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Experimental assessment of a solar photovoltaic-thermal system in a livestock farm in Italy

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ABSTRACT

This paper presents an experimental evaluation of the performance of a solar photovoltaic-thermal (PVT) system in a swine farm at Mirandola in Italy. In this project named RES4LIVE, funded by the EU's Horizon 2020 program, a PVT system is installed to replace fossil fuel consumption in one of the barns on the farm. The electrical energy from the collectors is utilized to operate the heat pump and provide electricity to the barn, whereas the thermal energy from the collector is stored in a borehole thermal energy storage (BTES) for further use by a 35 kW heat pump. The hybrid solar field consists of 24 covered PVT flat plate collectors (7.68 kW_{el} and 25 kW_{th}) with a total aperture area of 39.3 m^2, which can increase the temperature of the heat transfer fluid (HTF) to up to 40 °C. The PVT system is connected to a modular solar central (SC) with a standardized design that can also be used for other similar applications. The hybrid solar system complemented by energy storage is expected to save approximately 20,850 kg CO_2/year. The data collected from the PVT system, SC, and BTES are rigorously analyzed to evaluate its overall performance. A comprehensive performance assessment reveals the capability of the solar system to reduce carbon emissions and effectively replace fossil fuel consumption in the agricultural sector.

1. Introduction

The consumption of fossil fuels in the agricultural sector has become a major contributor to greenhouse gas (GHG) emissions, which are the main cause of global climate change and a threat to food security. Livestock farms are one of the main energy-consuming subsectors of agriculture [1], and are mainly powered by non-renewable sources. With initiatives such as Agenda 2030 [2] and the EU Green Deal [3] already in place, it is essential that livestock farming rises to the occasion and join the movement to transition to renewable energy sources (RES).

Globally, the pork market is expanding to satisfy the growing demand for animal protein. Europe's meat production is heavily based on pork meat, and this is evident from the fact that in 2018, an overall all-time high was reached, with around 23.8 million tonnes of pig meat being produced, which accounts for almost half of the EU's meat production for that year. As a consequence, swine farms are growing in size, presenting a significant challenge for swine farmers and industry stakeholders to meet proportional energy demands [4]. In swine farms, electricity is the main form of energy used, as it meets both heating and power needs. In these farms, fossil fuels such as diesel and liquefied petroleum gas (LPG) are mainly used to heat water in boilers and to drive power generators. In colder climates, fuel consumption is significant due to the need for supplementary heating. While ensuring the swines' thermal comfort at all times (e.g., temperature, relative humidity), the specific electricity and heating consumption values will rise, which in turn increases the energy costs. However, this comes with a large increase in average daily gain (ADG) that could even exceed 10%–15%. With declining costs and improved reliability and performance of key renewable energy source (RES) technologies, the opportunities for farmers, especially livestock producers, to engage in RES production are increasing and new business models are emerging in the market.

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Nomenclature

Abbreviations

ADG	Average daily gain
BHE	Borehole heat exchangers
BTES	Borehole thermal energy storage
COP	Coefficient of performance
DHW	Domestic hot water
EF	Emission factor
EPW	EnergyPlus weather
EU	European Union
GHG	Greenhouse gas
GOLI	Golinelli swine farm
HP	Heat pump
HTF	Heat transfer fluid
IEA	International Energy Agency
LPG	Liquefied petroleum gas
PCM	Phase change material
PV	Photovoltaic
PVT	Photovoltaic thermal
RES	Renewable energy source
RES4LIVE	Renewable energy source for livestock farming
SC	Solar central

Symbols

$\dot{m}$	Mass flow rate of the heat transfer fluid [kg/s]
I_{mp}	Max power current
I_{sc}	Short circuit current
T	Temperature [°C]
V_{mp}	Max power voltage
V_{oc}	Open circuit voltage
ΔT	Temperature difference between hot and cold sides of the collector [°C]
ρ	Density of the system fluid [kg/m^3]
A	Module aperture area [m^2]
c_p	Specific heat capacity of the system fluid [J/kgK]
P01	Pump
Q	Rate of heat transfer [kW]
RV01	Servo valve for warming up the system
TT02	Collector hot side temperature sensor
TT03	Collector cold side temperature sensor
YT01	Irradiation sensor

1.1. Literature review and state of the art

Among the established renewable energy technologies, photovoltaic thermal (PVT) is a very promising RES technology for the livestock sector since it can meet the electricity and heat demand of these farms [5–7]. A PVT collector is a hybrid system that combines photovoltaic and solar thermal technologies in a single module. Studies have shown that the overall efficiency of a PVT system is about 30% more than PV and solar thermal systems when considered separately [8–10]. However, despite the augmentation in overall efficiency, the aggregate number of global PVT installations is less than that of the corresponding standalone PV and solar thermal installations. With a motive to improve this scenario, a few studies reported earlier have been promising and insightful. In the last decade, a handful of studies have been conducted on the techno-economic analysis of residential [11,12] and industrial [7,13,14] PVT applications. Nevertheless, there are also a few reports on collector design optimization and modeling [15,16]. In all these studies and other related reports [17–19] as well, the overall efficiency of the PVT system has been shown to outperform the system considering the PV panels and solar thermal collectors working side by side. However, despite the great potential of such hybrid systems to accelerate decarbonization, only a few case studies have been reported to date that focus on the utilization of PVT systems for the agricultural sector. Moreover, most of the PVT systems studies found in the literature mainly address theoretical evaluations.

Wallerand et al. [20] conducted an optimization of a solar energy-based system for a dairy farm. This system included flat plate collectors, photovoltaic (PV) modules, high-concentration PV-thermal (PVT) collectors, heat pumps, and the existing natural gas and grid-electricity setup. The study showed that integrating solar technologies, combined with heat recovery and heat pumping, could lead to a significant decrease of 65%–75% in CO_2-equivalent emissions. The authors concluded that the strategic incorporation and utilization of solar energy could offer attractive economic and environmental prospects for dairy farms. In a case study conducted in northern Italy, Maturo et al. [21] evaluated various technologies while taking into account the weather conditions and energy prices. Using the TRNSYS simulation environment, the authors sought to identify the optimal scenario, and the results indicated attractive economic viability for all solutions, with discounted payback periods ranging from 3.7 to 8.6 years. The most beneficial scenario presented remarkable environmental benefits, preventing 2300 tCO_2/year in on-site electricity production and 1296 tCO_2/year through biogas displacement. Furthermore, there are also reports highlighting the economics of PVT collector based hybrid solar systems with an additional back up source (biomass heater). These studies critically evaluate the economic benefits of using solar-combi systems through case studies in school buildings [22] and sports facilities [23], which supplement the arguments for significantly lower payback periods using these technologies.

