Performance Analysis of a PVT-BTES-DSHP System with Nocturnal Aerothermal Collection in Agricultural Applications

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Abstract

This study presents the annual performance assessment of a hybrid photovoltaic–thermal (PVT) field coupled with Borehole Thermal Energy Storage (BTES) and a Dual Source Heat Pump (DSHP) operating in an agricultural swine nursery barn under the RES4LIVE project. The objective was to evaluate the effect of extending system operation into nighttime hours through a nocturnal aerothermal charging mode and to compare its performance against a baseline daytime-only configuration. Results show that from 1st April to 31st August 2024, the integrated system achieved a total heat storage of **12,154 kWh**, composed of **11,649 kWh** from daytime solar operation and **505 kWh** from nocturnal aerothermal recovery. Nighttime operation contributed an average of **4.16% of the total thermal storage**, with peak monthly improvements exceeding **8%** in July under favorable summer conditions. The additional operation did not introduce significant thermal drift in the BTES and enhanced overall solar field utilization through extended operating hours and reduced collector stagnation. The findings confirm the **feasibility and energetic advantage** of nocturnal aerothermal collection as a complementary charging strategy for hybrid solar–geothermal systems. This approach can enhance seasonal energy storage performance in livestock applications and improve energy self-sufficiency in the agricultural sector.

Keywords: Hybrid solar–geothermal system, Photovoltaic–thermal collector (PVT), Borehole Thermal Energy Storage (BTES), Dual Source Heat Pump (DSHP), Nocturnal aerothermal charging, Underground thermal energy storage systems (UTES), Geothermal Heat Exchanger (GHE), Renewable Energy Sources (RES),

1. Introduction

1.1. Literature review

Agriculture is a significant contributor to greenhouse gas (GHG) emissions in the European Union (EU), accounting for approximately 11% of total net emissions, of which nearly 66% come from the livestock sector (EEA, 2024; European Commission, 2025). Although CO_2 emissions from the sector declined by 24% between 1990 and 2000, progress has since slowed, with only a 5% reduction recorded between 2005 and 2022 (EEA, 2024). Current projections estimate a modest 7% decrease in agricultural emissions by 2030 compared to 2005 levels, with the potential for more if additional measures are implemented (EEA, 2024). However, achieving the EU's long-term climate targets will require a substantial reduction of around 60% in agricultural emissions by 2040, necessitating more ambitious climate policies and mitigation strategies (European Commission, 2025). The EU's Common Agricultural Policy (CAP) and the regulation on land use, land use change, and forestry (LULUCF) play a role in addressing climate impacts within the sector. Nevertheless, agriculture is currently not included in the EU Emissions Trading System (ETS) as of 2024, even though it is included in the EU Effort Sharing Regulation (ESR) (EEA, 2024; Climate Action Tracker, 2024). While discussions on integrating agriculture into carbon pricing frameworks are ongoing, no concrete policies have been implemented due to the sector's unique challenges and complexities.

Energy production from renewable sources proves particularly fit in farm buildings and agricultural facilities, as in those contexts, proper conditions for the exploitation of Renewable Energy Sources (RES) are generally met (Gorjian et al., 2022). At the same time, many farm buildings show high energy demand and, in some cases, a lack of connection to energy distribution grids. Energy needs typically include thermal and electrical energy, as

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indoor climate control is required in warm and cold weather conditions. Moreover, farm building equipment is generally powered with electricity. For these reasons, solar energy is particularly suitable for the agricultural sector, as it can be transformed into heat through solar thermal panels or electricity through photovoltaic (PV) systems. Also, both forms of energy can be produced simultaneously, thanks to photovoltaic-thermal (PVT) plants, which can be easily installed, especially in farm environments. The potential of solar power for energy production in farms, for agricultural production purposes, has been highlighted in recent decades (Wong & Pecora, 2015), and innovative applications and evolutions of the PVT technology have been recently under study (Fakhraei et al., 2024). Concerning livestock farming, the main recent scientific developments related to PVT have focused on climate control for optimal animal welfare, as underlined by van Heule et al. (2023) for the poultry sector.

