy dissipated, after a certain period is therefore:

$$En = \sum_{i=1}^{n_t} P_i \cdot t_i \qquad (12)$$

After obtaining the behaviour of T_{GeoUWT} along time, it was finally possible to estimate the time needed to reach the target temperature for different starting points with the following equation.

$$t_{target} = \exp\left(\frac{T_{GeoUWT,target} - b}{a}\right) - t_{undisturbed} \qquad (13)$$

where:

- $T_{GeoUWT,target}$ is the optimum temperature of the tank water, which is 18°C in the cow barn case study (°C);

- $t_{undisturbed}$ is the initial time of calculation, with the tank water at undisturbed temperature (s);

- t_{target} is the time needed to reach the target temperature (s).

Moreover, it has been necessary to evaluate the thermal storage potential of GeoUWT, and particularly whether and in which situations the system recovers the initial conditions between two different phases related to the milking sessions of the farm, presented in Table 1.

The water tank thermal resistance is the following:

$$R_{GeoUWT} = \frac{\ln\left(\frac{d_{out,GeoUWT}}{d_{in,GeoUWT}}\right)}{2 \cdot \pi \cdot \lambda_{GeoUWT} \cdot H_{GeoUWT}} \tag{14}$$

Where:

- $d_{out,GeoUWT}$ is the external diameter of the GeoUWT (0.630 m);
- $d_{in,GeoUWT}$ is the internal diameter of the GeoUWT (0.614 m);
- λ_{GeoUWT} is the thermal conductivity of the GeoUWT (made in PVC) (0.17 W/(m·K));
- H_{GeoUWT} is the height of GeoUWT (2 m).

The equations for the thermal behaviour of a fluid stored in a tank apply. The heat exchange between ground and the water inside the tank is compared to the heat capacity of the water kept inside the GeoUWT (Equation 15):

$$P = \frac{T_{w,st} - T_g}{R_{GeoUWT}} = -\rho_w c_w V_w \cdot \left(\frac{\partial T}{dt}\right) \tag{15}$$

Where:

- $T_{w,st}$ is the water starting temperature of heat release, after heat injection through the HHE;
- T_g is the average ground temperature along the GeoUWT external wall, varying according to seasonality;
- ρ_w is the water density inside the GeoUWT (1000 kg/m^3);
- c_w is the water specific heat capacity inside the GeoUWT (4186 J/(kg·K));
- V_w is the water volume inside the GeoUWT (0.572 m^3).

Knowing the possible ending temperature in the tank, after total heat release ($T_{w,end}$), it is then possible to obtain the time needed to reach the initial conditions (see Equation 16).

$$t_{heat,release} = R_{GeoUWT} \cdot \rho_w c_w V_w \cdot \ln\left(\frac{T_{w,st} - T_g}{T_{w,end} - T_g}\right) \tag{16}$$

By using Equation 16, inserting tank water and ground temperature difference for each time step of the heat injection phase, heat losses to the ground can be calculated for all the possible starting conditions (tank water temperature and ground temperature).

Additional analysis of the energy consumption of the pumps was based on the pump power of M-TRT machine, as it is sufficient for supplying one HHE:

$$El_{pumps,day} = P_{pump} \cdot t_s \cdot n_{GeoUWT} \cdot n_{s,day} \qquad (17)$$

where:

- $El_{pumps,day}$ is the electric energy consumption due to water circulation in one day (J);
- P_{pump} is the circulation pump power consumption (W);
- t_s is the time of a milk session (s).

3. RESULTS AND DISCUSSION

3.1 Main results of the preliminary experimental tests

In the comparison tests presented in paragraph 2.4.1, theoretical power analysis for cooling mode proved higher heat exchanger power for GeoUWT with peaks of improvement up to 200% in comparison with the conventional HHE, highly dependent also on weather conditions. Having a high frequency of temperature measurements, it was then possible to integrate all power results, avoiding considerable errors, thus getting a preliminary quantification of heat dissipation capacity of GeoUWT with respect to simple HHE. Total thermal energy dissipated in two systems, at different time periods of heat injection, is presented in Table ~~5~~6. Further details can be found in Tinti et al. [43].

Table 6. Thermal energy dissipated in the ground during the TRT tests by GeoUWT and conventional HHE both in summer and winter. T_s is the undisturbed temperature of the soil at the start of the test

TRT Results	Summer T_s = 24.8°C		Winter T_s = 12.9°C	
Time (h)	GeoUWT (kWh)	Conventional HHE (kWh)	GeoUWT (kWh)	Conventional HHE (kWh)
12	6.087	0.838	10.876	2.897
24	14.243	4.702	21.256	6.182
48	19.719	9.568	29.722	12.764
60	26.830	11.899	41.203	16.168

72	33.836	14.100	50.758	21.692
84	40.361	16.056	58.606	29.194
96	46.657	17.991	66.558	35.867
108	52.488	19.637	75.637	40.774
120	58.194	20.963	84.105	47.136

Despite the claimed advantages for cooling, further possibilities should be explored for a continuous work during the whole year, overall to avoid freezing problem in winter season. These reside in the potential for injecting and storing heat in winter and for the potential of re-using and changing the water in the annulus, thus partially restoring the natural state condition.

Moreover, thanks to the monitoring system of ground temperature during the test period, it was possible to verify that GeoUWT did not cause a faster thermal depletion of the surrounding ground than conventional HHE. On the contrary, theoretical efficiency of injected heat dissipation was higher in GeoUWT than in conventional HHE: 1.5 - 2.5 % in summer season and 5.0 – 10.0% in winter season [44]. Possible explanations for this reside in the larger heat exchange area and the induced natural convection effects inside of the casing.

