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An Integrated Renewable Energy Plant with Smart Monitoring System for Sustainable Farming

Stefano Benni
Department of Agricultural and Food Sciences
University of Bologna
40127 Bologna, Italy
stefano.benni@unibo.it

Francesco Tinti
Department of Civil, Chemical, Environmental and Materials Engineering
University of Bologna
40131 Bologna, Italy
francesco.tinti@unibo.it

Marco Bovo
Department of Agricultural and Food Sciences
University of Bologna
40127 Bologna, Italy
marco.bovo@unibo.it

Alberto Barbaresi
Department of Agricultural and Food Sciences
University of Bologna
40127 Bologna, Italy
alberto.barbaresi@unibo.it

Daniele Torreggiani
Department of Agricultural and Food Sciences
University of Bologna
40127 Bologna, Italy
daniele.torreggiani@unibo.it

Patrizia Tassinari
Department of Agricultural and Food Sciences
University of Bologna
40127 Bologna, Italy
patrizia.tassinari@unibo.it

Abstract— **Livestock farming is a highly energy-consuming sector within agriculture, currently causing significant GHG emissions. The necessity of replacing fossil fuels with Renewable Energy Sources (RES) is leading the scientific community toward the research of retrofitting strategies for existing farms, aimed to develop new equipment based on RES for the various farming activities. This study is focused on the development of sustainable heating systems for livestock barns, suitable to be adopted to replace fossil-based existing ones. The research is carried out with reference to a pilot case represented by a swine farm located in northern Italy, rearing 500 sows and 2500 weaners. The study takes into consideration a nursery barn and consists in the design and test of an integrated RES system combining a photovoltaic-thermal plant, a geothermal heat storage, and a modular heat pump. A smart control system was developed and installed to monitor energy uses and environmental conditions. The results demonstrate that a mix of RES can be properly defined for a given livestock farm, specifically designed to exploit the renewable resources typically available in farming environments. Specific smart monitoring systems have been developed and installed for automated data collection and remote control.**

Keywords—pig barn, geothermal storage, PVT, zero-carbon, sustainability

I. INTRODUCTION

Due to the pressure on the livestock farming sector to meet the increasing demand from a growing population with rising incomes, as well as the need to lessen the strain on resources and the environmental impact while preserving animal welfare, sustainability in animal-derived products is a relevant and challenging goal. Climate change is also a challenge for the dairy industry and will become more critical to solve in order to ensure its long-term economic, environmental, and social sustainability. For these reasons, it is necessary that livestock farming contributes to the mitigation of climate change by adopting energy-efficient solutions in every phase of the production process, including the proper operativity of farm buildings, which represent highly energy-demanding facilities. At the same time, the objective of assuring proper animal health and welfare inside livestock buildings is increasingly considered and vigorously pursued. This leads to coping with the current condition of climate change, causing increase in peak temperatures and in the frequency and duration of heat waves, thus calling for the implementation of highly effective systems for heating, cooling and ventilation. The combination of the requirements of sustainability and animal welfare results in the goal of developing renewable energy systems capable of meeting the demands of farm buildings, in terms of quantity and timing of the availability of renewable energy. Moreover, smart monitoring and actuation systems are necessary to optimally control the renewable energy production in relation to the real time demand and to activate the heating, cooling and ventilation systems on the basis of the environmental parameters monitored and the respected target values defined for animal welfare.

In fact, one of the most energy-consuming sectors of agriculture is intensive livestock, where both electricity and thermal energy are required to cover strongly diversified energy demands [1], such as cooling-heating of the indoor livestock buildings environment [2], powering equipment, lighting, and ventilation systems. Energy needs in livestock farming have been mainly met so far through fossil fuel, but it has negative effects as a major source of greenhouse gas (GHG) emissions, with significant contributions to global climate change. With declining costs and improvement of reliability and performance of key renewable energy sources (RES) technologies, the opportunities for farmers to engage in RES production in EU are increasing, also due to the geopolitical need to increase the independency from external energy sources and minimize the importation of fossil fuels.

In this context, the innovation project RES4LIVE "Energy Smart Livestock Farming towards Zero Fossil Fuel Consumption", running in the period 2020-2024 under the call "Defossilising agriculture – solutions and pathways for fossil-energy-free farming" of the European program Horizon 2020, aims to develop integrated, cost-effective and case-sensitive RES solutions towards achieving fossil-free livestock farming. The project adapts and tests promising RES technologies in energy-intensive livestock farming to greatly reduce the fossil energy that is the main source used so far to cover the energy demand.

