A borehole solar heat storage system with double circuit and dual source for a swine farm: first year of operation

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ABSTRACT

The present contribution illustrates the energetic results of the first period of operation of an innovative borehole thermal energy storage system (BTES) in Northern Italy. The research is finalized to develop a sustainable heating system for livestock building combining various renewable energy sources. The focus is on a pilot case, a swine farrow-to-nursery farm housing 500 sows and 2500 weaners. In fact, livestock farming is a significant energy-intensive branch of agriculture, which is substantially contributing to greenhouse gas (GHG) emissions. Recognizing the imperative to replace fossil fuels with Renewable Energy Sources (RES), the scientific community is actively exploring retrofitting strategies for existing farms. These strategies aim to create novel equipment based on RES for diverse farming activities.

The system developed in the research is comprised by borehole heat exchangers in “double circuit” configuration: the installation in the ground is the usual vertical double U, while the connection lines are separated: the first vertical U is linked to photovoltaic / thermal (PVT) system with a novel standardized solar central for underground energy storage, while the second is linked to a dual source heat pump (DSHP) for heating the livestock building. In swine farming, in particular, ensuring optimal environmental conditions in nursery barns is crucial for the health and proper growth of weaners. However, achieving ideal temperature and humidity levels is challenging in both hot and cold seasons, often necessitating high-energy HVAC systems. The “double circuit” configuration allows to fully exploit the mid-seasons (autumn and spring), where solar radiation and heating needs are both not negligible, thus enhancing the efficiency of the ground source. In summer season, the solar heat storage is prominent, allowing to modify the aquifer temperature in the BTES of several degrees, while in winter season, the heating use is prominent, and the air source is activated to cover the peaks, then the BTES is never thermally depleted. A tailored piezometer monitoring system allows to quantify the heat dissipation in the BTES due to groundwater flow. A smart control system was developed and implemented to monitor energy usage and environmental conditions. The findings underscore that monitoring environmental and energy parameters outdoor and inside buildings is fundamental to collect a database of the energy performances, assess the efficiency of the system and allow remote control of the equipment.

1. INTRODUCTION

Agricultural and livestock companies, and in general emprises located in rural areas, have wide availability of space to exploit shallow geothermal energy by the means of borehole heat exchangers (BHE) which are environmentally friendly, thanks to the limited impacts on the aquifers **[1]**. In order to exploit the required heat from underground by means of these geothermal heat exchangers (GHE), large volumes of subsoil are needed **[2]**. Due to the high costs of expanding the GHEs in depth, it is generally preferred to replicate and connect them in series and/or parallel, thus occupying significant amounts of space **[3]**. The agricultural and farm zones are therefore particularly appropriate for such systems. Moreover, the vertical types of GHEs, the borehole heat exchangers (BHE), can be used as underground thermal energy storage (UTES) systems, by injecting underground quantities of exceeding or waste energy, thus artificially heating the aquifers **[4]**. After the charge of the aquifer in summer, the enhanced heat can be subsequently exploited in the following winter season, by inverting the flow direction within the BHEs, to cover the thermal needs of the farms. Among the energy sources, solar thermal is one of the most promising for UTES, due to the time mismatch with respect to building heating needs.

The exploitation of solar energy integrated with BHEs in agricultural buildings has thus been the subject of several researches, and greenhouses are considered an important target in this sense, with particular reference to heating requirements. Other authors performed an assessment of the efficiency enhancement through the integration of geothermal and photovoltaic systems for heating a greenhouse for sustainable agriculture in a cold climatic region **[5]**. The results confirmed that the integration of renewable hybrid systems can be fundamental to achieving sustainable energy solutions for heating and keeping the indoor temperature between 19°C and 24°C throughout the year. The performances of the heat pump are crucial in these kinds of application for greenhouses, and this topic was further developed by various researchers, who focused on the models required for designing solar PV-driven greenhouses **[6]**. They demonstrated that low-carbon heating in greenhouses is achievable by using heat pumps powered by cost-effective renewable energy sources such as photovoltaic systems.

The integration of solar energy (by PVT systems) and geothermal sources have been deeply analysed in scientific research also with reference to animal production and livestock farming in particular. Studies carried out within the European project RES4LIVE focused on the RES potential of livestock farms by adopting these technologies **[7]**. In this context, the performances of a solar photovoltaic-thermal (PVT) system in livestock farms were analysed, providing valuable insights to meet the energy requirement of cattle **[8]** and swine farms **[9]**, considering the opportunity offered by the geothermal exchange for seasonal heat storage. The potential of geothermal storage was in turn studied through an experimental approach, considering the integration with a dual source heat pump (DSHP) **[10]**. In this research, a step-by-step procedure was developed and tested to characterize the shallow geothermal reservoir and define the optimal design of a Borehole Thermal Energy Storage (BTES) system. The results showed that the definition of an effective solution requires the collection of in-depth information about the geological and hydrogeological conditions of the site and the physical properties of the ground. For this purpose, the execution of Thermal Response Tests (TRT) at different depths proved to be fundamental to verifying the performances of the BHEs **[11]**. The research project thus proved that it is possible to effectively control the environmental conditions in a livestock barn through a smart heating system and renewable energy sources **[12]**. Preliminary performance analyses of the system were conducted over limited periods of time, which proved the validity of the approach **[13]**.