3.2 Undisturbed ground temperature analysis

An estimation of the ground temperature wave around the GeoUWT is needed, from the surface to the final depth (2m), to get the natural conditions where the analysis has been conducted. The wave was constructed by performing Equation (8).

Basic statistical method RMSE (Root Mean Square Error) was used to determine the deviation of synthetic model from measured data (Table 7). The ~~required~~ initial attempt value of ~~equivalent~~ effective thermal diffusivity, α_{eff} for the ground environment was estimated according to catalogue values for soil type at the test site and previously estimated values for similar soil formation near to the test site [43]. *Microsoft Excel Solver Add-in* was used in order to find the minimal value of deviation by changing the value of thermal diffusivity for the five layers, from 0.4 to 2.0 m depth. Results of the analysis are presented in Figure 11 (evidencing the discarded TRT period, with probable local thermal disturbance on the ground), while the development of the model for the whole year is shown in Figure 12.

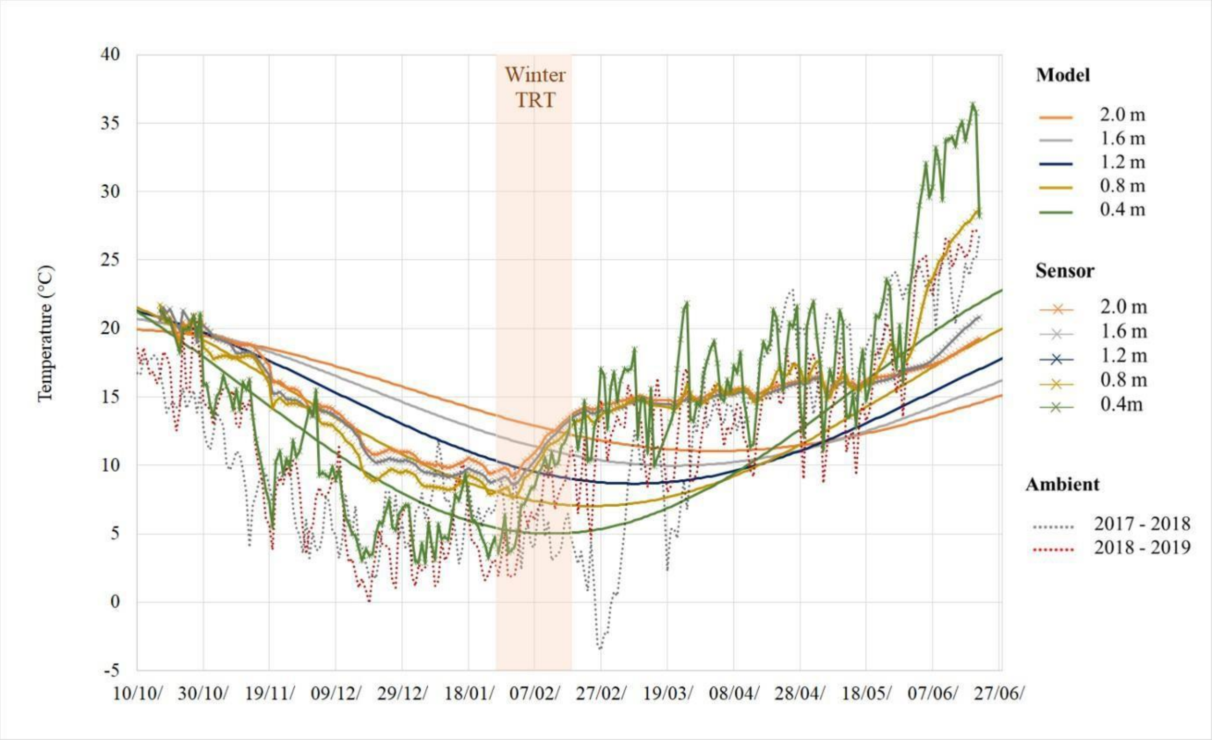


Figure 11. Wave temperature analysis in the ground from 0.4 to 2.0 m depth.

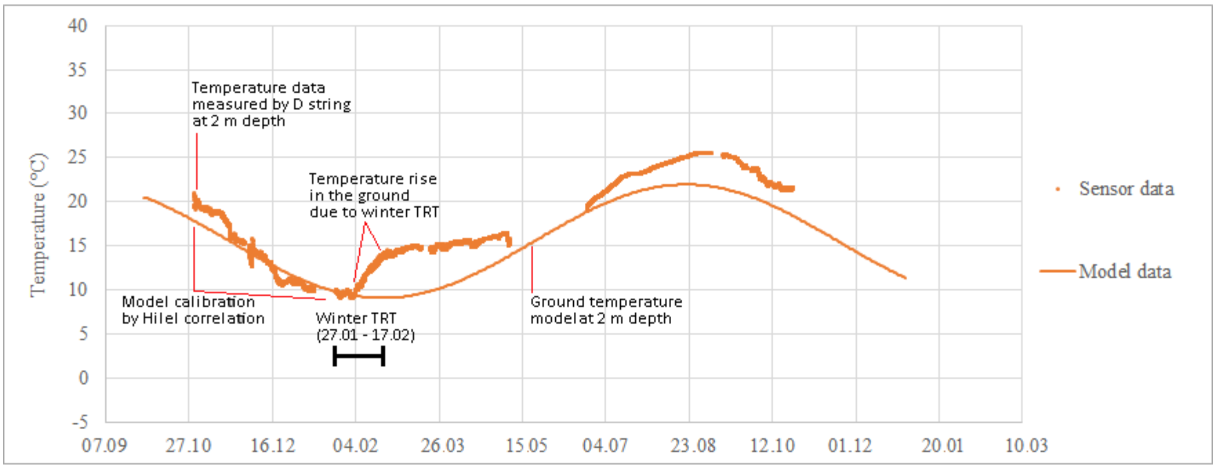


Figure 12. Wave temperature model of undisturbed ground at 2 m depth.