The availability of space typical of farmyards means that it is also possible to exploit geothermal sources, using closed-loop systems, consisting of a field of geothermal heat exchangers (GHE), which are environmentally friendly, thanks to the limited impacts on the aquifers (Barbaresi et al., 2020). Large volumes of subsoil are needed to exploit the required heat from underground by means of these GHE (Focaccia et al., 2016). 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 (Giambastiani et al., 2014). 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 borehole thermal energy storage (BTES) systems by injecting underground quantities of excess or waste energy, thus artificially heating the aquifers (Brown et al., 2024). 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 BTESs, to cover the thermal needs of the farms, through the use of a ground source heat pump (GSHP) (Luo et al., 2023). Among the energy sources, solar thermal (ST) is one of the most promising for BTES, due to the time mismatch with respect to building heating needs.

The exploitation of solar energy integrated with BTESs in agricultural buildings has thus been the subject of several studies, and greenhouses are considered an important target in this sense, with reference to heating requirements. Ghiasi et al. (2025) assessed the efficiency enhancement by integrating geothermal and PV systems to heat a greenhouse for sustainable agriculture in a cold climatic region. The results confirmed that integrating 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 performance of the heat pump is crucial in these kinds of applications, and this topic was further developed by Asgari et al. (2025), who focused on the models required for designing solar PV-driven greenhouses. 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 has been deeply analyzed in animal production and livestock farming research. Studies carried out within the European project RES4LIVE (Tyris et al., 2022) focused on the RES potential of livestock farms by adopting these technologies (Benni et al., 2023). In this context, the performances of a PVT system in livestock farms were analyzed, providing valuable insights to meet the energy requirement of cattle (Hosouli et al., 2023) and swine farms (Murali et al., 2024), considering the same hybrid installation investigated in those works comprising a PVT field integrated with BTES and a GSHP under the RES4LIVE project, forms the basis of the present study, where the system operation under nocturnal aerothermal mode is further evaluated. The potential of geothermal storage was, in turn, studied through an experimental approach by Tinti et al. (2023). 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 BTES system. The results showed that the definition of an effective solution requires collecting 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 in verifying the performance of the BTES. 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 (Benni et al., 2024).

1.2. Context and motivation for integrating PVT, DSHP, and BTES in farming applications

Livestock farming requires careful management of temperature and humidity conditions, which affect animal welfare and animals' health. On the other hand, heating, cooling, and ventilation are energy-consuming activities, where the intensity of carbon emissions must be reduced to mitigate climate change. In this scenario, electrification combined with RES is a key factor in fulfilling energy needs and, at the same time, keeping emissions under control. In livestock farms, wide spaces are available for installing solar panels (PV and ST) on the building roofs. The resulting electric energy can feed heat pumps, thermal lamps, air conditioners, and ventilation systems, while thermal energy can be directly used for hot water production.

On the other hand, peaks and the most significant heating needs occur during winter, when ST and PV have minimum production levels. Furthermore, low ambient temperatures force Air Source Heat Pumps (ASHP) to high energy consumption. In this context, using Ground Source Heat Pump (GSHP) instead of ASHP, linked to a BHE field, can be an efficient solution due to reduced electric energy needs. However, the drawback of this solution is the high cost of installation of the BHE field, which can cover the winter energy peaks. As a result, to reduce the installation costs and optimize the electric and thermal energy production by solar panels (PV and ST), as well as the needed space, a combined solution is proposed:

- integrate PV and ST into a unique PVT system to save roof space;
- install the BHE field with the configuration of a BTES, to allow the seasonal storage of solar thermal energy;
- Link the BTES field with both PVT and GSHP, in order to store excess solar thermal energy in summer for its reuse next winter. The proposed configuration achieves a more compact BHE field than conventional GSHP systems;
- integrate the system operation by modifying the pump control settings to enable nighttime operation, allowing heat exchange with the ambient air through the uninsulated PVT field when the cold side of the BTES permits it due to the low refrigerant temperature in the GSHP circuit;
- Substitute the classical GSHP with a Dual Source Heat Pump (DSHP), able to cover the peak energy demand by exploiting the air source, then reducing the BTES extraction rates, which reduces the dimension of the BHE field even more.

The case study presented in this research is a swine farm, located in northern Italy near the Po River in the municipality of Mirandola at an altitude of 10 m a.s.l. The farm is structured as a farrow-to-nursery system, rearing 500 sows and 2500 weaners. The details of the pilot plant modeling and design, the practical integration between BTES, PVT, and DSHP, and the preliminary results can be found in Tinti et al. (2023), Murali et al. (2024), and Benni et al. (2024).