In another research study, Wang et al. [7] explored the potential of a solar combined heat and power (S-CHP) system based on hybrid PVT collectors in a dairy farm in Bari, southern Italy. The system included a parabolic trough collector and a spectrum splitter. A transient model was created to analyze the selective features of the spectrum splitter, the characteristics of PV cells, and the heat transfer in the PVT system. The results of the simulation showed the advantages of incorporating spectral splitting technology, with PV cell temperatures averaging 40 °C and thermal output averaging 204 °C. For a 10,000 m^2 area, the PVT S-CHP system provided 52% of the high-temperature thermal demand, and 40% of the low-temperature hot water demand, as well as 14% of the total electrical consumption. Different utility price scenarios were evaluated, demonstrating the sensitivity of the S-CHP system to energy costs, and cost-competitiveness was achieved at Danish energy price levels. The study also estimated a reduction of 890 tons/year in CO_2 emissions due to the dairy farm's energy consumption, mainly due to reduced natural gas usage and displaced electricity. Veeramanipriya et al. [24] investigated the use of PVT collectors for cassava drying in the Thanjavur region of India. They compared the results of a hybrid solar dryer with those of natural sun drying and found that the hybrid dryer produced a better physical and chemical composition of cassava. In a study conducted by Hosouli et al. [25], a theoretical assessment of a C-PVT collector system for agricultural applications was presented, showcasing significant progress in addressing CO_2 emissions from livestock farms through renewable energy integration. Notably, a PVT system was devised to optimize heat recovery from milk coolers and enhance the thermal heat used in an electric boiler. The study's integration approach, using existing heat recovery and buffer tank systems, showcased its applicability and economic feasibility, offering a swift payback period of under six years.

Regarding thermal storage systems, there are reports on the performance of BTES for various applications [26]. Aldubyan et al. [27] conducted a systematic assessment of the electrical performance of a PVT system connected to BTES. In this study, the authors used computer simulations to analyze the system performance for two different cases, with and without a ground source heat pump (GSHP). It was observed that, without a GSHP, the PVT cell performance significantly improved. In one of the recent studies, Jian et al. [28] evaluated the merits of a hybrid residential heating unit using a PVT-heat pump system coupled with a BHE heating system. The output of the hybrid system was also compared to that of a standalone BHE heating system. It was reported that the hybrid system was capable of producing 3 times more heating power than the standalone system, and the former could operate independently utilizing the electricity from the PV module leading to a stable and environment friendly heating system. Maryam et al. [29] used a genetic algorithm to conduct a techno-economic analysis of a system comprising of PVT collectors, phase change materials (PCM) and ground source heat pumps. With an objective to minimize the LCOE and to maximize the energy efficiency, various system combinations were analyzed. It was observed that single-objective economic optimization of a combined ground source heat pump and photovoltaic thermal collectors with PCM gave the highest PVT efficiency. From these studies, it can be concluded that the utilization of BTES (Borehole Thermal Energy Storage) for the purpose of energy storage has the potential to enhance the overall efficiency of the system. Furthermore, it ensures the availability of energy consistently throughout the year.

1.2. Research gap and structure of the paper

The literature on state-of-the-art solar systems for agricultural purposes is divided into three categories: standalone PV panels, solar thermal collectors, and side-by-side PV and solar thermal configurations. However, these methods have drawbacks, such as providing only one type of energy, low efficiency, or requiring extra space for combined heat and power. Notably, one recurring limitation in these approaches is the relatively limited utilization of heat storage technologies, which are essential for optimizing energy usage in agricultural systems. It is also evident that there is a scarcity of studies related to hybrid PVT systems for agricultural applications, most of them approached by simulations. Based on the reports made available so far, the authors strongly believe that the following are the main obstacles to the uptake of solar energy as a solution to meet the growing energy demands of the agricultural sector.

(a) Hybrid energy requirement not being met: As previously mentioned, livestock farms require electricity and heat at various temperature levels. This multifaceted energy demand renders standalone solar options inadequate for meeting the diverse needs of these operations. Hybrid PVT collectors and systems, constituting a solar combined heat and power (S-CHP) alternative, are emerging as a solution. These systems, which seamlessly blend photovoltaic and solar thermal technologies, offer the simultaneous production of both electrical and thermal outputs. When designed and operated correctly, they exhibit higher efficiency compared to side-by-side standalone configurations. Therefore, further investigation is needed for the effective implementation of these systems in agricultural applications.

(b) Absence of an efficient energy storage system: It is crucial to consider the incorporation of advanced heat storage technologies during the development of solar systems. Without a suitable energy storage solution, excess energy produced, especially during summer months, will be wasted. This could result in the failure of the whole system to meet continuous energy needs. However, in-depth research and innovation are necessary in this area to fully unlock the potential of integrated solar solutions for agriculture.

(c) Lack of a standardized solar central (SC): Modern agricultural units require a very reliable and stable source of energy for the continuous operation of various processes. Currently, the integration of solar systems in such a facility requires detailed engineering and design on a case-to-case basis. Nevertheless, a modular and standardized SC to simplify the design, installation, operation, and maintenance is lacking for solar energy systems, not only for agriculture applications. The demonstration of such a sub-system is essential to give the sector more confidence in investing and implementing solar energy as a viable replacement for fossil fuels. Therefore, the development of a standardized SC able to integrate and optimize solar heat and power delivery is also necessary for the market uptake of hybrid energy systems.

Previous studies have demonstrated the potential of PVT systems in various contexts, such as residences and greenhouses, which suggests that hybrid PVT technology with improved heat storage integration could be a viable and efficient energy solution for farming operations. In this context, this paper presents an experimental evaluation of a PVT system coupled with a borehole thermal energy storage for efficient cogeneration and heat storage. This research is significant and timely, as there is a lack of integrated systems in the agricultural sector combining PVT collectors with BTES and heat pumps. This paper explores the combination of cutting-edge technologies to address energy challenges in the agricultural sector, examining the synergy between solar energy generation, efficient thermal storage, and the application of heat pumps through a modular and standardized solar central. This study is novel and important, as it provides a detailed and rigorous study of the implementation of a system that integrates these technologies, evaluating its design, commissioning, and performance within a temporal context. As the world moves towards greater sustainability and reduced carbon emissions, this research is a crucial step towards promoting environmentally friendly and economically viable agricultural practices.

The structure of the presentation of our findings in the rest of the article is as follows. Section 2 explains the general methodology followed for the installation of the RES system based on the annual energy consumption. A detailed overview of the system design is also given in this section. The results and discussion in Section 3 discuss the overall system configuration with emphasis on solar central (SC). Performance assessment of the system post-installation over a period of 2 months, which includes the thermal and electricity production analysis, has also been presented and discussed. Inferences from the data obtained from the nursery barn are presented in Section 4.

2. Methodology

The Golinelli swine farm (GOLI) is located in Mirandola, in the province of Modena (northern Italy), and rears 500 sows and 2500 weaners. The farm consists of a farrowing barn, a nursery barn, a gestation barn, and a hog barn with a gestation sector. Before the replacement with the PVT-BTES-HP system, heating was provided by two heat pumps of 59.7 kW and 29.9 kW and thermal lamps in the farrowing barn, a 34 kW LPG boiler, and 40 thermal lights in the nursery barn, and a diesel boiler in the hog barn. Cooling is achieved by evaporative cooling in the farrowing barn and gestation barn. The core objective of the RES4LIVE [30] project, funded under the EU's Horizon 2020 [31] program, was to de-fossilize the livestock agriculture industry by demonstrating technologies in various pilot farms. The goal of the project was to provide renewable heating and electricity for the nursery barn (identified as Building 16) and potentially reduce the fossil fuel consumption of the LPG boiler (approximately 7500 kg/year) that supplies it. To achieve this, a 35 kW water-to-water heat pump (HP) was installed on the premises. Furthermore, a PVT system was installed as described in Section 2.2.1.

