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Geothermal heat pumps for sustainable farm climatization and field irrigation

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ABSTRACT

In intensive breeding farms, maintaining an adequate indoor thermal environment and air quality is crucial in order to establish healthy conditions and increase productivity. In the EU, fossil fuels and electricity are the main energy sources adopted for this purpose, yet introducing renewable energy sources and efficient Heating Ventilating Air Conditioning systems would reduce energy consumption and improve sustainability.

Another environmental concern in agricultural production is related to the intensive use of fertilizers, causing nitrate contamination in surface water and groundwater. Therefore, innovative strategies to reduce fertilizers and simultaneously reduce primary energy consumption are worthy of investigation.

This paper addresses both issues, studying the application of geothermal heat pumps in the agro-zootechnical sector, where they are rarely applied and thus their potential needs to be verified. The study considers systems based on the closed loop configuration, i.e. Ground Source Heat Pumps (GSHP), and on the open loop configuration, i.e. Groundwater Heat Pumps (GWHP).

Firstly, a pilot GSHP system for a piglet stable in Northern Italy is presented. Thanks to the use of both ground source and thermal recovery of air ventilation, the system achieves an appreciable reduction in both primary energy consumption and running costs, compared with a more traditional system typically adopted in this kind of farm.

Secondly, the feasibility of an innovative concept of a GWHP combined with the irrigation system is studied through numerical modelling. The area of the piglet stable is represented in a flow and heat transport model; groundwater used by the heat pump is re-injected up-gradient during the cold season, while it is used for irrigation during the warm season. The system would provide energy-efficient climatization to the farm stables and, at the same time, promote the reuse of nitrogen in cultivated fields as a result of groundwater recirculation through irrigation.

1. Introduction

According to the Eurostat database (Eurostat, 2017), in 2014 in the European Union energy consumption by agriculture made up 2.8% of the final energy consumption, with the highest share in the Netherlands (7.2%) and Poland (5.6%). In all probability these figures are underestimated (Gołaszewski et al., 2012), since they account only for the so-called direct energy uses in agriculture, namely related to electricity and fuel consumption. Out of the total primary energy consumption in agriculture in the EU, the proportion of direct energy used is estimated at 61% (Meyer-Aurich et al., 2013), although it may largely vary for the specific activity. Considering pig production in Italy, according to the IPPC document (The European Commission, 2003), fossil fuels and electricity represent up to 74% of the total energy consumption, depending on the farm size.

Improving energy efficiency in agricultural production is important for reducing energy consumption, dependency on fossil energy input, energy related costs and greenhouse gas emissions. Energy efficiency measures have been proposed, impacting on the levels of crop production, greenhouse production, animal housing and system approaches (Meyer-Aurich et al., 2013).

Among the measures aimed at reducing indirect energy consumption, the efficient management of fertilizers is expected to contribute to a large extent. Elevated levels of nutrients in both surface water and groundwater as a result of the leaching of

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Nomenclature

ACH	Air changes per hour
AHU	Air handling unit
BHE	Borehole heat exchanger
COP	Coefficient of performance
EDZC	Experimental didactic zootechnical centre
EER	Energy efficiency ratio
GSHP	Ground source heat pump
GWHP	Groundwater heat pump
HVAC	Heating ventilating and air conditioning

excess fertilizers in agricultural regions have been acknowledged for decades (Thorburn et al., 2003; Zhang et al., 1996). In recent years, however, the magnitude of the phenomenon has increased in scale, resulting in one of the most common contamination problems worldwide (Baily et al., 2011; Buvaneshwari et al., 2017; Duwig et al., 2003; Kim et al., 2015; Rudolph et al., 2015), investigated by several authors and through different approaches (Carucci et al., 2012; Caschetto et al., 2017; Sorichetta et al., 2012; Stevenazzi et al., 2015).

In Europe, the Council Directive (Consiglio delle comunità europee, 1991) aims to prevent nitrates from polluting surface water and groundwater, and promotes the use of good farming practices. In general, any strategy allowing a reduction in the use of fertilizers in agriculture would have a positive impact on both indirect energy consumption and pollution in aquifers.

As far as direct energy consumption is concerned, interventions on animal housing are needed, aimed at reducing the energy demand of stables, increasing the efficiency of climatization systems and introducing renewable energy sources. Enhancement of indoor air quality (both in terms of thermo-hygrometric conditions and pollution) is also required to improve animal wellbeing and bolster production (Fabrizio et al., 2015). The climatization and ventilation systems currently installed are mostly based on fossil fuels or electricity from the grid, making livestock production a contributor to climate change (Rojas-Downing et al., 2017). Geothermal heat pump systems potentially represent an improvement both in energy consumption and indoor air quality; their applicability to the sector is eased by the fact that agro-zootechnical farms already withdraw groundwater from wells, or have the space to host them.