1.3 Research Gap and Contribution to the State of the Art

Despite significant progress in integrating renewable technologies into agricultural systems, the experimental validation of hybrid PVT–BTES–DSHP configurations remains limited. Most previous works addressing such integrated systems relied primarily on numerical simulations or theoretical modeling, which, while useful, often neglect the operational complexities and dynamic interactions between components under real boundary conditions. Consequently, there is a lack of long-term experimental data assessing these systems' real performance, seasonal storage behavior, and operational feasibility when applied to livestock farming contexts.

This study presents experimental results from a fully monitored installation in an intensive livestock environment. The system is analyzed under baseline (daytime-only) and extended nocturnal aerothermal operation. This work provides valuable empirical insights into the seasonal performance of the system, its thermal storage efficiency, and the influence of night operation on overall energy yield.

The research contributes to the advancement beyond the state of the art by offering one of the first comprehensive experimental evaluations of nocturnal aerothermal charging within a hybrid solar–geothermal configuration for livestock applications. The findings are expected to support decision-making processes for farm energy planning, highlighting the potential of hybrid renewable systems to reduce fossil fuel dependency, enhance energy resilience, and optimize the thermal management of agricultural facilities.

2. System Description

2.1. Overview of the PVT-BTES-DSHP system

The system consists of a 24 flat plate PVT collectors' field, which simultaneously generates electricity and captures thermal energy, representing a total aperture area of 39.3 m^2. Unlike conventional PV panels that discard excess heat, PVT collectors transfer the captured heat to a circulating fluid, which is then directed to a standardized solar station. The solar station regulates fluid movement, facilitating heat exchange between the heat pump and the borehole storage, and its design is standardized for easy replication and scalability, ensuring cost-effective deployment across similar applications while maintaining high operational efficiency. This preheating setup minimizes the required temperature lift by the heat pump, thereby improving its coefficient of performance (COP). This heat pump is a 35-kW air/liquid-to-liquid DSHP designed for heating use only. It extracts thermal energy either from the BTES, from air, or both, and raises the water temperature up to 50°C. Lastly, the BTES serves as a seasonal buffer, allowing residual thermal energy to be stored underground for later use, ensuring a stable heat supply during periods of low solar availability, with a total storage capacity of 22 MWh/year. A visual schematic of the installation, including additional technical specifications and system integration aspects, is provided to illustrate the configuration, operational flow, and interaction between the PVT collectors, GSHP, and BTES in **Figure 1.**