Fig. 1(a) shows the aerial view of the PVT collectors installed in Building 16 of the farm. To best design the PVT system and decide

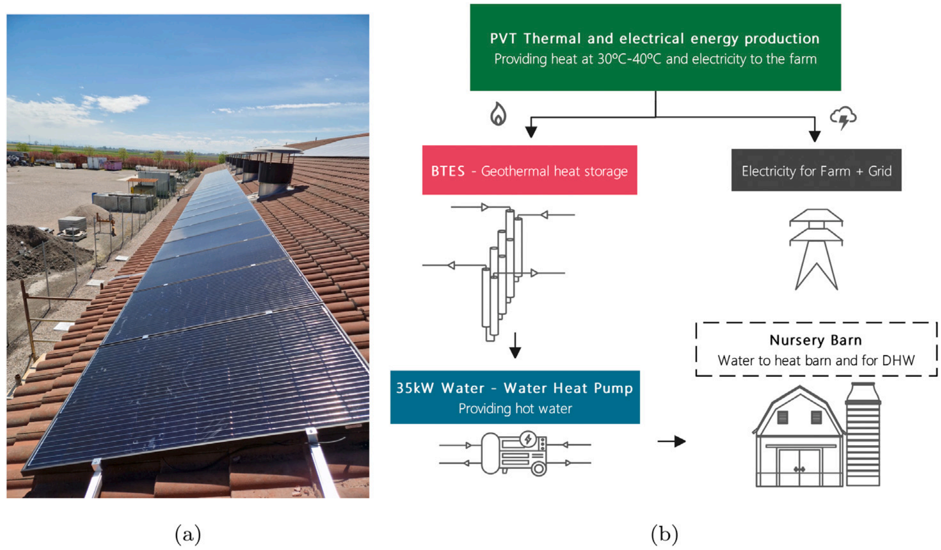


Fig. 1. (a) Aerial view of the PVT collectors installed in Building 16 and (b) schematic representation of the installed PVT-BTES-HP system in the farm.

on the PVT technology to be used in the farm, the heating demands of the farm were estimated from the available data. From the energy bills received from the farm, it was found that there was constant and consistent domestic hot water (DHW) demand throughout the year and for space heating, mainly in winter. There was no demand for space heating from June to September. The renewable energy technology system to be installed (Fig. 1(b)) during the project comprises a PVT system, a borehole thermal energy storage system (BTES), and a 35 kW heat pump. The higher the temperature that the PVT system could provide to the operating fluid, the more thermal energy would be available to increase the coefficient of performance (COP) of the heat pump. The BTES would act as a seasonal heat store to cover the winter months as much as possible.

2.1. Energy demand of the nursery barn

The GOLI being a commercial establishment, only limited data was available to evaluate the energy consumption. During the development stages, the project team spent several days on the farm to understand the daily and monthly heating needs. Based on the farm's energy bills, the nursery barn consumed a total of 90 MWh of LPG annually for space heating and domestic hot water. Additionally, the farm provided estimates for daily hot water usage and mentioned a consistent need for hot water throughout the year to clean and disinfect the barn and showers. The farm demonstrated a weekly consumption of 18 cubic meters of hot water, with temperatures ranging from 60 to 70 °C. Based on these estimates, it was determined that the annual demand for domestic hot water was 60 MWh. Therefore, the remaining 30 MWh was allocated for space heating. The purpose of space heating is to maintain a room temperature of 25 to 30 °C for weaning piglets throughout the year. The farm clarified that heating is not used during the summer months and is only necessary in winter, spring, and autumn. Fig. 2 depicts the monthly energy demand of Building 16 over a one-year period. Positive values represent the energy required for heating (in kWh), while negative values (during the summer months) indicate the need for cooling. Since data on the electricity needs of the farm were not readily available, the same was evaluated from a survey conducted by CERTH, a Greek partner of the project.

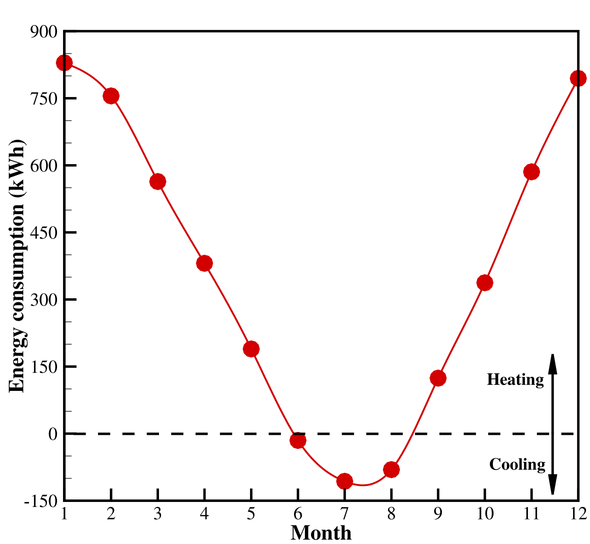


Fig. 2. Annual energy demand of Building 16 estimated from the energy bills provided by the farm.

2.2. System design

The overall system development considered three main pillars: cost-effectiveness, seamless integration with farm processes, and potential for replication. Based on data collected to estimate the farm's energy needs, a renewable energy system comprising PVT collectors, and a seasonal heat storage system coupled with a heat pump was designed, implemented, and is now fully operational in GOLI.

2.2.1. PVT collectors

Given the hot climate and the limitations on the injection temperature of the BTES, it was decided to go with uninsulated PVT collectors as a more cost-effective option than insulated PVTs. This would also eliminate the risk of condensation in the collector in areas with high humidity. The PVT collector chosen for the GOLI farm was the *Samster-SunPro 320 W* monocrystalline model from Samster AB in Sweden. This model was capable of generating a maximum power of 320 W with an efficiency of 19.55%. A thermal absorber of 1.64 m^2 is located beneath the photovoltaic module. The PVT system consists of 24 PVT collectors arranged in a single row on the roof, resulting in a total aperture area of 39.3 m^2 on the roof of the nursery barn. These collectors can provide a total of 25 kW_{th} and 7.68 kW_{el} peak power, providing thermal energy to the BTES and electricity for HP operation and the electrical needs