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This study aims to define the design and technological solutions of a sustainable heating system for a nursery barn of an intensive swine farm, suitable to replace the fossil-based existing plant. The research was carried out with reference to a real study case where the solutions developed have been implemented.

II. Materials and Methods

Dedicated, optimal designs combined with energy efficiency and other solutions are proposed, demonstrated in pilot farms, as fundamental phases of RES4LIVE.

A. *Design of the pilot system*

The pilot case presented in this research is a swine farm located in Modena province (northern Italy), rearing 500 sows and 2500 weaners (Fig. 1).

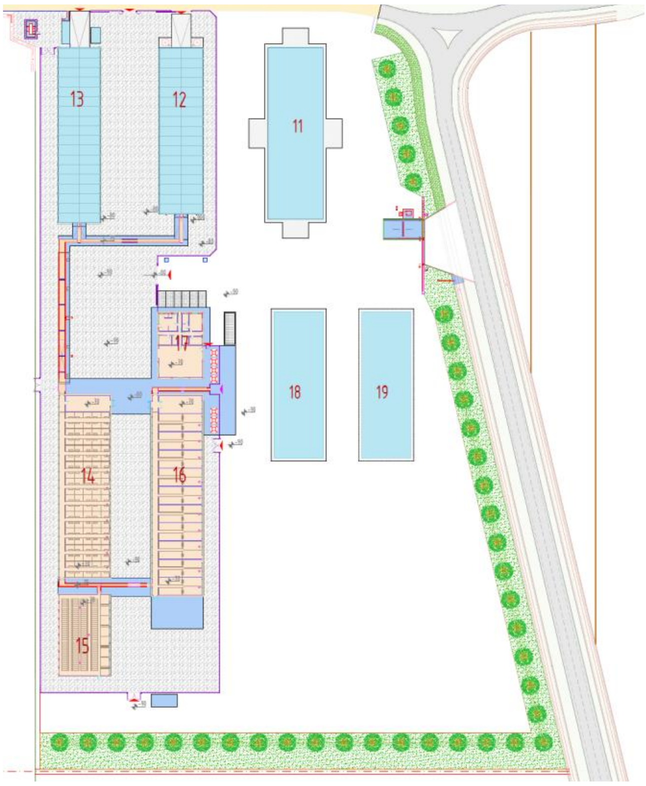

Fig. 1. Plan layout of the pilot farm. The nursery barn is indicated as nr 16.

The de-fossilization project focuses on the nursery barn of the farm (building nr 16 in Fig. 1; represented in detail in Fig. 2, Fig. 3, and Fig. 4): in this building, we carried out the development and design of an integrated RES system combining a photovoltaic-thermal plant, a geothermal heat storage [3], and a modular heat pump.

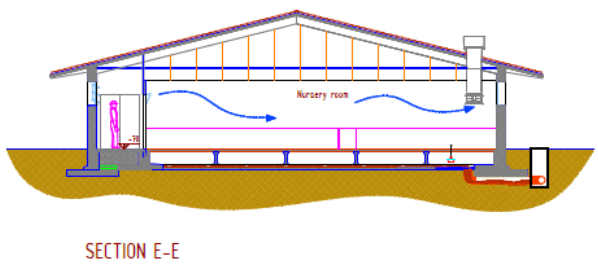

Fig. 2. Cross section of the nursery barn. The hallway along the wstern side allows to access the nursery rooms and also represents a zone for pre-treatment of the clean air conveyed inside the nursery rooms.

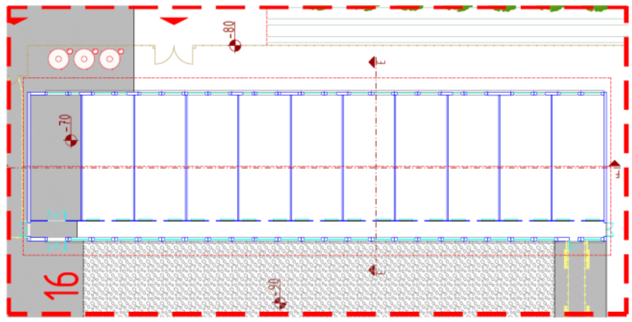

Fig. 3. Cross section of the nursery barn. The equipment is located in the technical room, the first on the left.