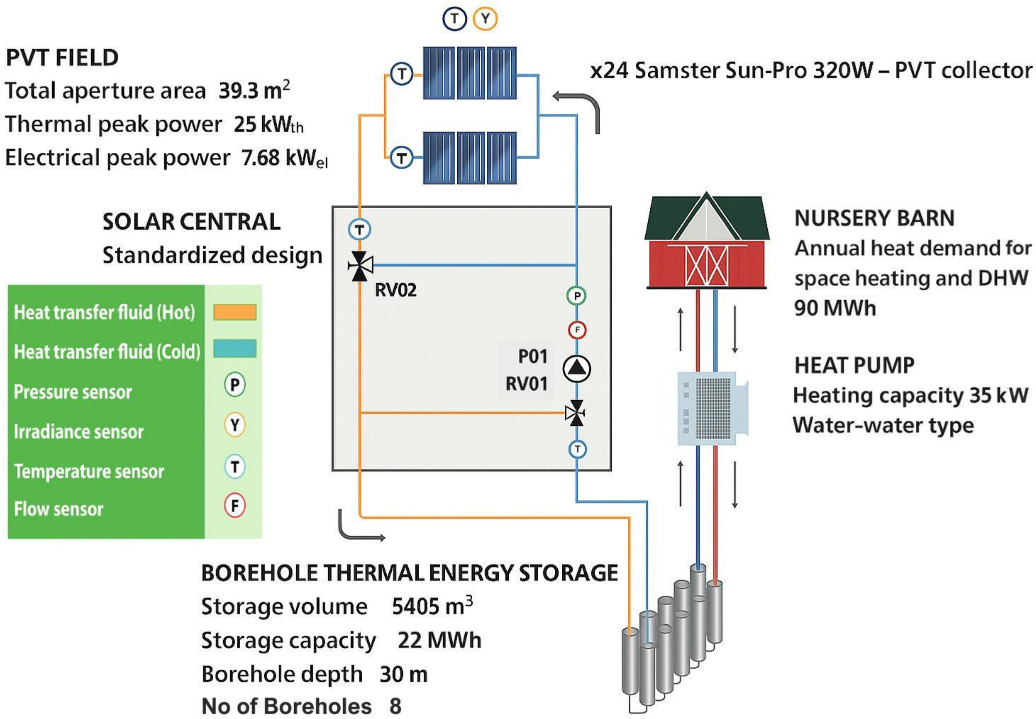

Figure 1: Visual schematic of the PVT-GSHP-BTES installation.

2.2. Details of the installation and operational setup at the swine farm

The RES system was designed 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, had an adequate temperature during the cold season. The core of the integrated system was thus the BTES, where the thermal energy produced was injected and from which it was extracted. The BTES is composed of 8 double U BHEs, 30 m deep, spaced from 3 to 2 each. The innovative configuration of the connection circuits, which allows the proper underground solar energy storage and the proper integration with both PVT and DSHP, has been recognized as an invention, with the patent "Closed-loop seasonal heat storage system for agro-industrial and agro-livestock structures". **Figure 2** illustrates the experimental setup of the hybrid renewable energy system, comprising the PVT field, the BTES, the DSHP, and the centralized control station.

Figure 2: Experimental setup of the hybrid renewable energy system: (a) Installation of the Borehole Thermal Energy Storage (BTES) field in the courtyard; (b) Dual Source Heat Pump (DSHP); (c) PVT system installed on the roof; (d) Standardized Solar Central Station connecting the PVT field and BTES.

3. Methodology

3.1. Monitoring approach and data collection methods

A smart monitoring and control system was developed and installed in the farm under study to monitor environmental variables and automate the integrated RES plant. The system was described in detail in Benni et al. (2023). Nursery barn data have been collected since May 2021, while RES data have been collected since June 2023, at the time of the system's commissioning. For this study, any reading between 20:00 and 06:00 was considered as night data. The system comprised a gateway, a weather station, and monitored nodes for gases and environmental conditions in different areas, including the hallway and two rooms.

3.2 Computational methods or software tools used for performance analysis

The monitored data were collected through the Resol VBus monitoring platform, which receives real-time measurements from the field instrumentation installed across the PVT subsystem. Each sensor transmits data to two destinations: (1) a controller that operates the actuators and (2) a dedicated datalogger connected to the VBus portal for continuous recording. The dataset comprising flow rate, temperature, and irradiance values was retrieved from the cloud at five-minute intervals and subsequently exported for offline analysis.

Data post-processing was performed using Microsoft Excel, where the raw readings were filtered and organized to evaluate energy balances. The thermal power exchanged in the PVT field ($Q_{1\rightarrow 2}$) between consecutive measurements was determined from:

$$Q_{1\rightarrow 2} = \dot{m} \cdot c_{p,fluid} \cdot (T_2 - T_1) \quad \text{(eq. 1)}$$

where $\dot{m}$ *is* the mass flow rate (kg s^{-1}), $c_{p,fluid}$ is the specific heat capacity of the propylene-glycol/water mixture (J kg^{-1} K^{-1}), and (T_2 −T_1) is the temperature difference between inlet and outlet readings (K).

The corresponding **thermal energy stored** over a time step Δt was then obtained as:

$$\Delta E_{t_1\rightarrow t_2} = \int_{t_1}^{t_2} Q dt \approx Q\Delta t \quad \text{(eq. 2)}$$

expressed in kWh. This relationship was implemented in Excel by multiplying the instantaneous power by the elapsed time between two records.

3.3 Description of the baseline case (no nocturnal aerothermal operation)

The baseline configuration corresponds to the operational period of 2023, when the integrated PVT–BTES–DSHP system at the farm functioned exclusively under daytime solar charging conditions, without nocturnal aerothermal support. This configuration represents the initial real-field implementation of the system, prior to the introduction of nighttime operations in 2024.