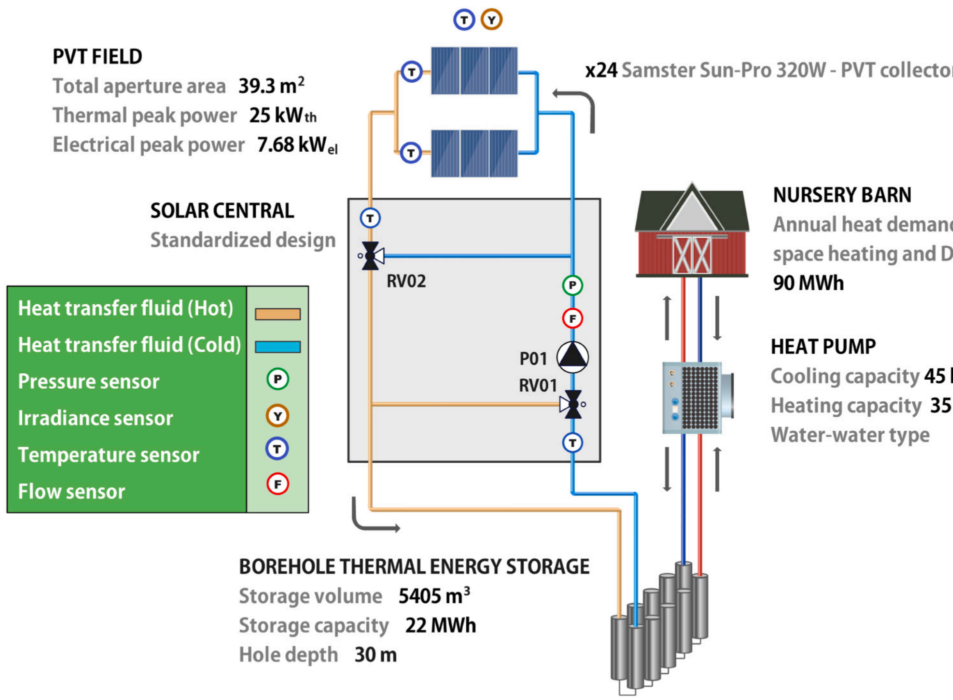


Fig. 3. Schematic representation of the installed RE system indicating the technical specifications.

of the nursery barn. The collectors were hydraulically distributed in four rows, each containing six of them. Nevertheless, each row was designed to have the same volumetric flow of 400 l/h. The pressure drop across one collector was estimated to be 10 kPa. Fig. 3 illustrates the schematic representation of the installed RE system that shows the technical specifications of various subsystems. The specifications of the installed PVT system are given in Table 1.

The PVT system was designed to use the thermal energy of the collectors to heat the heat transfer fluid (HTF). The heated operating fluid (a mixture of water and antifreeze glycol with a concentration of 35%) was then directed to the borehole thermal energy storage (BTES) using U-pipes, where the heat would be stored in the shallow sandy aquifer. Another set of U-pipes was present in the BTES to transfer the heat stored to the cold side of the HP (35 kW). The system flow rate and control were designed so that the thermal part of the collector was capable of increasing the temperature of the HTF up to 40 °C under a maximum operating pressure of 6 bar. The flow rate of the system was set to 1 l/min for each m^2 to achieve nearly 39 l/min for the entire solar circuit.

The PVT system and solar station (balance of the plant) were designed to achieve a standardized configuration scheme that could be replicated in other applications with similar operational requirements. Thus, the solar central was explicitly made for this project and is detailed in Section 2.2.2.

Table 1
Total capacity (thermal and electrical) of the installed system.

Total aperture area	39.3 m^2
Total electrical capacity of the installation	7.68 kW_{el}
Maximum circuit voltage	797 V
Maximum circuit current	9.64 A
Total thermal capacity of the installation	25 kW_{th}
Flow rate in the thermal circuit	39 l/min

2.2.2. Standardized solar central (SC)

A solar central (SC) is the most crucial subsystem of any solar station and plays a significant role in controlling and optimizing process variables. It consists of all the equipment that is required for a solar system to perform effectively for a specific application, including mechanical (pumps, heat exchangers, valves), electrical (valve actuators, power systems), instrumentation (temperature, pressure, flow, and solar radiation sensors), and various other control components. A novel and modular SC was designed to achieve a standardized design that would be used as the basis for other installations within the RES4LIVE project. This was done to address one of the main barriers to adopting solar thermal and PVT technologies, which is the relative complexity of their installation and configuration compared to conventional systems. The goal was to design a standardized solar central for PVT systems in the range of 40–100 m^2 capable of meeting the temperature needs of up to 90 °C. All the components in the solar central and their location were defined to have fewer sensors and flow control devices (valves) on the roof so that preventive and corrective maintenance activities could be easily performed. Moreover, the definition of the required elements was precise and based on several years of experience in solar thermal systems, with the objective of avoiding or minimizing future shutdowns, maximizing the performance of the entire system, and increasing the PVT plant's lifetime.

As shown in Fig. 4, the PVT collectors are connected to the solar central, which is managed by the automated control system to adjust all components of the solar central. The standardized solar central was designed with all necessary components, such as the main pump, safety valve (6 bar), expansion vessel connection, fill and drain valves, and check valves. Additional elements for the optimal functioning of the solar central were also included, such as valves, filters, and temperature sensors. Supplemental valves were also included for the lifetime maintenance of the station. The solar central also incorporated a 2-step start-up procedure with a 3-way valve (RV-01) that could bypass heating loads. This is necessary for larger systems to allow the pump to start circulating the fluid around the solar field during start-up, stabilizing the temperature and becoming constant throughout the

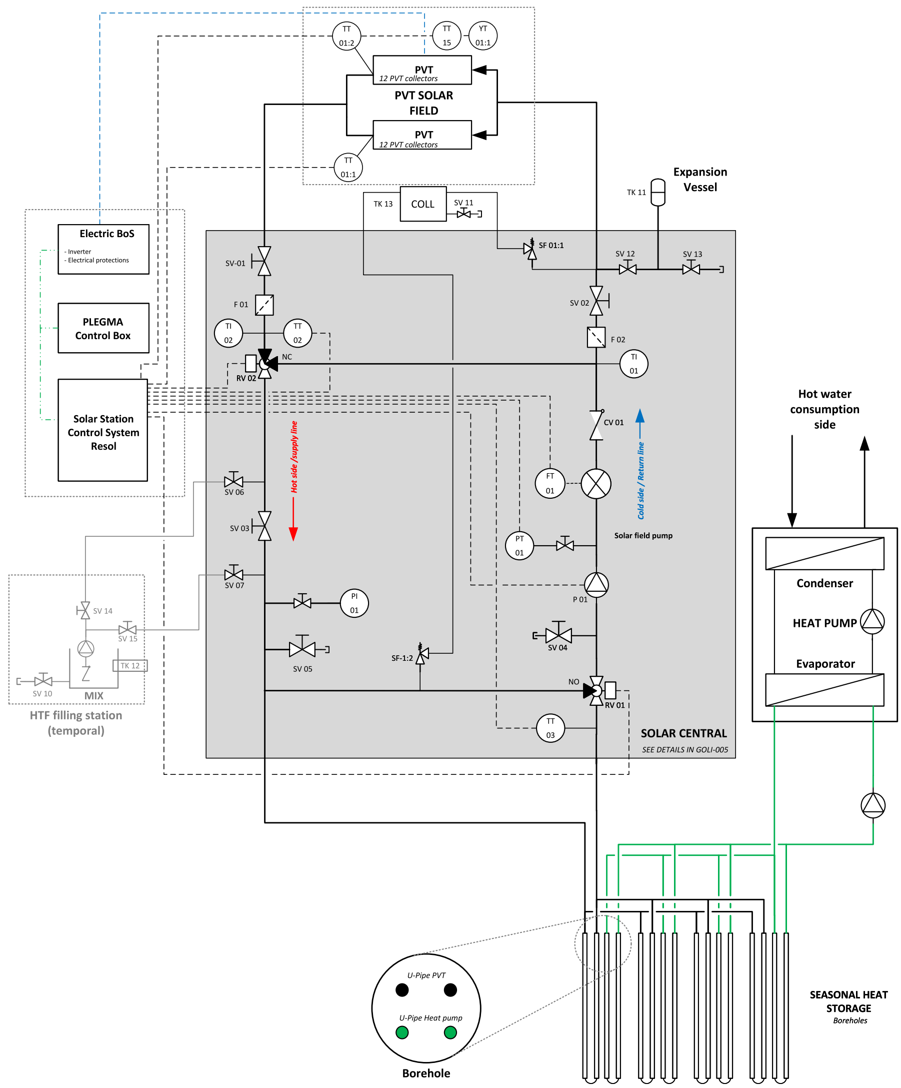


Fig. 4. P&ID of the installed PVT-BTES-HP system.

circuit. Once TT02, the temperature sensor on the hot side of the solar station was higher than the heating load, RV-01 would open, and the solar heat would start loading. This could prevent the loading of colder temperatures from the pipes and ensure that the whole circuit was hot before the heat loading.