2. THE CASE STUDY

The Golinelli swine farm is located in Mirandola, in the province of Modena (northern Italy), and rears 500 sows and 2,500 weaners. The farm consists of a farrowing barn, a nursery barn, a gestation barn, and a hog barn with a gestation sector. The goal of the RES4Live project was to demonstrate the efficiency of renewable heating and electricity for the nursery barn. In such building, originally, heating was provided by a 34 kW LPG boiler, supported by 40 thermal lamps, divided in 10 nursery rooms (**Figure 1**). The boiler was then replaced by the integrated PVT-BTES-DSHP system, consisting of:

- a 35-kW_{th} dual source heat pump (DSHP), able to select the ambient source (air or ground) as an alternative or in combination (**Figure 2**);
- a BTES field consisting of 8 double-U BHE, 30 m deep, occupying around 18 m^2 of the courtyard (**Figure 3**);
- a PVT system formed by 24 SAMSTER SunPro 320 W PVT collectors, with a total electric and thermal capacity of 25 kW_{th} and 7.68 kW_{el}, respectively, and covering 39.3 m^2 of the building roof (**Figure 4**);
- a solar central station with a novel standardized design, the heart of the system, able to switch the direction of the flows according to the needs (**Figure 5**);
- a fully integrated measuring and monitoring system (by PLEGMA Labs) of both the ambient variables of the nursery barn and of the working variables of the plant (**Figure 6**).

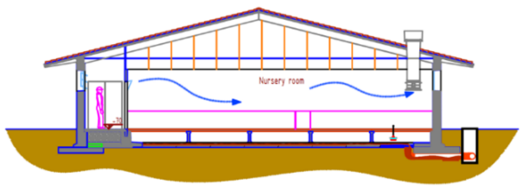

Figure 1: View of a nursery room, heated mainly by the radiant heat from the hallway.

Figure 2: Dual Source Heat Pump.

Figure 3: Installation of the BTES field in the courtyard.

Figure 4: PVT system on the roof

Figure 5: Standardized Solar Central Station

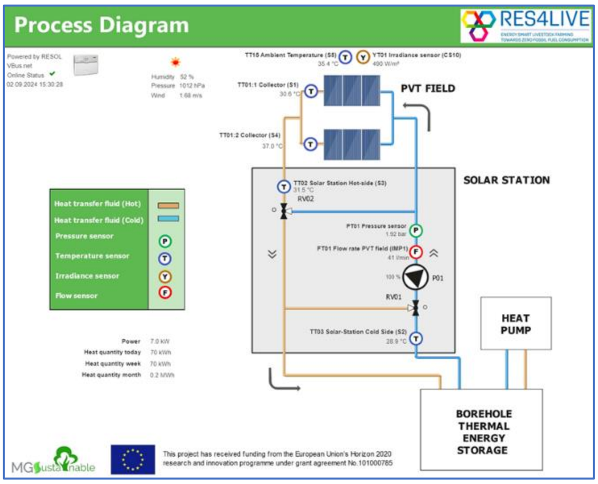

Figure 6: A screenshot of the heat injection phase, controlled by the solar station and monitored by PLEGMA Labs.

The exact configuration of the BTES cannot be presented, since it is a patent-pending innovation.

The energy loads presented in **Table 1** were originally used for the modeling and design of the integrated PVT-BTES-DSHP system. The loads were found by imposing the temperature injection limit in the BTES of 35°C, due to the local environmental regulations for aquifer protection. Moreover, such loads are not supposed to cover the whole demand of the nursery barn, since the peak power is covered by the air source.

Table 1: energy loads used for modeling and design

	Ground energy extraction (kWh)	Solar energy storage (kWh)
Jan	4,503	904
Feb	4,442	1,043
Mar	1,807	2,490
Apr	810	2,720
May	404	3,842
Jun	11	3,735
Jul	1	4756
Aug	1	3,984
Sep	26	2,859
Oct	1,149	1,905
Nov	2,319	1,013
Dec	3,965	1,005
TOT	19,437	30,256

As already presented in the previous cited scientific papers, the application of the BTES, in the specific subsoil and aquifer conditions, allowed to increase the average ground temperature from natural 15°C to around 20°C, without harming the environment.