During this period, the system configuration remained identical for the baseline operation 2023 and the nocturnal operation mode 2024, as described in Section 2.1. The same PVT field, BTES array, and DSHP unit were used without hardware or hydraulic modifications. The only distinction between the two operational phases concerned the control strategy: in 2023, the system operated solely under daytime solar charging, with BTES charging restricted to irradiance or temperature difference thresholds, whereas in 2024, the control logic was updated to enable nocturnal aerothermal operation, allowing recovery and storage of low-grade ambient heat during night hours (Benni et al., 2024).

The 2023 data indicated a total building heat delivery of 40,870 kWh, with 30,396 kWh extracted from renewable sources (ground, air, and hybrid) and 10,474 kWh consumed as electrical input. This resulted in a Seasonal Performance Factor (SPF) of 3.78. The DSHP operated 37.91% of the time in ground mode, 53.93% in hybrid mode, and 7.13% in air mode (Benni et al., 2024).

4. Results and discussion

4.1 Annual performance overview

Throughout 2024, the system achieved a total annual heat injection of 15,776 kWh. During the period from 1st April to 31st August 2024, the integrated system achieved a total heat storage of 12,154 kWh, composed of 11,649 kWh from daytime solar operation and 505 kWh from nocturnal aerothermal recovery **(Figure 3).** Nighttime operation contributed an average of 4.16% of the total thermal storage, with peak monthly improvements exceeding 8% in July under favorable summer conditions. The pumping system exhibited a total operational duration of 3,087 hours during the day and 828 hours at night, indicating active circulation and efficient control logic engagement throughout the storage season. The results confirm that the integration of nocturnal operation significantly enhanced total heat injection into the BTES and improved year-round energy utilization, particularly during spring and summer when ambient conditions favored nighttime heat recovery. This annual performance trend can be attributed to the complementary operation of solar and aerothermal modes, which allowed the system to exploit high solar availability and favorable nighttime air-to-ground temperature gradients.

Regarding storage stability, the BTES exhibited consistent thermal behavior throughout the year, with no evidence of abnormal temperature drift or significant performance degradation. As expected for borehole systems, gradual temperature equalization occurred towards the end of the storage season, primarily due to conductive dispersion into the surrounding ground and the reduced temperature gradient between boreholes and soil. This phenomenon represents standard heat loss mechanisms inherent to long-term storage and does not indicate system inefficiency. The thermal field remained sufficiently stratified to ensure adequate seasonal storage, suggesting that the injected heat was retained mainly for future recovery. Overall, the BTES maintained a stable energy balance throughout the year, confirming that continuous operation during daytime and nocturnal charging did not adversely affect ground stability or storage performance.

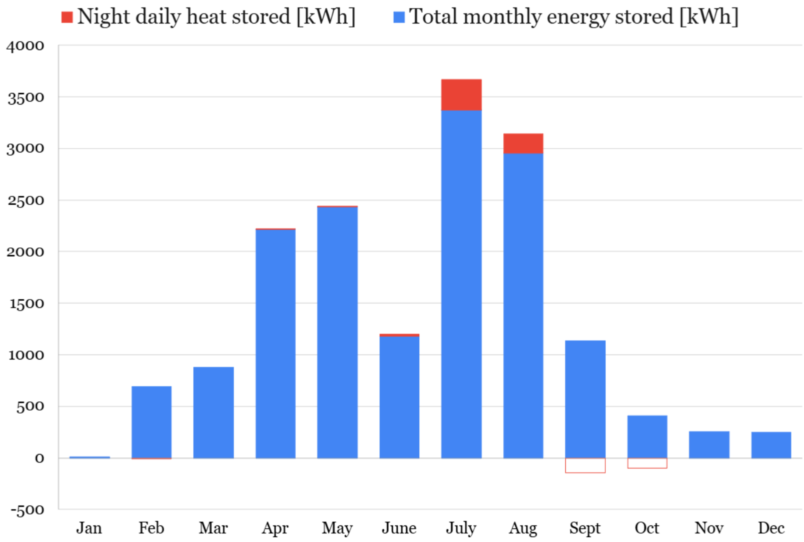

Figure 3: Monthly distribution of total and nocturnal heat storage in the BTES during 2024.