All components that are in accordance with the standardized solar central can be observed in Fig. 4. The solar station on the GOLI farm has a 3-way valve (RV-02), as shown in the figure. This has the same function as RV-01, equalizing the temperature in the borehole storage, which is needed for optimum control of the whole system. This enables a modular approach where additional circuits could be added based on the equipment needed.

The SC is also connected to the BTES system, which accumulates and stores thermal energy from the collectors, thus acting as a central hub for all the connected subsystems.

2.2.3. Control strategy

An advanced solar controller was used to control the solar system for the GOLI nursery barn. It was configured in such a way that the pump (P01) would start to work when the irradiance level exceeds 200 W/m^2 for 2 min or depending on the differential temperatures of the solar field and the BTES temperature. The controller was also programmed to initiate a 2-step start-up operation for the solar circuit. The controller would decide when the heat produced by the PVT collectors should be stored on the BTES on the basis of a differential temperature control scheme.

2.2.4. Borehole thermal energy storage (BTES)

During the summer months or when there is comparatively less need for heating, the excess solar heat produced by PVT collectors can be dissipated or stored. In this project, surplus thermal energy produced, mainly during summer, is stored underground inside polyethylene pipes that act as heat exchangers and recovered during the cold winter months when the barn needs space heating. For this purpose, a borehole thermal energy storage (BTES) system was designed and developed based on the energy needs of the livestock barn and the potential productivity of the PVT. It consists of n8 PE100 PN16 DN32 double U borehole heat exchangers (BHE), 30 m deep, which are spaced 2 m×3 m apart in a rectangular configuration. The BTES is connected, with two separate circuits, to the PVT and the heat pump (HP), the latter to extract the stored thermal energy. The system is also equipped with three monitoring points (one BHE 10 m deep and two piezometers 25 m), to measure and register the groundwater and soil temperature at 1 m intervals in depth around the BTES area to calculate the effective heat stored and to comply with the aquifer protection local regulations. In fact, after a superficial layer of clay (up to 10–12 m), the BTES is immersed in the sandy shallow aquifer of Po Plain (up to BHE bottom and beyond), commonly used for agriculture, farming, and industrial purposes. During the initial tests, the substantial stability of the aquifer was verified, with very limited groundwater flow. The conditions, therefore, seem appropriate for attempting solar thermal energy storage. More information on BTES design and implementation can be found in Tinti et al. [32].

2.3. Estimation of CO_2 emissions

The CO_2 emissions from the combustion of fuel are estimated based on Eq. (1) reproduced from the International Energy Agency (IEA) statistics report [33].

$$CO_2\ emissions\ from\ fuel\ combustion = Fuel\ consumption \times Emission\ factor\,(EF) \tag{1}$$

where, fuel consumption is the amount of fuel combusted and, emission factor is the measure of the amount of carbon dioxide (CO_2) released per unit of energy produced [34].

3. Results and discussion

Together with heat production, solar energy was also used to produce electricity for the partial needs of the farm. The commissioning took place on April 14, 2023, and the whole system is fully operational now and being regularly monitored.

3.1. PVT system performance analysis

The performance of the PVT system is essential to understand its effectiveness and potential benefits for the swine farm and to expand its utilization to other potential sectors. The electrical energy generated from the PVT collectors is used to power the heat pump and cover the barn's partial electricity needs, while the thermal energy is stored in a BTES system and used when needed. Since there are two forms of energy generation (heat and electricity) in the system, the analysis is done separately for heat generation and electricity generation as given in Sections 3.1.1 and 3.1.2.

3.1.1. Heat production analysis

On a sunny day, when the irradiance exceeds the threshold and the required operational criteria as discussed in Section 2.2.3 are met, the HTF is directed into the cold side of the PVT collectors (TT03, see Fig. 4). Solar energy is used to increase the temperature of HTF, which in turn produces an elevated fluid temperature on the hot side of the collector field (TT02). The amount of heat transferred (Q) in kilowatts (kW) to the HTF can then be calculated using the equation given below.

$$Q = \dot{m} c_p \Delta T \tag{2}$$

Where $\dot{m}$ is the mass flow rate in kg/s whose value is obtained from the flowmeter FT01 shown in Fig. 4. c_p is the heat capacity of the HTF at constant pressure in J/kgK and ΔT is the temperature difference between the hot and cold sides of the PVT collector field in K. Note that, the value of c_p of propylene glycol, which is the heat transfer fluid, is estimated using the weighted average method as given below in Eq. (3) considering 65% water and 35% propylene glycol.

$$\bar{x} = \frac{sum\,of\ weighted\ observations}{sum\,of\ weights} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

Here, $\bar{x}$ is the value of the system fluid parameter. w_i represents the weights in percentage of the mixing quantities and x_i represents the typical value of the observed parameters of the mixing quantities. n is the number of observations. Table 2 shows the parametric values of the mixing fluids (water and glycol) used for estimating the properties of system fluid.

Based on Eq. (3) and the quantities in Table 2, the c_p and ρ of the system fluid are found to be 3490.9 J/kgK and 1038.5 kg/m^3.

Table 2
Quantities used for the estimation of system fluid parameters.

	Propylene glycol	Water
Mix percentage (w_i)	35%	65%
Specific heat, c_p [J/kg K] (x_i)	2200	4186
Density, ρ at 25 °C [kg/m^3] (x_i)	1110	1000

The field data post-installation from the farm has been collected, and analysis is done on a regular basis. Note that the system was warming up during the month of April and was undergoing several trial runs before the actual data could be retrieved. Hence, the data made available from the month of May onward are considered reliable.