Geothermal heat pump systems can be classified into Ground Source Heat Pump (GSHP) and Groundwater Heat Pump (GWHP) systems (Kavanaugh and Rafferty, 1997). In the first case, the heat pump extracts heat from the ground by means of a closed water loop consisting in several Borehole Heat Exchangers (BHEs). In the second case, the heat pump operates on an open water loop circuit, where groundwater is extracted from a well and re-injected into another well after heat exchange. The advantage in both cases is the exploitation of a heat source (the ground or groundwater) whose temperature is unperturbed all year round (e.g. between 13 and 17 °C in Milan (Davoglio and Ghezzi, 2014)), resulting in high energy efficiency and low running costs (Farabi-Asl et al., 2018; Lee et al., 2010; Lo Russo et al., 2009; Pulat et al., 2009; Yang et al., 2009). In both cases, the heat pump operation can be inverted in the warm season, so that the heat pump provides cooling to a building by injecting heat into the ground or the aquifer.

While geothermal heat pumps are commonly installed in residential, public and commercial buildings (Allaerts et al., 2016; Zhou et al., 2016), their use in agriculture is mostly limited to greenhouse heating (Huang and Mauerhofer, 2016; Noorollahi et al., 2016), aquaculture pond heating and crop and food drying (Erbay and Hepbasli, 2016; Lund and Boyd, 2016). The possibility to adopt geothermal heat pump systems in animal farms was investigated only recently by some authors (Borge-Diez et al., 2015; Islam et al., 2016; Wang et al., 2012). Wang et al. (2012) performed an economic comparison among different systems for a typical swine farm in Beijing, China. They concluded that considering the cooling effect obtained without increasing indoor relative humidity, as well as the energy saving in the heating period and the avoided air pollution from PM 2.5, the GSHP system is likely to be preferred in the upcoming future. Islam et al. (2016) experimentally investigated the performance of a GSHP and a conventional electrical heating system in a nursery pig house in Korea. GSHP provided a 46% reduction of energy consumption, and CO_2 and other noxious gas emissions were significantly lowered.

From the analysis of the state of the art, the necessity arises to verify the possibilities of implementing low-temperature geothermal solutions in the agro-zoo-technical sector. Geothermal heat pumps are rarely adopted in farms and, compared to conventional building applications, design for farms has to address specific issues: high ventilation requirements, deriving from the necessity to remove noxious emissions by the animals, and relatively high indoor temperature requirements, necessary in the first life stages of the animals. The possibility to improve the indoor thermo-hygrometric conditions and air quality as well as animal wellbeing can be foreseen, yet it needs to be proved. At the same time, application to the agro-zoo-technical sector opens the way to innovative strategies combining the traditional irrigation uses of groundwater with less common climatization uses. In order to demonstrate the potential for low-temperature geothermal solutions in this new field, the EcoZoo project was promoted by the Lombardy Region. The project, concerning both GSHP and GWHP, consisted of two parts:

- design, installation and monitoring of a pilot GSHP system for heating and cooling a typical piglet room. The aim was to adapt the GSHP system design to animal housing applications and to verify energy performance and possible savings compared with more conventional solutions typically adopted in farms;
- development of a new concept of a GWHP system integrated with the irrigation system of a farm. The objective was to assess the possibility to optimise the use of groundwater in farms, by coupling thermal and irrigation uses through a proper designing of the wells. At the same time, a further aim was to reduce pollution by agricultural inputs in groundwater by adopting a smart groundwater management strategy. The feasibility of this innovative system was numerically studied, assuming the well-known hydrogeological conditions of the Experimental Didactic Zootechnical Centre (EDZC) site, as well as the energy demand for heating and cooling of the entire Campus building dedicated to animal housing.

2. Case study

2.1. Location

The case study for both parts of the research is a portion of the EDZC in the Lodi Campus of the Università degli Studi di Milano. The EDZC is located in the South Western part of Lodi, in an area where many agricultural and breeding farms are present (see Fig. S1 in the Supplementary Material).

The pilot GSHP system was installed in the post-weaning piglet room, located in one of the sheds of the EDZC (Fig. 1) dedicated to experimental research on breeding (Savoini et al., 2002). At the same time, for the concept of the innovative GWHP system, it was assumed that the latter system would satisfy the heating and cooling demand of the entire shed, as shown in Fig. 1c.