4.2 Seasonal analysis

The system exhibited a clear seasonal storage trend, with the majority of BTES charging occurring between April and September, when solar irradiance exceeded 250 W/m² on average.

Summer months July & August recorded substantial charging rates, with 3,370 kWh and 2,952 kWh, respectively, while shoulder months April & May recorded 2,214 kWh and 2,425 kWh, respectively. The nighttime mode contributed an additional fraction of energy during several months, visible as incremental bars in the monthly heat storage curve. The most significant nocturnal gain occurred in July, with a +8.0% increase relative to daytime-only operation, followed by August, with a +5.9%. On the other hand, September (–14.5%) and October (–30.3%) exhibited slight reductions due to reduced solar and air-side thermal gradients. In contrast, late autumn and winter months displayed minimal or negligible storage, with total monthly injected heat far below 1 MWh and nighttime contributions between 0 and –2 kWh, reflecting unfavorable ambient conditions and low irradiance levels <100 W/m². During these months, the BTES mainly remained in standby, with energy transfer limited to system maintenance operations, as shown in **Figure 3**.

In terms of energy for circulation, pump operation closely followed solar availability, with around 609.70 hours in July. The nighttime pump activity, reaching up to around 230.67 hours in July, confirmed the proper functioning of the control logic in maintaining heat transfer during nocturnal intervals (**Figure 4**).

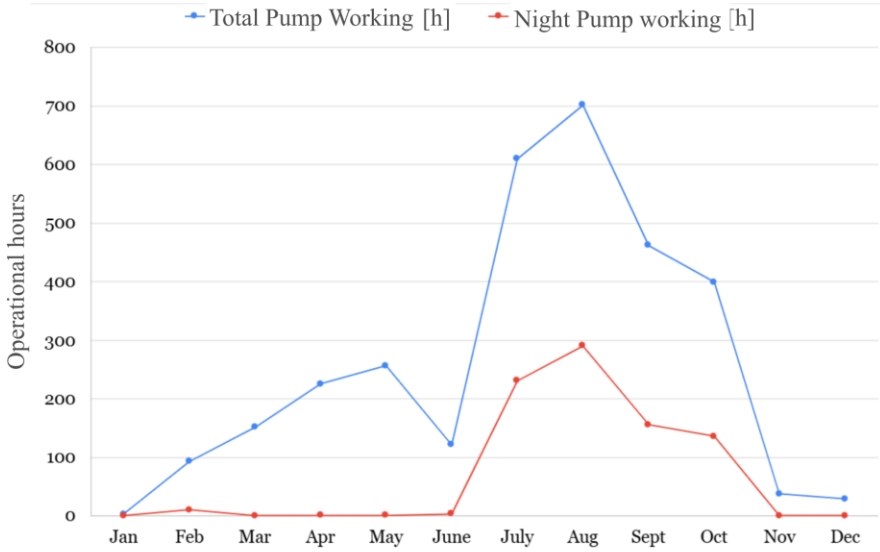

Figure 4: Seasonal variation of total and nocturnal pumping activity in the integrated PVT–BTES system.

The observed seasonal behavior reflects the interplay between solar resource variability, ambient air temperature, and BTES thermal inertia. High performance during spring and summer corresponds to large temperature differentials (ΔT) between the collector field and the ground, enabling efficient heat transfer and active nocturnal charging. Conversely, during September and October, the system experienced a clear reduction in nocturnal gains due to multiple physical factors: (i) decreasing solar irradiance, which limited daytime collector temperatures; (ii) progressive warming of the BTES, which reduced the ΔT available for nighttime heat injection; and (iii) higher atmospheric humidity and lower air temperatures, which decreased convective heat exchange efficiency. As a result, the potential for effective aerothermal recovery was significantly constrained in late autumn.

4.3. Comparison with the baseline case (no night operation): focus on an 11-day period

Regarding the daily performance gains, the inclusion of nocturnal aerothermal collection resulted in measurable performance improvements. As shown in **Figure 5** and Table 1, daily energy collection in 2024 increased by:

- Approximately +3% on July 5th, as lowest,
- Over +16% on July 11th, as maximum,
- Averaging 10–12% across the ten days.