Fig. 5(a) shows the amount of thermal energy available for storage in BTES every day during the month of May. The irradiance values integrated over time (insolation) for each day are also shown in the figure. As evident, there were days when the daily thermal energy production was high (day 22) and negligible (days 10–11). Some days could be observed to be more cloudy, especially on 19 May, indicating lower energy production. It is also apparent that the thermal energy produced was higher during the last few days, specifically between 20 May and 31 May, which is due to the availability of a higher amount of insolation. The thermal energy data exhibits a clear correlation with the corresponding insolation data. This indicates that high thermal energy corresponds to high insolation, and conversely, low thermal energy output corresponds to low insolation. However, for the month of June, the thermal energy production was nearly consistent, except for some days (5 and 10 June). As illustrated in Fig. 5(b), unlike May, thermal energy production was considerably high for the month of June, specifically during the second half between June 15 and 27. Here

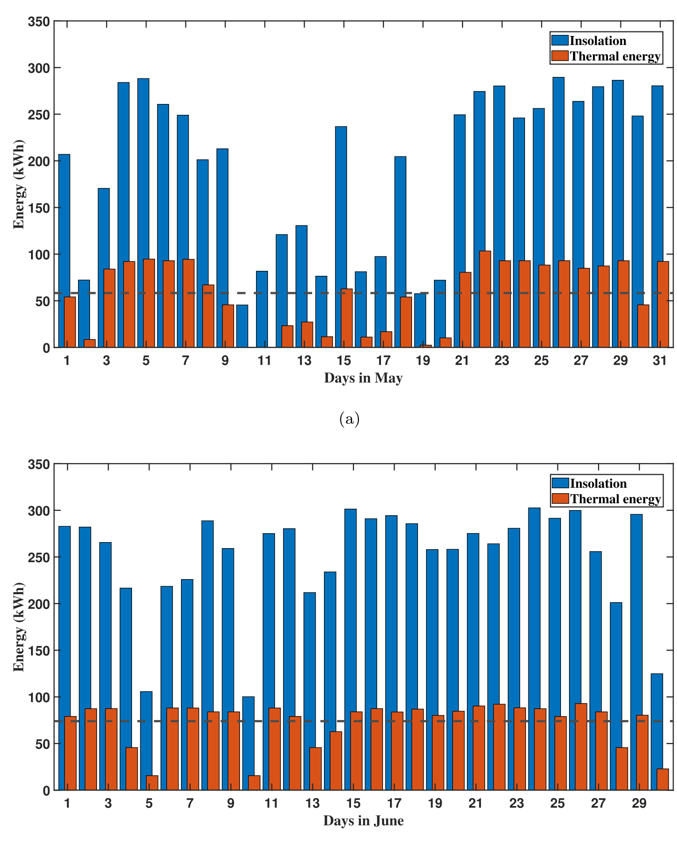


Fig. 5. Thermal energy production and insolation during (a) May and (b) June. *(Thick dashed lines correspond to the average thermal energy production in each month.)*

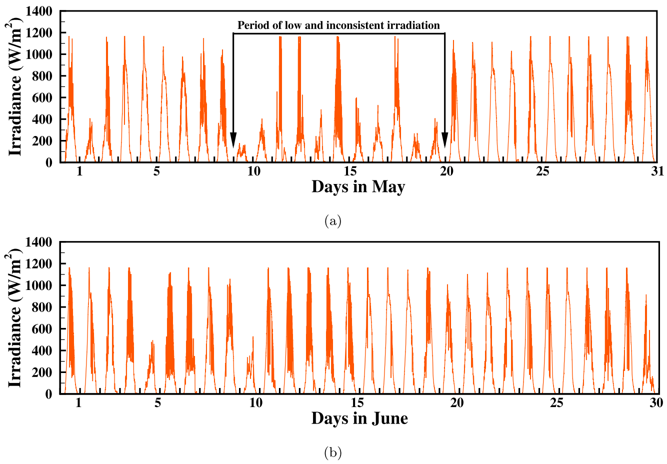


Fig. 6. Irradiance levels during the month of (a) May and (b) June.

as well, the thermal energy levels for each day are proportional to the amount of insolation. It could also be seen that the average thermal energy produced during June was nearly 28% higher as compared to the preceding month. This could be attributed to the higher amount of consistent irradiation levels during the month of June. Also, the estimated average energy production value during May was approximately half of the maximum value recorded in the same month (on May 21), which also reflects the inconsistency in irradiation levels.

Figs. 6(a) and 6(b) show the insolation data available from the pyranometer (sensor YT01) on the farm, respectively, for May and June. It is obvious that the irradiance values were substantially higher during the first and last weeks of May. However, between 10 May and 20 May, the insolation was observed to be low and highly varying. For example, on 10 May, the irradiation was less than the threshold, and due to this, the pump did not operate. This is the reason why the thermal energy production was negligible that day. Similarly, on the next day (11 May), although the irradiance value crossed 200 W/m^2, it was not consistent enough for the pump to start operating. It is obvious that there was a period of low and inconsistent irradiation levels between 10 and 20 May that resulted in below-average system performance (Fig. 6(a)). It should also be noted that, as illustrated in Fig. 6(b), the available solar energy was high during the same period in June. Also, the low amount of insolation on 5 and 10 June clearly substantiates the comparatively lower thermal energy production, as shown in Fig. 5(b). All these observations clearly indicate that the system performance is continuously driven by the availability of solar irradiation.

Having said that thermal energy production is vastly influenced by the amount of solar radiation, we found it necessary to explore the field data between 10 and 20 of May and June to understand the prime factors affecting thermal energy production. The main reason for the selection of this period was that it was during these days in May that the recorded irradiation levels were low and varying, as shown in Fig. 6(a). Figs. 7(a) and 7(b) show the representative data from various sensors for May and June during the period 11–20. The data from temperature sensors TT15, TT03, and TT02 have been included in the analysis. The difference between TT02 and TT03 has been estimated together with the thermal power (kW) and shown in the figure. It could be seen that the thermal power curves were significantly driven by the corresponding values of the PVT collector outlet temperature (TT02). The ambient temperature (T_a) was also another influencing factor, as both curves followed similar variation trends. It is imperative that these sensor readings be greatly influenced by the insolation. Interestingly, the corresponding field data analysis for the same period in June clearly