The RES system was design to replace a 34 kW LPG boiler used to pre-heat the air in the hallway of the building, so that the inlet airflows into the nursery room, driven by extraction fans, have adequate temperature during the cold season. Specifically, the integrated system is composed by photovoltaic thermal collectors (PVT), a dual source heat pump (DSHP) and a borehole thermal energy storage (BTES) [4].

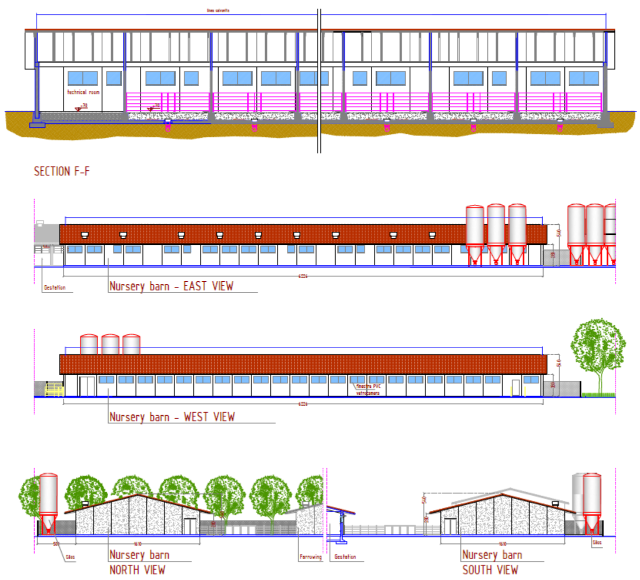

Fig. 4. Longitudinal section and front views of the nursery barn.

B. *Geology and hydrogeology*

An in-depth analysis of the geological and hydrogeological characteristics of the site was carried out to obtain the parameters needed for the design of the borehole thermal energy storage. The case study is located in the Po Plain, where alluvial sediments can reach 150 m and more. Up to that depth, no salt intrusion is expected, since the limit of marine deposits is set around 300 m of depth. Table 1 reports the stratigraphy with indicative values of ground thermal diffusivity.

Confined aquifer can be found around 10 m; however, drilling down to the aquitard and the top of the confined aquifer, the groundwater level reaches from 1 m to 3 m depth, due to capillary action and varying with seasonality. Groundwater movement is very low, due to low pressure drop over large distances; while hydraulic conductivity reaches 10^{-4} m/s, and porosity is between 30% and 40%. In such conditions, it is expected a high specific heat storage.

TABLE I. STRATIGRAPHY OF THE STUDY CASE

Depth	Stratigraphy	Thermal diffusivity
0-10 m	Silt and clay	0.03 m^2/d
10-12 m	Sandy humps and clayey sands (aquitard)	0.07 m^2/d
12-50 m	Sand (aquifer, confined)	0.10 m^2/d
≈ 50 m	Clay and clayey sands	0.03 m^2/d
50-80 m	Sand (aquifer, confined)	0.10 m^2/d
80-100 m	Clay and clayey sands	0.03 m^2/d
> 100 m	Sand (aquifer, confined)	0.10 m^2/d

C. Smart monitoring system for boreholes

The effectiveness of the geothermal heat storage is under assessment by measuring and recording soil and aquifer temperatures at different depths in three drillings available near the BTES. In particular, a smart monitoring system composed by chains of thermometers measuring along the hole depth at 1 m distance has been implemented, on the basis of the system developed in [5] and [6]. The Smart Monitoring System (SMS) integrates specifically designed sensor networks in a customized system architecture. It has been designed for the acquisition, storage, Wi-Fi transmission and management of large datasets of physical and environmental features to be collected in farms, enabling a diagnosis of the operating conditions, and early alerts in case of anomalies. The system has been developed to work in several environmental situations, including underground and submerged conditions, and is able to make the data remotely available in real time in a cloud. The system is thought to be composed by a central unit (gateway), connected to the internet and to the power grid. The central unit communicates wirelessly with nodes that can be connected to the grid or operating with a battery. In this configuration, the SMS can handle all the data locally; for the data transmission, the gateway sends data to a remote server and then to a cloud using the internet, in order to make them available remotely and in real time [7]. The monitoring system is made by three main hardware: "nodes", "gateway" and "server", nodes and gateway are placed in the monitored facilities, the server is placed in the University of Bologna DISTAL Lab (Italy). In addition, the server copies data on a cloud service to improve data availability and as a backup copy. Nodes are locally and wirelessly connected to the gateway that collects data and send them to the server via the internet. The system has been recording data since December 2022.