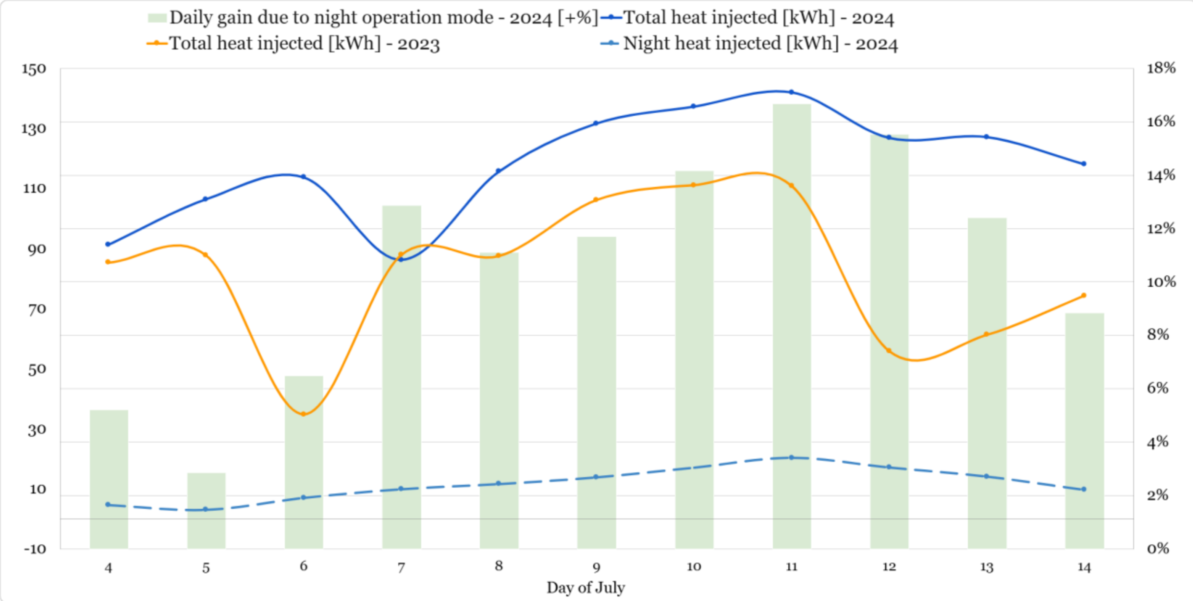

Figure 5: Day and night heat injection into BTES across the two periods (left axis), alongside daily energy gain due to night operation (right axis).

The observed gains in energy injection into the BTES (Table 1) occurred notwithstanding the intermittent fluctuations in solar irradiance experienced during 2024 compared to 2023. As depicted in **Figure 5**, only specific dates, such as July 6th and 13th in 2024, recorded more irradiance levels. However, the cumulative energy introduced into the BTES during 2024 surpassed that of the previous year, thus exemplifying the thermal buffering capacity afforded by nocturnal operational strategies. As shown in Fig. 5 and Table 1, the BTES received consistently higher heat input in 2024. Notable observations include:

- Nighttime heat injection contributed 10–20 kWh/day, depending on conditions.
- The difference between the solid and dashed blue lines in **Figure 5** represents the net gain from night operation in 2024.
- Night contributions became critical in maintaining performance on days with low solar gain, such as July 7th and 8th.

Table 1: Summary of Daily Heat Injection Gains During Nocturnal Operation (July 4–14)

Day of July	Avg Daily Irradiance [W/m²] – 2023	Total Heat Injected [kWh] – 2023	Avg Daily Irradiance [W/m²] – 2024	Night Heat Injected [kWh] – 2024	Total Heat Injected [kWh] – 2024	Daily Gain Due to Night Operation [%]
4	503.59	85.26	443.67	4.51	86.69	5.21
5	483.73	87.63	455.61	2.97	103.37	2.87
6	281.84	34.76	431.81	6.93	106.69	6.50
7	491.63	87.81	283.94	9.83	76.34	12.87
8	490.77	87.43	384.81	11.54	104.01	11.10
9	483.71	106.00	412.28	13.78	117.79	11.70
10	474.72	111.00	397.16	17.01	120.16	14.16
11	458.76	110.70	408.80	20.28	121.64	16.67
12	416.26	55.75	381.45	17.05	109.69	15.54
13	288.23	61.22	398.33	14.03	113.00	12.41
14	602.03	74.26	416.24	9.60	108.39	8.85