With respect to the coefficient of performance (COP) of the DSHP, it is presented in **Table 2**.

Table 2: Coefficient of Performance design data of the DSHP

Heat source temperature (°C)		Heat pump COP
Water	**Air**	
-	1	2.5
0	6	2.8
5	11	3.0
10	16	3.4
15	21	3.9
20	26	4.5
25	31	5.0

The activation of the fans (air source) is based on two temperature levels of the geothermal circuit (outlet from the heat pump and return to the BTEST). The first level is imposed at 4°C. When the fluid outlet temperature drops below this value, the fans activate and the air source is exploited as an integration of the ground source, to reach the peak power of 35 kW_{th}. The second level is imposed at -1°C. When the fluid outlet temperature drops below this value, the geothermal circuit is shut down and the air source covers entirely the power. In both cases, the heat release in the geothermal circuit makes the ground recovers, for a soon reactivation.

3. RESULTS OF THE FIRST MONITORING YEAR

The results of the first monitoring year are presented in **Table 3**, which shows the total energy provided to the building E and the ambient energy exploited (from both ground and air sources) Q. The gap is covered by electric energy consumption of the compressor, fans and pumps L. For each month, the ratio between the provided energy E_i and the absorbed electric energy L_i is the Monthly Performance Factor (MPF).

$$MPF = \frac{E_i}{L_i} = \frac{E_i}{E_i - Q_i} \quad \textbf{(1)}$$

The ratio applied to the whole heating season (the monitoring year) provides the Seasonal Performance Factor (SPF).

$$SPF = \frac{\sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} L_i} = \frac{\sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} E_i - \sum_{i=1}^{n} Q_i} \quad \textbf{(2)}$$

Table 3: Comprehensive results of the DSHP for the first monitoring year.

	Heat provided to the building (kWh)	Ambient energy extraction (All sources) (kWh)	Monthly Performance Factor (MPF)
Jan	9,011.20	6,782.35	3.85
Feb	5,448.45	4,087.72	3.80
Mar	4,228.71	3,094.05	3.70
Apr	1,353.83	1,032.40	4.06
May	0.00	0.00	-
Jun	0.00	0.00	-
Jul	0.00	0.00	-
Aug	0.00	0.00	-
Sep	10.78	8.80	5.42
Oct	0.00	0.00	-
Nov	9,634.88	7,182.78	3.87
Dec	11,180.78	8,206.55	3.65
TOT	**40,870.20**	**30,395.84**	**3.78**

Since the DSHP works by exploiting ground (also charged by solar), air, or both, it was then possible to define the energy amounts for each of the working type (**Table 4**), and also of the source: ground (**Table 5**) and air (**Table 6**).

Table 4: Detailed results of the working type of the DSHP for the first monitoring year.

	Ground only energy extraction (kWh)	Air only energy extraction (kWh)	Hybrid energy (ground+air) extraction (kWh)
Jan	2,587.24	688.51	3,515.75
Feb	1,843.55	126.12	2,123.61
Mar	792.28	0.00	2,301.84
Apr	774.64	0.00	257.09
May	0.00	0.00	0.00
Jun	0.00	0.00	0.00
Jul	0.00	0.00	0.00
Aug	0.00	0.00	0.00
Sep	8.80	0.00	0.00
Oct	0.00	0.00	0.00
Nov	2,389.48	228.70	4,563.97
Dec	3,334.29	788.05	4,108.07
TOT	**11,730.74**	**1,831.38**	**16,871.07**

Table 5: Detailed results of the use of ground source by DSHP for the first monitoring year

	Ground energy extraction (total) (kWh)	Ground only energy extraction (kWh)	Ground energy extraction (hybrid) (kWh)
Jan	3,171.24	2,587.24	584.00
Feb	2,172.43	1,843.55	328.87
Mar	1,058.83	792.28	266.55
Apr	824.80	774.64	50.16
May	0.00	0.00	0.00
Jun	0.00	0.00	0.00
Jul	0.00	0.00	0.00
Aug	0.00	0.00	0.00
Sep	8.80	8.80	0.00
Oct	0.00	0.00	0.00
Nov	3,205.42	2,389.48	815.94
Dec	4,006.85	3,334.29	672.56
TOT	**14,973.64**	**11,730.74**	**3,242.90**

Table 6: Detailed results of the use of air source by DSHP for the first monitoring year.