The hardware device called "node" is able to acquire one or more physical quantities of interest via on-board sensors or commercial sensors. The node in fact is designed to have the possibility of interfacing with the most widespread commercial sensors. The node is made by an electronic board provided with a small processing and storage capacity. The board manages the power supply of the entire node and sensors, battery charging and energy harvesting from photovoltaic solar panels. It is provided with wireless transmission capacity to the gateway.

The gateway is a device connected to the internet and manages the reception of data transmitted by the nodes and forwards data to the remote server. The gateway has no storage capacity but only acts as a bridge between the wireless local area network used by the nodes and the cloud server. Due to its characteristics, the gateway must be connected to the power grid. The server is a machine accessible via the internet where information from the nodes is saved, then make them accessible via the web interface. It allows to consult charts, control dashboards and download data to allowed users.

An electronic device is created able to acquire information relating to different physical quantities via sensors. Based on the specific size related to the particular application context, the appropriate sensor is chosen among custom or commercial solutions. For this reason, the node will be equipped with the most widespread communications interfaces for sensors, such as serial UART, I2C, SPI, Modbus on RS485, analog interfaces in 4-20mA current and in 0-10V voltage. The basic operation of the node concerns the acquisition of the information detected by the sensors, the execution of small elaborations on board, the transmission of the detected data to the gateway of the structure. After installation, a trial period for calibration and validation of measurements was planned.

Low power radio technology was chosen on the ISM band with LoRa modulation. In addition, to maintain excellent scalability and flexibility in distribution, the implementation of the top-level communication protocol, LoRaWAN, based on this technology was chosen. This technology is open and demonstrates very low energy consumption compared to GSM or WiFi technologies, finally allowing battery operation for long periods. The LoRaWAN network topology is based on a "star" structure, which means that each node communicates solely and directly with the gateway. Each transmission received is forwarded by the gateway to a server in the cloud, which takes care of decoding information and saving it permanently and securely. In this configuration the gateway does not keep the information received in memory but transmits it directly to the server via the Internet. To allow proper operation, the gateway must be in a suitable position to optimize the reception of transmissions and must be powered by the grid.

D. Smart monitoring system for buildings, energy and control

A further smart monitoring and control system was developed and installed by Plegma, partner in RES4LIVE, to monitor outdoor and indoor environmental variables and automate the integrated RES plant. Data have been collected since May 2021.

The system consists in a gateway collecting every data; a weather station powered via PV, communicating via Wi-Fi and three nodes with basic monitoring of gases and environmental conditions: one for the corridor of the nursery barn, one for a nursery room and one node with detailed monitoring sensors for another nursery room. The RES4LIVE gateway utilizes various communication protocols and enables security features for its communication with the IoT platform that offers the data to the users. The gateway module is a Raspberry pi 4 model B as its main unit, enforced with 4gb (GigaBytes) of RAM (Random Access Memory), an M.2. SSD (Solid State Drive) with 128gb of storage and minimum 32gb microSD for initialization and configuration purposes on first boot. The gateway hardware that was selected is lightweight, cost-effective and is utilizing as its base on the Raspberry Pi platform that has adequate processing power and memory to meet the arisen requirements and perform all the needed actions. The nodes and the gateway are powered by AC 230V and are linked with ethernet cables.

The PVT system is controlled through RESOL VBus, a communication protocol that allows different devices to connect and exchange data with each other and with a central controller. The VBus system consists of a number of different components, including thermostats, sensors, actuators, and controllers. The VBus protocol is based on the RS-485 standard, which is a widely used communication protocol for connecting devices in a network. It allows for the transmission of data over long distances and is resistant to noise and interference. The VBus protocol is used to transmit data between different devices in a building, such as between a thermostat and a heating system, or between a solar panel and a heat pump. The control system has been working since May 2023.

One of the main benefits of the VBus system is that it allows for the centralized control and monitoring of multiple systems within a building. This can help to optimize energy usage and improve the efficiency of the systems, as well as providing greater control and convenience for the building owner or operator. The VBus system can also be used to monitor and control other systems within a building, such as lighting and security.

III. Results and Discussion

The results of the design and implementation phases of the RES system are reported as follows.