Over the eleven days, cumulative nighttime injection reached 127.53 kWh, accounting for 9.45% of the total thermal input (1,331.72 kWh) from the PVT system into the BTES. The ambient temperature values recorded during the study period are also included, as the temperature difference between the ambient air and the BTES can enable heat collection, particularly during summer, thus promoting seasonal thermal energy storage. Also, it is essential to note that dual-mode operation can show strong complementarity. The nocturnal mode can elevate BTES temperatures and improve morning thermal conditions in the PVT field by reducing startup lag and enhancing inlet temperature conditions. Nevertheless, further analysis needs to be developed to understand if additional heat can be stored during the summer and used during the winter. Also, the impact of heat pump operation on the PVT and BTES systems should be considered since the heat pump is not currently being used during summer due to the lack of heat demand. Moreover, the additional electricity consumed during nocturnal operation should be accounted for to analyse whether it outweighs the additional heat production.

The total heat provided to the building by the DSHP in its first year of operation was 40,870.20 kWh, of which 14,973.64 kWh were extracted from the BTES (ground source), and 15,459.55 kWh were extracted by the fans (air source). The system, in fact, worked 55% of the time in hybrid mode, with both ground and air sources activated at the same time. The total SPF was 3.78, while the average COP was 4.07 (Tinti at al., 2025). It resulted in a total electric energy consumption of 10,474.36 kWh.

According to the temperature values in the monitoring system installed in two piezometers upwards and downwards in the BTES, no drift of groundwater temperature could be appreciated. Therefore, at the moment, the system appears to be fully sustainable, and the nocturnal operations do not seem to have any environmental effect. On the other hand, in order to provide a robust result, 5 or 10 years of continuous monitoring of groundwater temperature is needed.

5. Conclusions

5.1 Summary of key findings

This study assessed the performance of a PVT field coupled with BTES and a DSHP installed in a livestock nursery barn. The comparison between the baseline daytime-only configuration (2023) and the nocturnal aerothermal mode (2024) confirmed measurable performance improvements under the extended operation strategy. Across 2024, the system achieved a total annual heat injection of 15,776 kWh. In particular, from April to August the integrated system achieved a total heat storage of 12,154 kWh, of which 505 kWh were recovered through nocturnal aerothermal charging. This resulted in over 4% annual energy gain compared to the baseline mode. Over the ten-day comparative analysis, the nighttime contribution accounted for 9.45% of total daily energy injection, confirming the effectiveness of nighttime heat recovery. The BTES remained thermally stable throughout the operation, exhibiting no observable drift or degradation in storage performance. These findings validate the technical feasibility and energetic benefit of incorporating nocturnal aerothermal collection into hybrid solar–geothermal systems.

5.2 Implications for livestock farming and renewable energy integration

Integrating nocturnal aerothermal operations offers significant practical advantages for agricultural and livestock facilities. Extending energy collection beyond daylight hours enables more stable year-round thermal energy management, reducing dependence on fossil fuels for space or water heating. The enhanced storage utilization mitigates the “cool borehole” effect, ensuring higher ground temperatures during winter extraction periods and improving overall system efficiency and durability. For livestock farms, this operational flexibility translates into greater energy self-sufficiency and resilience against fuel price fluctuations. The results demonstrate that combining solar and ambient aerothermal recovery can effectively support the transition toward low-emission, renewable-powered agricultural systems, while maintaining stable indoor thermal conditions critical for animal welfare.

5.3 Limitations and future research directions

While the results are promising, the study has certain limitations. The analysis is based on a single-site installation with a limited monitoring period, which may not capture long-term climatic variability or the cumulative impact of multi-year operation. Additionally, heat pump performance indicators such as the COP and SPF were not fully assessed, and their relationship with nocturnal operation remains to be quantified. Future research will focus on the dynamic modeling and optimization of the integrated PVT–BTES–DSHP system to further refine control strategies and enhance operational efficiency. Expanding monitoring efforts across multiple climates and farm configurations will allow for broader nocturnal aerothermal charging concept validation. Furthermore, including detailed COP evaluation and long-term BTES thermal response analysis will be essential to assess the economic and environmental viability of scaling this technology within the agricultural energy sector.

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