Table 7. Results of effective ground thermal diffusivity.

Sensor name	t_5	t_4	t_3	t_2	t_1
Depth (m)	0.4	0.8	1.2	1.6	2.0
Hillel model					
average α_{eff} (D, E) (m^2/d)	0.03	0.03	0.03	0.03	0.03
average RMSE (D, E) (°C)	3.887	2.418	1.814	3.110	2.240

Predicting ground temperature wave is useful to determine the GeoUWT behaviour (in both charge and discharge phases) subjected to different boundary conditions in the surrounding ground.

3.3 Results of the dedicated TRT data analysis

Using the data of paragraph 2.4.3, a dedicated TRT was conducted on GeoUWT on 21st of January 2019, to recreate a similar situation to that of the cattle barn case study (Figure 13), with recordings at time step of 15 seconds. At the beginning of the test, water temperature was around 11°C. Circulation with the turned-on heaters was conducted for one hour in order to heat up the water inside the protective casing from undisturbed 11°C to 14°C, which is the constant temperature of the cow's drinking water supply coming from the groundwater well. Real time monitoring of temperature water along the strings A, B and C allowed reaching the desired value. Afterwards, water inside the tank of M-TRT machine was heated up, without circulation, to approximately 40°C, which is the temperature of the milk at the cow barn after production. All three heaters of the M-TRT machine were switched on during the heating, with power approximately 1300 W. While heating the water, no circulation in the HHE was allowed. After temperature of the water reached target temperature of 40°C, circulation started, with heaters still on. Theoretical power of the heat exchange was calculated for each interval of recorded inlet and outlet temperature from M-TRT machine. Since energy consumption of the milk refrigerating process depends on the initial temperature of the stored milk, attempt of this test was to estimate the minimal achievable temperature of the circulating fluid via heat exchange with the water inside the GeoUWT. The test ended when the temperature of the water inside of the GeoUWT approximately reached target temperature of optimal drinking water conditions for the cows (18°C). At the same time, the resulting temperature differences of the inlet working fluid at the beginning of the test (40°C) and the end of the test (20.5°C) were recorded. With this information, it was possible to insinuate the achievable temperature difference of the produced milk after heat exchange with water inside of GeoUWT. The period of heat injection (with subsequent cooling of the M-TRT machine's tank water) and heat exchange between the HHE and the water inside the GeoUWT, lasted 1.9 h. During the TRT, no modifications on ground temperature were recorded by the D string.

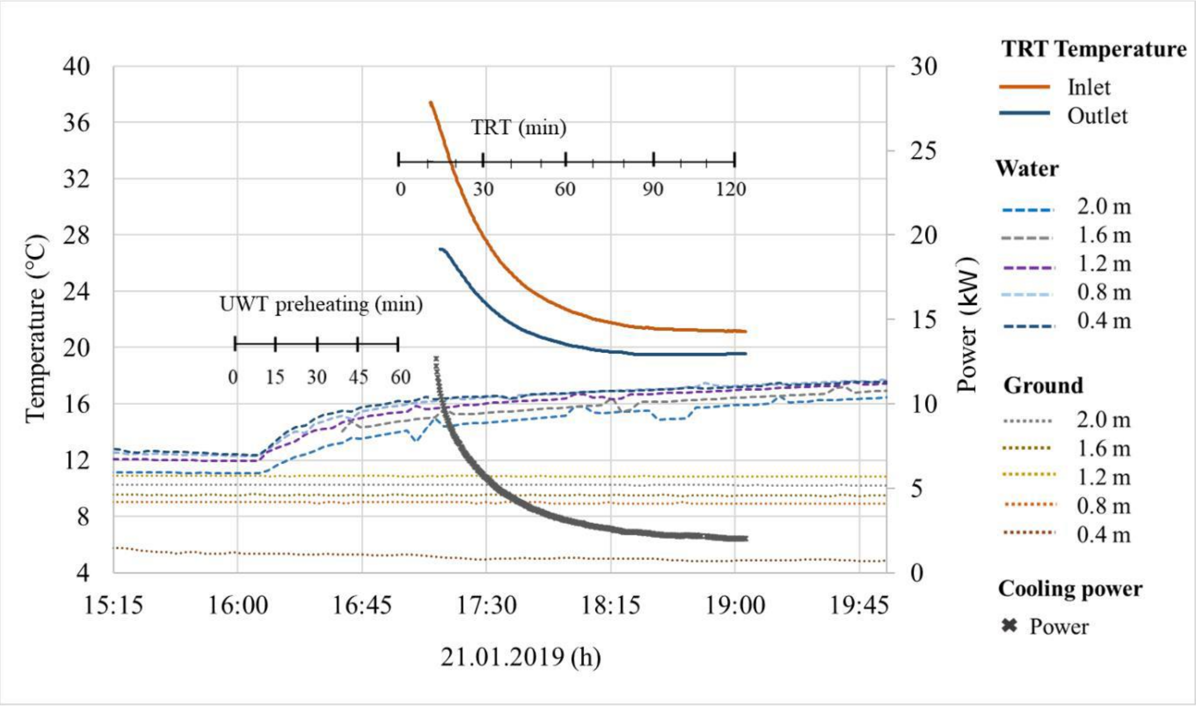


Figure 13. TRT dedicated test to simulate the inclusion of GeoUWT in the cow barn milking process.

Moreover, the discharge phase, between two milking sessions, has been calculated as well, to understand the storage potential of GeoUWT.

Heat exchange was calculated for each measured time step. The temperature release in the circulating fluid follows a logarithmic behaviour.

By using the procedure described by Equations (9-14) in paragraph 2.4.3, it has been possible to get an estimation of energy dissipated, peak and average power, water temperature reached in the tank and time to reach the target temperature of 18°C for each different case of starting water temperature (see Table 8).