A. *Implementation of the geothermal heat storage*

In the investigation phase, two piezometers 2” wide, 25 m deep and distant each other 40 m, were installed, in a line over direction North-South. Between the two piezometers, two PE100 PN16 DN32 Borehole Heat Exchangers (BHE) were installed, the first one 10 m deep (crossing the first layer of clay with sandy lens), while the second one 30 m deep (crossing the second layer of fine sand, hosting the shallow aquifer). Two Thermal Response Tests (TRT) were performed, one per each BHE, while temperature and hydraulic head values were taken in the observation boreholes, by using both fixed recording sensors and movable measurements tools.

The TRTs carried out showed how the operation of the BHE at 10 m depth is excessively influenced by the climatic conditions in order to guarantee the stability of the long-term thermal storage. The hydrogeological conditions of the aquifer present in the sand deposit seem to guarantee a limited flow and a substantial groundwater stability, therefore proficient long-term solar heat storage should be performed by means of a deeper BTES. In order to enhance the performance of the solar storage, all year long, it was decided to keep the "solar" source (the thermal storage circuit) separate from the "geothermal" source (the heat exploitation circuit). For this reason, each "Double U" probe has been divided in two separate single U circuits, one fully dedicated to heat storage, and the second fully dedicated to heat exploitation.

B. *Borehole Thermal Energy Storage dimensioning*

The data gathered and the results of the tests have been used to select the most suitable working depth for the BTES field, to quantify the potential for underground thermal storage, to understand the heat dispersion due to groundwater movement and to model the BTES behavior under various operation scenarios. The results led to adopt 30 m BHE as the most efficient solution. Based on the dimensioning of the integrated system, 8 BHEs proved suitable for the energy storage and thus they were drilled to make the BTES (Table II).

In order to obtain a Thermal Core (TC) at the center of the system, suitable for thermal storage, in BTES practice it is preferable to create hybrid connections in series/parallel among the BHEs. Connecting the BHEs in series and injecting heat from the TC of the field to the boundaries, leads to a higher temperature rise, in comparison to other configurations. During the exploitation phase, the direction is reversed, first extracting heat from the boundary and then from the TC. The BTES field, capable of supplying the required thermal loads of the weaners’ nursery building, is made up of 4x2 BHEs 30 m deep, in a rectangular configuration, spaced 3 m in N-S direction and 2 m in E-W, in order to optimize the land available in the farmyard.

C. *Integration of BTES, DSHP and PVT*

The DSHP is able to exploit energy from only ground, only air, or combined, according to two temperature thresholds set up by the operator. Based on the technical features of the DSHP, developed and installed by Psyctotherm, partner of RES4LIVE, the expected performances of the system were obtained, as reported in Table III.

TABLE II. MAIN DESIGN PARAMETERS OF THE GEOTHERMAL STOTORAGE

Energy to be stored April - September	22 MWh
Borehole Capacity	0.37 kWh/ (m^3 K)
Estimated Raise in the Storage	11 K
Total BTES Pressure Drop 8 holes – 2 holes in series	12 kPa
Injection Power Needed per 30 m Hole	1.5 kW

The circulation of the vector fluid (water and propylene glycol, in percentages not higher than 35%) between the BTES and the DSHP is automated by the smart control system of the heat pump, developed by Plegma, as well as the circulation of the heating fluid within the livestock barn. The controller allows to select the most convenient temperature thresholds to switch from one source to the other, thus optimizing the system operation.

TABLE III. EXPECTED PERFORMANCE OF DSHP, AT VARIOUS TEMPERATURE LEVELS

DSHP	**Heat Source temperature (°C)**		**COP**
	Water	**Air**	
Only Heat Pump	-	1	2.5
	0	6	2.8
	5	11	3.0
	10	16	3.4
Heat Pump + Geothermal Storage	15	(21)	3.9
	20	(26)	4.5
	25	(31)	5.0

The circulation of the vector fluid (water and propylene glycol) among PVT and BTES is controlled through RESOL VBus by a solar station developed and installed by MG Sustainable Engineering, partner in RES4LIVE (Fig. 5). The control by RESOL VBus allows to keep the temperature of the injection fluid in the BTES below 35°C, the limit imposed by the regional environmental authority for aquifer protection.

The plant started operating 1st of June 2023. During summer months, solar heat is injected in the BTES, while during winter months, it is subsequently extracted to heat the barn. Monitoring is active all year long to measure and register the system effective operation, which is necessary to verify the correctness of the design assumptions.