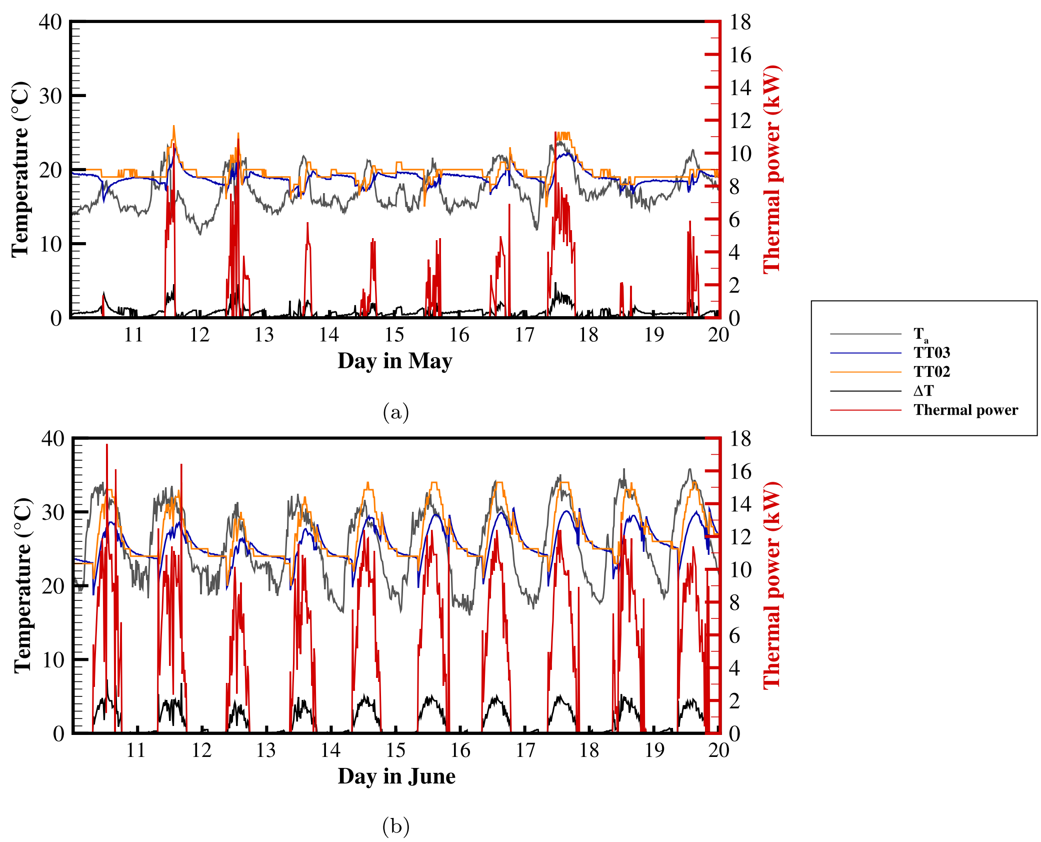


Fig. 7. Temperature sensor data and thermal power for 10 days during (a) May 11–20 and (b) June 11–20. *(In the legend; T_a: ambient temperature, TT03: collector inlet temperature, TT02: collector outlet temperature, ΔT: TT02-TT03).*

indicated higher thermal power availability. As seen in Fig. 7(b), the thermal power values are considerably higher than in May which is complemented by the higher levels of collector outlet temperature (TT02). A one-to-one comparison with the corresponding data from May also shows the impact of TT02 sensor values on thermal power output.

From the data made available from the farm, the total heat energy produced by the PVT system during the month of May was estimated to be 1807 kWh and for June it was 2220 kWh. The comparatively lower energy production during May was due to the low amount of insolation. The field data also showed that the energy production reached its peak during the midday hours, typically between 11:00 h and 15:00 h when the irradiance was highest. Note that during summer the days are longer and hence the thermal energy production on sunny days continued until around 20:00 h.

3.1.2. Electricity production analysis

The electrical production of the PVT field offsets the power consumption that the farm conventionally gets from the grid. This production could be supplied to the heat pump or any other electricity consumption point at the farm.

Given the Italian local regulations, the electricity metering was not able to be commissioned at the same time as the thermal part of the PVT system. Hence, the electrical production of the PV array was estimated through simulations developed in TRNSYS [35], which is a well-known component-based software that allows the modeling of dynamic systems such as solar thermal collectors, photovoltaic arrays, as well as HVAC systems (Fig. 8). These simulations considered all the electrical and thermal performance parameters given by the manufacturer (Table 3). EPW weather files for Mirandola (Italy) were used to run the simulations with a time step of 5 min. For the months under study, the electrical production of the PV system was estimated to be 0.86 MWh and 1.11 MWh for May and June, respectively.

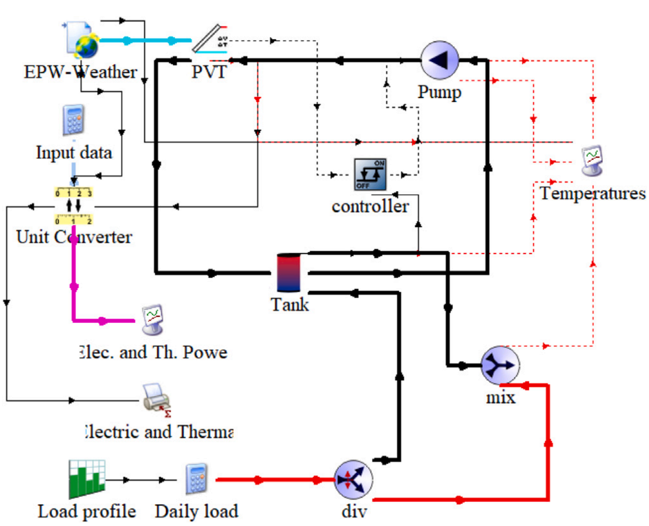


Fig. 8. PVT system setup at TRNSYS simulation environment.

Table 3
Electrical characteristics of the PV module.

Parameter	Value	Unit
Max power voltage (V_{mp})	33.2	V
Max power current (I_{mp})	9.64	A
Open circuit voltage (V_{oc})	40.9	V
Short circuit current (I_{sc})	10.15	A
Module efficiency rate	19.55	%
Module aperture area (A)	1.64	m^2

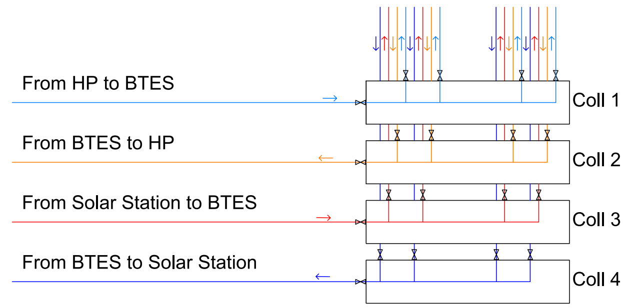


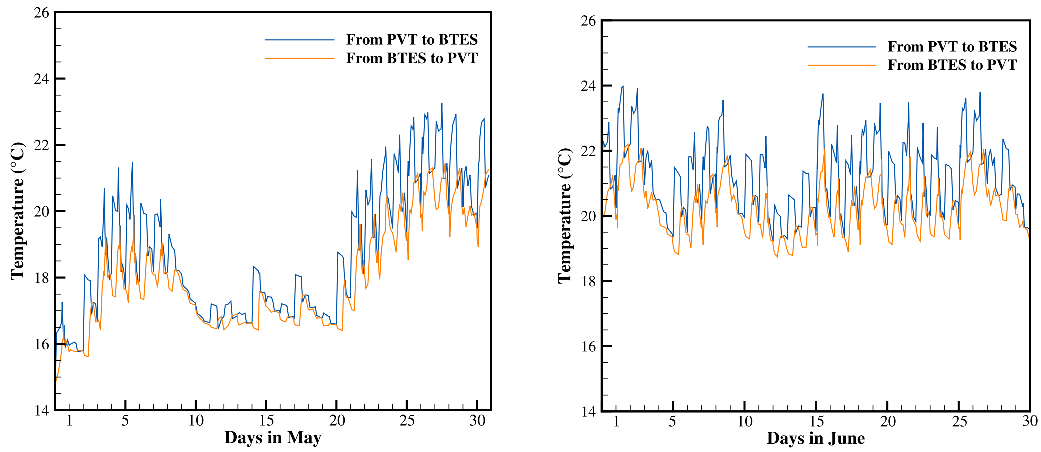
Fig. 9. Collectors' scheme.

3.2. Analysis of borehole thermal energy storage (BTES) system

Within the BTES system, two moistures of water-propylene glycol (concentration of 35%) circulate, one storing the PVT heat in the aquifer (mainly in summer) and the second extracting the thermal energy needed for the work of the HP (mainly in winter) (Fig. 9). A temperature control system in the solar station allows keeping the maximum working temperature of BTES lower than 35 °C, a limit imposed by the environmental regional authority for the protection of the aquifer. Regarding the minimum temperature, the addition of glycol allows us to overcome 0 °C, without the risk of freezing. However, for the sake of HP performance, it is expected not to go below 5 °C. In fact, the BTES is designed in a way to inject energy first in the central BHEs, the thermal core (TC), increasing the chance of heat storage, while heat is recovered first from the lateral BHEs, thus enhancing the ΔT between inlet and outlet of the HP and consequently the coefficient of performance (COP).