Table 8: Interest parameters calculated for the specific test conditions of TRT and estimated for other starting temperature.

Interest parameters	TRT (T_{start} = 15.4°C)	T_{start} 10°C	T_{start} 11°C	T_{start} 12°C	T_{start} 13°C	T_{start} 14°C	T_{start} 15°C	T_{start} 16°C	T_{start} 17°C	T_{start} 18°C	T_{start} 19°C	T_{start} 20°C
Energy GeoUWT after 1 h (kWh)	2.83	3.75	3.58	3.41	3.25	3.08	2.91	2.74	2.58	2.41	2.24	2.07
Energy GeoUWT after 2 h (kWh)	3.97	5.25	5.02	4.78	4.55	4.31	4.08	3.84	3.61	3.37	3.14	2.90
Average power after 1 h (kW)	2.82	3.73	3.57	3.40	3.23	3.07	2.90	2.73	2.57	2.40	2.23	2.06
Average power after 2 h (kW)	1.63	2.15	2.06	1.96	1.87	1.77	1.67	1.58	1.48	1.38	1.29	1.19
Water temperature reached after 2 h (°C)	16.86	15.09	15.24	15.46	15.74	16.12	16.59	17.17	17.83	18.59	19.41	20.28
Time to reach target temperature 18°C (h)	4.76	7.16	7.01	6.79	6.47	5.98	5.24	4.14	2.48	0.00	-3.72	-9.31

The following considerations apply:

- By the modelling, it has been possible to define the behaviour of GeoUWT for the exact temperature of the water well, which is 14°C.
- At temperature of 14°C, energy dissipated in the GeoUWT for the 2 hours of the test is 4.31 kWh. After 2 hours, tank water temperature reaches 16.2°C, while around 6 hours of heat injection are necessary to reach 18°C.
- The modelling allows defining the behaviour of the system for different starting temperature, which is the case if ground and water temperature are influenced by weather variations (not the case of water taken from the well). In fact, in case water is taken by aqueduct, with pipes buried at 1.5-2.0 m depth, its temperature can vary from 5-8°C (winter) to 22-25°C (summer), following seasonal ground temperature behaviour (See Figure 12). The model allows also defining the behaviour of the system in these conditions.
- To get 18°C within the two hours of the test, a starting temperature of more than 17°C is needed. In that case, the dissipated energy of milk precooling would be less, around 3.61 kWh.

The data correspondent to initial temperature of 14°C are assigned to the HHE in the test conditions and they are used for the energy improvement of the cow barn case study.

After that, thermal storage potential has been calculated by following the procedure expressed by Equations (15-17). Results have been obtained for two distinct situations:

- Situation A: water for cows is taken from the well (Table 9). In this case, the initial temperature is always at 14°C, independently from the ground temperature.
- Situation B: water for cows is taken from the aqueduct (Table 10). In this case, the initial water temperature is conditioned by the ground temperature. In the present case study, the temperature monitoring inside the GeoUWT and in the ground allowed considering a difference among them around 1.5 °C constant throughout the year.

Table 9: Time for heat release calculated for the situation A, with water taken from the well, at constant temperature of 14°C. In the table it is evidenced the specific case investigated in this work.

Time for heat release (h)				Temperature reached (°C)										
				15,09	15,24	15,46	15,74	16,12	16,59	17,17	17,83	18,59	19,41	20,28
Ground temperature (°C)	8.0	Water temperature, from the well (°C)	14.0	1.34	1.51	1.74	2.04	2.42	2.88	3.39	3.96	4.55	5.15	5.74
	8.5		14.0	1.45	1.63	1.88	2.20	2.61	3.09	3.64	4.24	4.86	5.48	6.10
	9.0		14.0	1.58	1.78	2.05	2.39	**2.83**	3.34	3.93	4.56	5.21	5.87	6.51
	9.5		14.0	1.74	1.96	2.24	2.62	3.09	3.64	4.27	4.94	5.63	6.32	7.00
	10.0		14.0	1.93	2.17	2.49	2.90	3.40	4.00	4.67	5.38	6.12	6.85	7.56
	10.5		14.0	2.18	2.44	2.79	3.24	3.79	4.44	5.16	5.93	6.71	7.48	8.23
	11.0		14.0	2.49	2.78	3.17	3.67	4.28	4.99	5.77	6.59	7.43	8.25	9.04
	11.5		14.0	2.90	3.24	3.67	4.23	4.91	5.70	6.55	7.45	8.34	9.22	10.06
	12.0		14.0	3.49	3.87	4.38	5.02	5.78	6.66	7.60	8.58	9.55	10.49	11.38
	12.5		14.0	4.38	4.84	5.43	6.17	7.05	8.04	9.09	10.16	11.22	12.23	13.18
	13.0		14.0	5.91	6.47	7.20	8.08	9.11	10.24	11.43	12.62	13.78	14.88	15.90
	13.5		14.0	9.28	10.01	10.92	12.02	13.26	14.59	15.96	17.30	18.58	19.78	20.88

Table 10: time for heat release, varying according to the maximum temperature reached by water in the GeoUWT and ground temperature around the GeoUWT. The temperature of the specific case study, but considering it depending on the ground temperature, is evidenced.