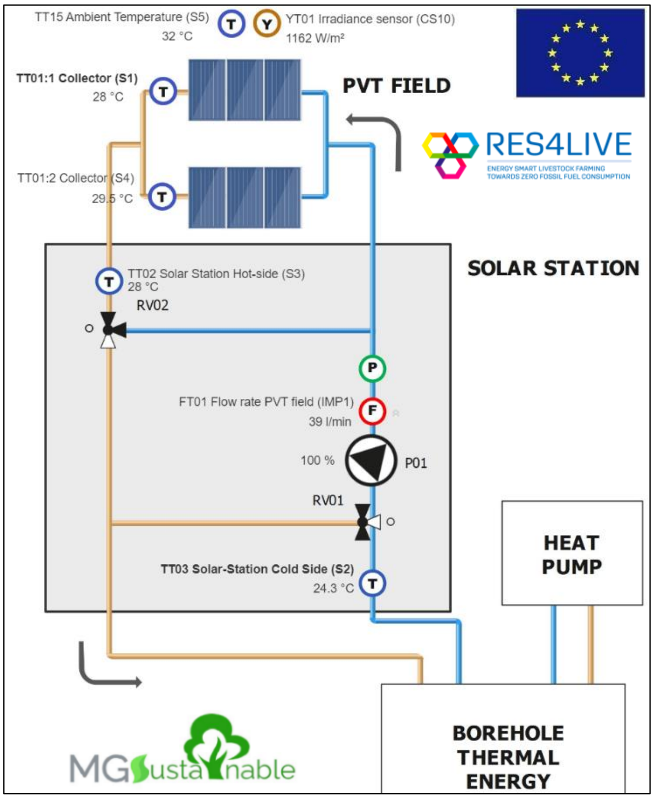

Fig. 5. Visual interface of the remote control and monitoring system of energy flows between the solar station and the geothermal heat storage

D. Adaptability and potential replications

The system developed in this project is suitable for the replication in locations with similar characteristics in terms of space available and energy demand. In fact, livestock farms and in particular those rearing pigs, hens, broilers or rabbit show similar configurations in terms of building shapes and dispositions and have in common the requirement of thermal energy continuously during the cold seasons. This implies that these facilities can significantly benefit from a thermal energy storage and, at the same time, the farmyards are suitable for drilling the boreholes and the roofs of the barns can host PVT panels. Moreover, it is worth mentioning that the DSHP operation can be reversed, thus providing cooling, which in many climatic contexts can improve animal welfare.

As for the electronic components, the smart monitoring system described above, can be set up in any farm, just replicating the hardware architecture with the necessary adaptation to specific cases. Of course, the data management platform implemented within the project is already in condition to be adopted for applications in different farms. While PVT system and heat pump should be designed based on the energy demand of the livestock barn and the climatic conditions of the site, the BTES dimensioning requires also the knowledge of the hydrogeologic conditions. This makes unique this part of the integrated plant, as it has to be designed depending on the local underground stratigraphy.

A specific procedure involving surveys, computations, TRT and numerical simulations has thus to be implemented, similarly to the pilot case illustrated above, to properly design the BTES. For this aspect, the replicability of the solution will be assured by means of guidelines specifically devoted to BTES design and installation. The preparation of this document is planned to be carried out in the next phases of the research project.

IV. Conclusions

The results underline that the underground areas of farmyards can be effectively exploited to install BTES, to store excessive heat produced by RES system, such as solar panels, PVT or CHP plants fed by biogas. These applications prove particularly appropriate in livestock farms, which are characterized by a great availability of rooftop areas, suitable for the installation of solar panels, and large outdoor paved areas. The results demonstrate that a mix of RES can be properly defined for a given livestock farm, specifically designed to exploit the renewable resources typically available in farming environments.

A step-by-step procedure was developed and tested to characterize the underground for thermal storage purposes and define the optimal design of the BTES. The study carried out and the pilot application realized showed that the definition of an effective solution requires the collection of in-depth information about the geological and hydrogeological conditions of the site, the physical properties of the ground, as well as the monitoring of the temperatures of the various components of the integrated plant, including the vector fluid of the BTES and the TC. Moreover, environmental parameters outdoor and inside the livestock buildings should be monitored and recorded to control the activation of the equipment and to assess the effectiveness of the system.

Data about energy usages are also subject to a specific analysis to assess the efficiency of the new heating solution. For all these purposes, smart monitoring systems have been developed and installed for automated data collection and remote control. The databases created and currently fed by the systems will be the objects of specific data processing, which will be set up as a development of the research.

Acknowledgments

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