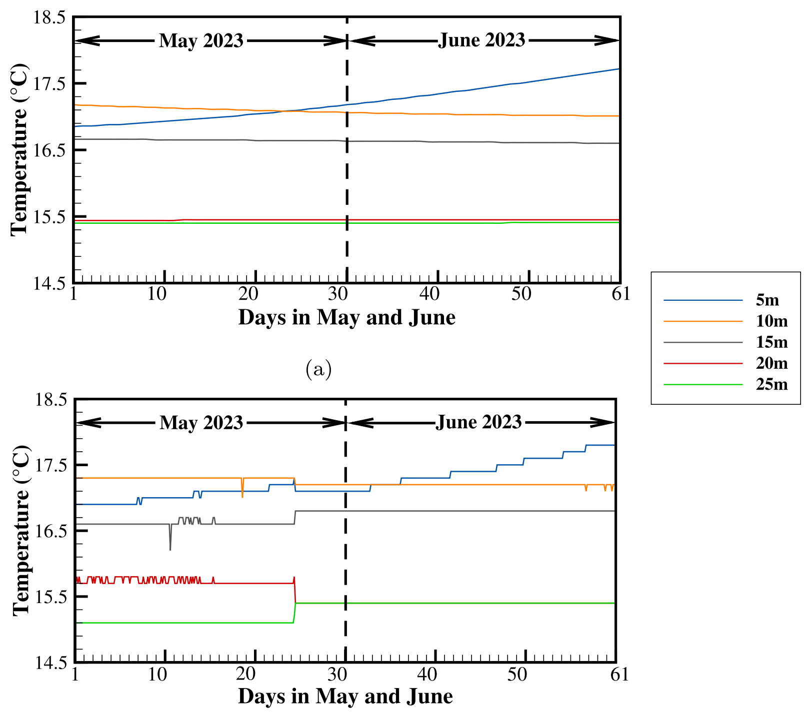
The PVT system started full operation in May 2023. At the time of the present work, it was possible to extract the energy values of the first two months of operation, May and June 2023, with subsequent heat injection in the BTES. These data were used to feed the numerical model of the BTES system, realized with *FEFLOW*® software at the design phase, and to check the quality and coherency of the modeling and the entire work. The measured energy data inserted into the model also consider periods of system inactivity (basically, during the night and when the temperature exceeds the imposed limit of 35 °C). Fig. 10 shows the temperature curves of the entire BHE array in injection mode. Based on the results of numerical simulations, it is evident that the aquifer can handle much more solar thermal energy than what was stored in the reference period. The maximum simulated ΔT between the inlet and outlet was 3 °C, due to the low amount of injected energy during that period. However, the maximum temperature value was more than 10 °C below the imposed limit of 35 °C. Therefore, as a rough estimate, the aquifer should be able to handle double the amount of solar thermal energy injected during the reference period. The PVT system implemented in GOLI is a pilot installation, and with the increase in energy demand, the aim is to expand the size of the PVT system by adding more collectors in the future. With evidence that the BTES system can handle additional heat, the expansion is expected to be a seamless process.

On the other hand, the measurements in the monitoring points for the two investigated months have confirmed that the whole heat was kept inside the BTES boundaries without dissipation due to groundwater flow. As an example, Fig. 11 presents, for the piezometer located 6 m below the BTES, the comparison between the theoretical natural standard behavior of the aquifer temperature and the effective measured values. It is worth noting that the temperature of the aquifer, at shallow depths, is affected by the presence of the farm structure itself (pig barn and farmyard), whose temperature increases during the study period following the climatic trend, independently of BTES [36].



(a) (b)

Fig. 10. Results of numerical simulation for the two initial months of operation.



(a)

(b)

Fig. 11. Comparison between (a) calculated standard aquifer temperature behavior and (b) measurements at various depths for the two months of investigation, in the piezometer located 6 meters downwards the BTES.

3.3. CO_2 *Emission savings analysis*

This section discusses the CO_2 emissions saved as a result of the installed RE system. Since the analysis is carried out only for two months (May and June) after installation and the energy consumption data from the farm are not available for these months, the following assumptions are considered for the estimation of savings in CO_2 emissions.

1. The thermal and electrical energy produced by the installed RE system is consumed completely.
2. The energy produced by the installed RE system is equivalent to the energy consumed by burning the LPG before replacing the latter.

Based on Eq. (1), the amount of CO_2 emissions from fuel combustion are computed and tabulated in Table 4. As mentioned in Section 2.1, the estimated energy demand based on the energy bills was 90 MWh.

Table 4
Emission savings in kg of CO_2.

	May	June
EF for heat generation (tCO_2/TJ) [37]	64.35	
Thermal energy produced (kWh)	1807	2220
Equivalent CO_2 emissions saved (kg)	418.6	514.3
EF for electricity generation (tCO_2/TJ) [38]	74.4	
Electrical energy produced (kWh)	860	1110
Equivalent CO_2 emissions saved (kg)	230.3	297.3

For this annual energy demand, the CO_2 emissions saved by replacing LPG is estimated to be 20,850 kg CO_2/year.

4. Conclusions

A PVT system comprising 24 collectors was installed in the nursery barn of the Golinelli swine farm (GOLI) in Italy, a pilot farm of the EU Horizon 2020-funded project, RES4LIVE. The standardization measures taken in the project led to the implementation of a modular and standardized solar central (SC) for photovoltaic thermal (PVT) systems not only in agricultural sectors but also suitable for other similar applications as well. The commissioning took place in the 2^{nd} week of April 2023 and the system is functioning satisfactorily and is being constantly monitored. Our inferences based on the real-time monitoring of the field variables are summarized below.

1. During the 2-month continuous monitoring of the system operations, the standardized solar central was found to be efficient in regulating the control parameters to maximize the system performance.
2. Analysis of heat production revealed that the thermal energy available for storage during May was lower than that of June, which could be attributed to the reduced amount of insolation.
3. The analysis also showed that from 10 to 20 May there was a period of low and irregular irradiation that had a major impact on thermal energy production during that month.
4. The levels of ambient temperature (T_a) also influenced the storage of thermal energy since T_a could directly affect the temperature of the soil, thus shaping the performance of BTES.
5. In addition to the heat demands, the installed RE system could partially meet the electrical energy needs of the farm.
6. The BTES installed capacity is ready for a further expansion of the PVT system, up to approximately 50 kW_{th}.
7. The project led to replacing fossil fuel-based energy consumption for the nursery barn with RES and additional efficiency enhancement measures, thus reducing 20,850 kg CO_2/year.

The whole system is being continuously monitored and it will be interesting to know how much heat energy could be stored in the coming months to be extracted during winter. Livestock being a contributor to GHG emissions and PVT still a nascent technology on the market for these applications, this project deserves further significance in the path towards climate-neutral energy production.

Declaration of competing interest

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

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