Time for heat release (h)		Temperature reached (°C)										
Ground temperature (°C)	Initial water temperature in the tank (°C)	15.09	15.24	15.46	15.74	16.12	16.59	17.17	17.83	18.59	19.41	20.28
8.0	9.5	12.44	12.61	12.84	13.14	13.52	13.98	14.50	15.06	15.65	16.25	16.84
8.5	10.0	11.86	12.04	12.29	12.61	13.01	13.50	14.05	14.64	15.26	15.89	16.51
9.0	10.5	11.23	11.42	11.69	12.04	12.47	12.99	13.57	14.20	14.86	15.51	16.16
9.5	11.0	10.54	10.75	11.04	11.42	11.89	12.44	13.07	13.74	14.43	15.12	15.79
10.0	11.5	9.79	10.02	10.34	10.75	11.26	11.86	12.53	13.24	13.97	14.70	15.41
10.5	12.0	8.96	9.22	9.57	10.02	10.58	11.22	11.95	12.71	13.49	14.27	15.01
11.0	12.5	8.04	8.33	8.72	9.22	9.83	10.54	11.32	12.15	12.98	13.80	14.59
11.5	13.0	7.00	7.33	7.77	8.33	9.01	9.79	10.64	11.54	12.44	13.31	14.15
12.0	13.5	5.80	6.18	6.68	7.32	8.09	8.96	9.90	10.88	11.85	12.79	13.68
12.5	14.0	4.38	4.84	5.43	6.17	**7.05**	8.04	9.09	10.16	11.22	12.23	13.18
13	14.5	2.67	3.23	3.95	4.83	5.86	6.99	8.18	9.37	10.53	11.63	12.65
13.5	15.0	0.48	1.21	2.12	3.22	4.46	5.79	7.16	8.50	9.78	10.98	12.08
14.0	15.5				1.20	2.76	4.38	5.98	7.52	8.95	10.27	11.47
14.5	16.0					0.60	2.66	4.61	6.40	8.03	9.49	10.80
15.0	16.5						0.47	2.94	5.10	6.98	8.63	10.08
15.5	17.0							0.84	3.54	5.78	7.67	9.28
16.0	17.5								1.61	4.36	6.57	8.39
16.5	18.0									2.64	5.30	7.40
17.0	18.5									0.45	3.78	6.26
17.5	19.0										1.92	4.94
18.0	19.5											3.35
18.5	20.0											1.36

The following considerations occur:

- In case of water taken from the well, at constant temperature of 14°C and ground temperature at 9°C (February), then the system takes around 3 hours to release the heat and restore the initial condition. Therefore, heat storage lasts 3 hours after the milk precooling, in which cows can exploit drinking water at higher temperature than the well.
- In case of water taken from the aqueduct, then water at 14°C can be found when ground temperature is set at 12.5°C, which means mid-December and April (See Figure 12). In this case, heat storage lasts 7 hours after the milk precooling.

In both cases, according to information on milking phases of Table 1, between two milking sessions, water returns to original temperature, thus ground is not affected on the medium-long term by excessive heat injection. The system is completely sustainable without ground thermal modifications.

Finally, using Equation 16, heat losses to the ground during the heat injection phases (2 hours) have been calculated for different starting conditions (water tank temperature and ground temperature). Results for ground temperature in the range 8-22°C (the ground temperature model boundaries at 2 m depth) are presented in Table 11.

Table 11. Heat losses to the ground for different starting temperature of the tank water and ground temperature

Heat losses after 2 hours of operations (kWh)		Starting temperature of the water in the tank (°C)										
		10	11	12	13	14	15	16	17	18	19	20
Ground temperature (°C)	8	0.50	0.55	0.62	0.69	0.78	0.87	0.97	1.07	1.18	1.29	1.40
	9	0.38	0.44	0.50	0.58	0.66	0.76	0.85	0.96	1.07	1.18	1.29
	10	0.27	0.32	0.39	0.46	0.55	0.64	0.74	0.84	0.95	1.06	1.17
	12	0.07	0.10	0.15	0.23	0.31	0.41	0.51	0.61	0.72	0.83	0.94
	14	0.00	0.00	0.00	0.02	0.08	0.17	0.27	0.38	0.48	0.59	0.71
	16	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.14	0.25	0.36	0.47
	18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.13	0.24
	20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

For many working conditions, heat losses are present (see Table 8 for comparison with injected heat). Therefore, only one part of the injected heat is stored in the tank. As an example, for the selected case study (red box in the Tables), of the 4.310 kWh injected in the two operation hours, 0.660 kWh are transmitted to the ground, while 3.650 kWh are stored. Being the heat losses relatively small with respect to the total heat injected, the ground temperature variation around the GeoUWT during the two operation hours was not taken into consideration at this stage of research.

A research survey allows analysing different milk pre-cooling solutions in case-study region. Currently, milk direct pre-cooling systems circulate wastewater used for cleaning and provide ΔT of 10-12°C, with milk temperature decrease from 40°C to 30°C, approximately. On the other hand, ΔT of approximately 20°C from dedicated TRT indicates the opportunity for significant milk-precooling potential of GeoUWT concept. Final temperature of the water inside the GeoUWT is in the range with optimal temperatures of the drinking waters for the cows. With the available informatiaon related to the ground annual temperature profiles (Figure 12), it is possible to consider the storage function of the GeoUWT for the water at requested temperature range.

3.4 Sizing of the GeoUWT for the case study

Several scenarios were developed for the estimation of the impact of GeoUWT implementation in the case study based on the combination of the data from Azienda Agricola Famiglia Montagnini and from other barns in Emilia Romagna Region, resulting in the theoretical model of 300 cows (see Table 2).

A specific insight about effect of different input parameters has been applied. As a fixed scenario, complete temperature recovery of GeoUWT system is expected between the milk production sessions. Implementation of the novel system of water-heating/milk-cooling in the dairy barn would require installation of circulation pump to induce circulation of the working fluid from the tank with milk to GeoUWT.

The target temperature of milk precooling defines the energy needed by the system, and so how many GeoUWTs must be used. Equations (3-5) have been applied for this scope.

Calculated energy data of the GeoUWT from the dedicated TRT on the prototype are presented in Table 12. The rough evaluation of electric energy cost in Emilia Romagna region is also reported.