	Air energy extraction (total) (kWh)	Air only energy extraction (kWh)	Air energy extraction (hybrid) (kWh)
Jan	3,620.25	688.51	2,931.74
Feb	1,920.85	126.12	1,794.73
Mar	2,035.29	0.00	2,035.29
Apr	206.93	0.00	206.93
May	0.00	0.00	0.00
Jun	0.00	0.00	0.00
Jul	0.00	0.00	0.00
Aug	0.00	0.00	0.00
Sep	0.00	0.00	0.00
Oct	0.00	0.00	0.00
Nov	3,976.74	228.70	3,748.03
Dec	4,223.56	788.05	3,435.51
TOT	**15,459.55**	**1,831.38**	**13,628.17**

Finally, **Table 7** Shows the average COP for the various operation modes for the different modes and as a whole.

Table 7: Average Coefficient of Performance of the DSHP during the year and for the different operation modes.

	COP total	COP ground	COP air	COP hybrid
Jan	4.24	4.64	3.79	4.13
Feb	4.23	4.62	3.82	4.00
Mar	3.81	4.20	-	3.67
Apr	4.40	4.72	-	3.51
May	-	-	-	-
Jun	-	-	-	-
Jul	-	-	-	-
Aug	-	-	-	-
Sep	5.55	5.55	-	-
Oct	-	-	-	-
Nov	4.03	4.60	3.39	3.78
Dec	3.96	4.31	3.65	3.88
TOT	**4.07**	**4.51**	**3.69**	**3.88**

The presented results were achieved by boosting the natural ground geothermal potential with the solar heat injected in the BTES. Specifically: in spring, the DSHP was on and off, so some days contemporary geothermal energy extraction and solar heat injection occurred; in summer the DSHP system was off, and the BTES system was able to fully store the solar heat from PVT; in autumn and winter, the DSHP recovered the injected heat of the previous two seasons to boost the performance of the system. The total injected heat for the reference year is presented in **Table 8**

Table 8: Solar injected heat in the BTES in the first year of monitoring

	Solar injected heat in the BTES (kWh)
Jan	400.00
Feb	500.00
Mar	1,400.00
Apr	1.800.00
May	2,700.00
Jun	2,000.00
Jul	3,700.00
Aug	3,400.00
Sep	1,600.00
Oct	900.00
Nov	300.00
Dec	300.00
TOT	**19,000.00**

In conclusion, for the first year of monitoring, the DSHP system worked 14.86% of the time, corresponding to around 53 full days, almost distributed from November to beginning of April. The total SPF was about 3.78. The compressor of the DSHP worked 37.91% of the time exploiting the ground source only, 53.93% exploiting the combined ground and air source and 7.13% exploiting the air source only, covering the peaks. Finally, the compressor worked 1.03% of the time to perform defrosting of the fans during some cold winter nights.

The electric energy consumption of the DSHP was around 10,500 kWh for the reference year, calculated based on the SPF (see **Table 3).**

Table 9: Resume of electric energy consumption coherent with the SPF value

	Heat provided to the building (kWh)	**Ambient energy extraction (All sources) (kWh)**	**Electric energy consumption (kWh)**
TOT	**40,870.20**	**30,395.84**	**10,474.36**

The estimated electricity production from the PVT system (still not connected to the grid at the moment of the present paper) is between 10,000 and 11,000 kWh, thus covering between 95% - 105% of the system energy consumption, although in asynchrony operation.

4. DISCUSSION

After the first operation year, it was then possible to compare the design energy values with the effective results, considering the unpredictability of weather conditions. Regarding the real extracted ground energy (around 15,000 kWh), it was 23% smaller than the design value (around 19,500 kWh). On the other hand, the real injected solar energy (around 19,000 kWh) was 36% smaller than the design value (around 30,000 kWh). Nonetheless, the DSHP was able, thanks to the use of air source, to provide all required energy to the building, keeping acceptable SPF (3.78).

The achieved results proved the validity of combining PVT with BTES and DSHP, where aquifer and subsoil conditions allow the underground thermal storage. With such integrated system, it was possible to reach a valuable SPF with a limited number of very shallow borehole heat exchangers: 8 BHE, 30 m deep, for a total BHE length of 240 m. As a rough comparison, in standard geothermal projects, not benefitting neither the geothermal storage and the dual source, in order to fulfill a peak power of 35 kW with such SPF, around 640 m of BHEs are necessary, almost three times the installed BHE length at Golinelli farm.

5. CONCLUSIONS

The main conclusions of the first-year of monitoring of the PVT-BTES-DSHP system installed at the Golinelli farm can be resumed below:

- The system has proved to be able to satisfy the energy needs of the farm;
- The Seasonal Performance Factor was 3.78;
- The system worked around 50% of the time exploiting both ground and air source, while keeping the full air source only to cover the energy peaks of the building.

Further analyses over the optimization of the solar heat storage and the benefits due to the production of electric energy will be conducted in the future.

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