Table 12. Energy data of the GeoUWT.

Input parameter	Value	Unit
En_{GeoUWT}	4.31	kWh
P_{pump}	50	W
t_s	2	h
Electric energy cost	0.3	€/kWh

A complete preliminary investment analysis is presented in Annex Table A3, with the hypothesis of installation of 25 GeoUWTs, by homemade solution, supposing that the equipment and man-work are already available for the farm.

Different target temperatures of the milk were taken into consideration, with fixed number of the cows in the theoretical barn model, so to define the energy needed by the system for different configurations with Equations (3-5).

This allowed to compare the results of necessary number of GeoUWTs to suit the energy demand of single milk session with different target ΔT of produced and precooled milk (Table 13).

Table 13. Data set of number of required GeoUWTs, based on different target milk temperature, for 300 cows.

Target T_{milk} (°C)	En / session (kWh)	n_{GeoUWT} (milk precooling)	El_{pump} / year (kWh)	Yearly pump energy cost (€)	Initial investment (€)
29.0	60.04	14	1 022.00	306.60	13 758
28.0	65.50	16	1 168.00	350.40	15 770
27.0	70.96	17	1 241.00	372.30	16 855
26.0	76.42	18	1 314.00	394.20	17 781
25.0	81.88	19	1 387.00	416.10	18 946
24.0	87.33	21	1 533.00	459.90	21 038
23.0	92.79	22	1 606.00	481.80	22 043
22.0	98.25	23	1 679.00	503.70	23 049
21.0	103.71	25	1 825.00	547.50	25 140
20.0	109.17	26	1 898.00	569.40	26 146

Full version of this table with comparison of required number of GeoUWT for different water demand scenarios is present in Annex Table A1. Being the water volume contained inside a GeoUWT equal to 576 l, it has been possible to calculate the water availability for the different drinking scenarios considered, varying from 75 l/session up to 200 l/session, using Equation 6. For set requirements of selected typical barn, n_{GeoUWT} necessary to cover drinking water demand exceeds the required number of units to cover milk precooling energy demand. Being the GeoUWT used for both purposes at the same time, according to the chosen scenario, the user can choose to dimension the field either based on water demand, thus covering the whole energy need, or based on energy demand, thus covering a percentage of the whole water need.

In this way, it was possible to find the most suitable combination according to the farm owner preferences. The number of installed GeoUWT can be chosen to entirely cover the milk precooling energy needs, or, on the other hand, to supply cows with optimal temperature of water, according to the four proposed water demand scenarios. Moreover, additional analysis was done for the target ΔT = 20 °C, corresponding to the performed dedicated TRT and optimal drinking water temperature, for variable number of cows (Table 14). This approach gives insight about required number of installed GeoUWT units for smaller barns or increase of cattle number for existing barns.

Table 14. Data set of number of GeoUWTs, based on different number of cows, for target milk temperature 20°C.

n_{cows}	En / session (kWh)	n_{GeoUWT} (milk precooling)	El_{pump} / year (kWh)	Yearly pump energy cost (€)	Initial investment (€)
20	7.28	2	146	43.80	1 451
50	18.19	5	365	109.50	4 468
100	36.39	9	657	197.10	8 570
150	54.58	13	949	284.70	12 673
200	72.78	17	1241	372.30	16 855
250	90.97	22	1606	481.80	22 043
300	109.17	26	1898	569.40	26 146
500	181.94	43	3139	941.70	43 641
1000	363.89	85	6205	1 861.50	86 836

Full table of corresponding required number of GeoUWTs for fixed precooling ΔT and fulfilling water demand for different scenarios and variable number of the cows is presented in Annex Table A2.

With respect of the chosen model of typical Emilia-Romagna Region barn, two possible solutions for required number of GeoUWTs were selected: the first one based on the energy demand for precooling produced quantity of milk for target milk temperature 20°C and the second one based on sufficient water volume at optimal temperature for drinking or/and cooling purposes. For all scenarios presented in Section 2.3, alternative numbers of GeoUWTs, based on water and energy demand, have been calculated. Table 15 shows the results for winter scenarios (1a and 1b), while Table ~~15~~16 shows the results for summer scenarios (1c and 1d), both on the typical case study barn. It is worth noticing to say that once dimensioned the ground heat exchangers field for one of the two seasons, the same system will be used also for the remaining one, at the best of its capacity.

Table 15. Winter scenarios for the required number of the installed GeoUWTs

	Scenario **1a**	Scenario **1b**
$V_{w,GeoUWT}$ (l)	576	576
n_{cows}	300	300
$n_{s,\,day}$	2	2

Per day		
Drinking water needs / cow (l)	150	200
Total water demand (l)	45 000	60 000
Per session		
Drinking water needs / cow (l)	75	100
Total water demand (l)	22 500	30 000
n_{cows} / GeoUWT (water demand)	8	6
n_{cows} / GeoUWT (milk precooling)	12	12
En (kWh)	109.17	109.17
$El_{pump,}$ (kWh) (water demand)	3.9	5.2
$El_{pump,}$ (kWh) (milk precooling)	2.6	2.6
n_{GeoUWT} (water demand)	40	53
n_{GeoUWT} (milk precooling)	26	26

Table 16. Summer scenarios for the required number of the installed GeoUWTs

	Scenario **1c**	Scenario **1d**
$V_{w,GeoUWT}$ (l)	576	576
n_{cows}	300	300
$n_{s,\ day}$	2	2
Per day		
Drinking water needs / cow (l)	200	200
Cooling water needs / cow (l)	0	200
Total water demand (l)	60 000	120 000
Per session		
Total water demand / cow (l)	100	200
Total water demand (l)	30 000	60 000
n_{cows} / GeoUWT (water demand)	6	3
n_{cows} / GeoUWT (milk precooling)	12	12
En (kWh)	109.17	109.17
$El_{pump,}$ (kWh) (water demand)	5.2	10.4
$El_{pump,}$ (kWh) (milk precooling)	2.6	2.6
n_{GeoUWT} (water demand)	53	105
n_{GeoUWT} (milk precooling)	26	26

Tables 15 and 16 clearly show that it is possible to install a system of ground heat exchangers capable to meet the requirement of precooling the entire milk yield and to rise the temperature of drinking water to the target set point. In particular, an investment of 53 GeoUWTs appears suitable to assure a quantity of drinking water at appropriate temperature which can fully cover the demand of a high producing herd: in winter time this is a necessary condition to allow a water intake adequate to high production performances. At the same time, the same investment is suitable to assure all the necessary drinking water at optimal temperature also in summer period. In any case a smaller investment, involving only 40 GeoUWTs, is enough to assure milk precooling and proper heating of a quantity of drinking water adequate to the current standard production of the farm, however it is not enough in case milk yield substantially increases, e.g. by 15%. On the other hand, a notably greater field, comprising 105 GeoUWTs, would be suitable to provide, in the warm season, also sprinkler water at the preferred temperature.

Novel GeoUWT configuration has a significant potential for providing clean and renewable solution for precooling the produced milk on diary barns. Temperature difference of precooling achieved with this concept is greater than that obtained by conventional direct milk precooling systems, which exchange heat with water to be used for cleaning purposes. Besides, multipurpose of GeoUWT concept is what provides an additional value since the same water used as heat sink for precooling the milk can be used as drinking water for cows. Optimal temperature of drinking water for cows is expected to improve living conditions and thus to increase the production of milk. At the same time, the frequent water substitution, temperature driven, guarantees the restoration of the heat exchange potential of GeoUWT, avoiding the ground thermal saturation in the surroundings.

Even though tested GeoUWT prototype is installed in very shallow depth of 2 m, hence is affected by seasonal ambient conditions, several advantages of such kind of configuration can be shown. The most important is the simplicity of installation and corresponding costs since depth up to 2 m can be excavated with digging machines which are expected to already be available in farms. Generally, the most expensive part of installation of ~~GHE~~ ground heat exchangers for shallow geothermal systems is drilling/excavating part. Moreover, such a size makes the system easily adaptable for variable number of cows and provides extra flexibility for farmers in terms of deciding about the leading parameter for dimensioning the system: energy for milk precooling, target temperature water supply or cost.

Further research on this aspect is necessary, as well as considering various input parameters such as water supply form different sources and at different temperatures. With the respect of chosen number of installed GeoUWT units, pre-planned connection between the units can help in achieving the most efficient configuration, since some of the unites could be left inactive during the winter period, without cooling needs.

4. CONCLUSIONS

An original application of UWT as UTES was investigated to define a smart system to improve energy efficiency in the dairy livestock sector. The study of energy and water requirement of dairy barns showed that a suitable application for the UTES technology in the form of a spiral-shaped pipe immerged in a fluid, called GeoUWT, can perform suitably to match the energy demand for milk cooling with the needs of water heating for cow drinking and watering.

The study assessed the technical feasibility of the implementation of such a shallow geothermal system in the dairy livestock farming sector. Specifically, the study analysed the application of a new system to enhance the free heat/cool exchange between water and milk in a case study cow barn in Northern Italy.

The performances of GeoUWT were tested in the LAGIRN Lab of University of Bologna. The test aimed at identifying the GeoUWT heat exchange potentiality using different experimental sets, one of those was specifically designed for the system application in a cow barn, since the fluid temperature was set according to cow milk temperature. Results demonstrate the efficacy of GeoUWT if compared to traditional shallow geothermal systems. They also showed the increased efficiency due to regular changes of thermal exchange fluid.

Scientific literature review and surveys in several cow barns carried out by the research group allowed to achieve data about milk production, water consumptions in different seasons etc., allowing to create a sound data set as input data in the study. Experimental tests and surveys assured the reliability of study simulations.

The study of energy needs and water usage of dairy barns showed that a suitable application for the GeoUWT can enhance the direct thermal exchange between milk and water. Preliminary calculations, in fact, showed the suitability to match the energy demand for milk cooling with the needs of water heating for cow drinking and watering.

Temperature difference of precooling milk achieved with this concept is greater than conventional direct systems; besides, multipurpose of GeoUWT concept provides an added value since the same water used as heat sink for precooling the milk can be used as drinking water for cows.

Four scenarios have been created to simulate recurrent different conditions that can be found in the case study barn. The calculations have been implemented considering that all the water used for milk/water thermal exchange is necessary water for the barn operations (drinking, soaking and cleaning). The calculations were made fixing the target temperature of the water to 18.0°C, which is considered in literature the proper temperature of drinking water for cows. The analysis of the scenarios showed that different options are available in terms of levels of investment, depending on the quantity of drinking or sprinkler water that is meant to be led to the target temperature, thanks to the scalability of the system proposed. Moreover, the heat exchange potential of the system is planned to be exploited both in the cold and in the warm season.

The results show the theoretical feasibility of the system and the enhancement of the free exchange due to the GeoUWT, moreover the necessity of the water usage allows proper fluid changes in the GeoUWT increasing its efficiency. Another important result concerns the use of GeoUWT as water thermal storage in fact the water can be kept at the fixed temperature, so that GeoUWT provides short-term underground heat storage with enhanced direct thermal exchange between water and milk.

Through a dedicated design of the GeoUWT field, this system can provide the water at the proper temperature with no need of heaters and can reduce the power and the electric consumption to the milk refrigerators. Moreover, the provision of water at the proper temperature is expected to improve living conditions and increase water intake, thus increasing milk production, as acknowledged by survey ad interviews with farmers and technicians of the sector.

Finally, this paper demonstrated the theoretical feasibility of the system, based on scientific literature, survey and experimental data. Further studies will focus on the technical feasibility by means of experimental tests in the case study barns. They also will concern on the system equipment (such as pumps, pipes, valves, control systems, etc.) and they will consider maintenance procedure to guarantee the correct hygiene and therefore the system safety.

ACKNOWLEDGMENTS

The authors wish to thank the *Azienda Agricola Famiglia Montagnini* of San Pietro in Casale (Bologna), Italy, for their collaboration during the survey and design activities. Thanks also go to all technicians and researchers (particularly, S. Kasmaee, F. Peddis, S. Focaccia and G. Pollicino) who have helped install, improve, work and maintain the experimental prototype of GeoUWT installed at the LAGIRN Lab of University of Bologna.

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APPENDIX

Table A1. Results of required number of GeoUWTs, supplied cows and pump energy consumption for fixing 300 cows for various target T_{milk}.

Target T_{milk} (°C)	*ΔT (°C)*	*En/ session (kWh)*	*n_{GeoUWT}*	*V_w in GeoUWTs (l)*	*$n_{cows},_{GeoUWT}$ (milk precooling)*	*Cows supplied by hot water (1a)*	*Cows supplied by hot water (1b,1c)*	*Cows supplied by hot water (1d)*	*El_{pump} / session (kWh)*	*El_{pump} / day (kWh)*	*El_{pump}/ year (kWh)*	*Yearly pump energy cost (€)*
29.0	11.0	60.04	14	8 064	22	36%	27%	13%	1.40	2.80	1 022.00	306.60
28.0	12.0	65.50	16	9 216	19	41%	31%	15%	1.60	3.20	1 168.00	350.40
27.0	13.0	70.96	17	9 792	18	44%	33%	16%	1.70	3.40	1 241.00	372.30
26.0	14.0	76.42	18	10 368	17	46%	35%	17%	1.80	3.60	1 314.00	394.20
25.0	15.0	81.88	19	10 944	16	49%	36%	18%	1.90	3.80	1 387.00	416.10
24.0	16.0	87.33	21	12 096	15	54%	40%	20%	2.10	4.20	1 533.00	459.90
23.0	17.0	92.79	22	12 672	14	56%	42%	21%	2.20	4.40	1 606.00	481.80
22.0	18.0	98.25	23	13 248	14	59%	44%	22%	2.30	4.60	1 679.00	503.70
21.0	19.0	103.71	25	14 400	12	64%	48%	24%	2.50	5.00	1 825.00	547.50
20.0	20.0	109.17	26	14 976	12	67%	50%	25%	2.60	5.20	1 898.00	569.40

Table A2. Results of required number of GeoUWTs and related pump energy consumption for ΔT 20°C for various number of cows

n_{cows}	*En*/ session (kWh)	n_{GeoUWT} (milk precooling)	*Cows supplied by hot water (1a)*	*Cows supplied by hot water (1b,1c)*	*Cows supplied by hot water (1d)*	El_{pump} / session (kWh)	El_{pump}/ day (kWh)	El_{pump}/ year (kWh)	Yearly pump energy cost (€)
20	7.28	2	77%	58%	29%	0.2	0.4	146	43.80
50	18.19	5	77%	58%	29%	0.5	1.0	365	109.50
100	36.39	9	69%	52%	26%	0.9	1.8	657	197.10
150	54.58	13	67%	50%	25%	1.3	2.6	949	284.70
200	72.78	17	65%	49%	24%	1.7	3.4	1241	372.30
250	90.97	22	68%	51%	25%	2.2	4.4	1606	481.80
300	109.2	26	67%	50%	25%	2.6	5.2	1898	569.40
500	181.9	43	66%	50%	25%	4.3	8.6	3139	941.70
1000	363.9	85	65%	49%	24%	8.5	17.0	6205	1 861.50

Table A3. Preliminary analysis of installation costs for a scenario of 25 GeoUWTs.

Excavator rent	n_{GeoUWT}	Height (m)	Width (m)	Length (m)	Hours / GeoUWT	Working hours/day	days	€/day	
Hole excavating	25	2.5	1	1	1	12	3		
Duct excavating	25	0.5	0.5	0.5	0.5	12	2		
GeoUWT placement	25	2	0.6	0.6	0.2	12	1		
GeoUWT burying	25	2.5	1	1	0.4	12	1		
Duct burying	25	0.5	0.5	0.5	0.05	12	1		
Total							**8**	**80**	**640**
GeoUWT	n	Height (m)	Width (m)	Length (m)				€/GeoUWT	
External tank (prototype)	25	2	0.6	0.6				500	**12 500**
	n	External diameter (mm)	Internal diameter (mm)	m	Coils/HHE	Spacing (mm)		€/pipe	
HHE PE-X (material)	25	25	20	40	26	80		150	**3 750**
	n	HHE diameter (mm)	HHE length (m)	Weight (kg)	Hours / HHE	Working hours/day	days	€/day	
HHE (installation in the UWT)	25	500	2	7.5	2	12	5	50	**250**
PE Pipes connections (materials)	n	External diameter (mm)	Internal diameter (mm)	PN	Average length (m)		Total length (m)	€/m	
PE inlet pipes	50	32	26	16	50		2 500		
PE outlet pipes	50	32	26	16	50		2 500		
Total							**5 000**	**1.5**	**7 500**
Pipe welding	n	n welding / GeoUWT	n welding / milk collector	n welding / water well	n valves / cows	n valves / milk	Total number	€/each	
	25	4	2	1	1	2	250	2	500
TOTAL									**25 140**

October 19th, 2019

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