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DECARBONISATION THROUGH INNOVATION

"Performance analysis of multi-source heat pumps coupled with dual-layer seasonal thermal energy storage: operational data and insights after the first year"

Jakub Garbacik[a,b,*], Kamil Kwiatkowski[a], Tomasz Walczak[a]

[a]Euros Energy, ul. Macieja Rataja 4f, 05-850 Koprki, Poland
[b]Warsaw University of Technology, pl. Politechniki 1, 00-661 Warsaw, Poland

Abstract

In the face of the need to decarbonise district heating systems, multi-source heat pumps (MSHPs) combined with seasonal heat storage are a viable alternative to conventional, emission-intensive technologies (i.e. coal-fired boilers). In this work we present the results of an operational analysis of a full-scale MSHP-based heating system implemented in Lidzbark Warmiński, northern Poland, which has been in continuous operation for more than a year, covering more than 90% of the heat demand from renewable energy sources.
This heating plant is based on a cascade of heat pumps cooperating with three sources: air-to-water heat exchanger, borehole thermal energy storage (BTES) and pit thermal energy storage (PTES).
In this paper we examine the operating conditions and performance for each of these sources, their seasonal availability and the variation of COP with temperature parameters. In addition, an analysis of the charging and discharging strategies of the seasonal storage, with a particular focus on the long-term temperature behaviour of the PTES storage and maximising economic efficiency was performed. Hence, the system is designed to consume electricity from a dedicated local photovoltaic farm, we analyse also the level of electricity self-consumption.
The overview of current MSHP technologies points out their potential for integration with both BTES and PTES. It also identifies the main challenges of implementing this technology, such as the need for adequate space for sources. This factor can be solved by dual-layer configuration when PTES is built above the BTES. In this paper we analyse the data collected from system as an assessment of real energy efficiency compared to design values and results of the numerical simulations. The results confirm that MSHP technology integrated with heat storage is not only technically feasible, but also replicable, providing a solid basis for the development of decarbonised district heating systems.

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Keywords: multi-source heat pumps; thermal energy storage; district heating network

1. Introduction

Decarbonising district heating (DH) systems remains a major challenge in Poland, where many networks still rely on fossil fuels [1]. Low-carbon transformation requires integrating renewable sources and large-scale heat pumps coupled with seasonal thermal storage. The Heating Plant of the Future (HPF) project,

* Corresponding author. Tel.: +48-22-250-16-05
E-mail address: jgarbacik@eurosenergy.com

implemented in Lidzbark Warmiński, Poland, demonstrates a new approach based on multi-source heat pumps (MSHPs) and hybrid thermal energy storage solutions.

Despite growing interest in MSHP technology [2], there is limited operational data from full-scale systems combining air, ground, and water sources with long-term thermal energy storage in both the Pit Thermal Energy Storage [3] and Borehole Thermal Energy Storage. The key research questions addressed here are: what are the seasonal energy flows and efficiency variations across sources and how do measured results compare with design simulations.

Previous studies on district MSHPs mostly focus on simulations of air and ground as heat sources [2]. The HPF project is unique in demonstrating a fully integrated, multi-source, dual-layer storage PTES/BTES system operating at MW-scale. Dual-layer storage system means that PTES was built directly on top of BTES. It was designed to accommodate both the maximum number of boreholes and the largest possible water storage facility within the limited area of the parcel. The configuration enables year-round renewable heat supply with minimal reliance on power grid supply and near full self-consumption of locally produced electricity from PV power plant.

The system designing process was supported using numerical modelling software [4]. The hydronics and individual components of the HPF: heat pumps, heat storage tanks, PV and PVT installations, buffer, heating network, air heat exchangers, circulation pumps, etc. were represented by specific device models available in the TRNSYS 18 libraries. The numerical model was controlled by a Python script integrated with TRNSYS 18.

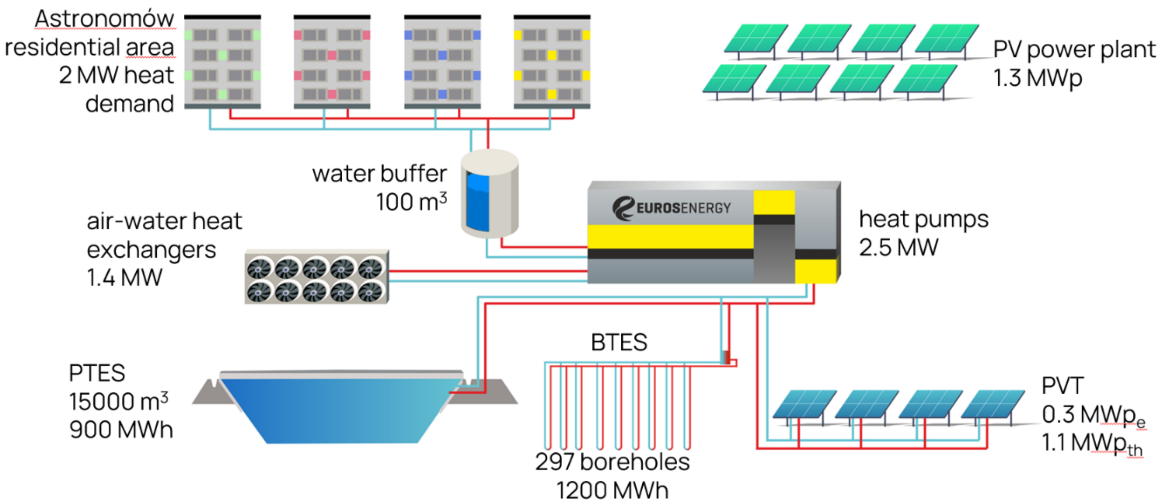

Figure 1. HPF system concept scheme.

2. Methods / Approach

The HPF installation supplies space heating and domestic hot water (DHW) to 17 residential buildings (ca. 28 000 m²) via a local district heating network. The system includes:

- Multi-source heat pump cascade (48 modular units providing up to 2.5 MW thermal output),
- Borehole Thermal Energy Storage (BTES) – 297 boreholes, 100 m deep each,
- Pit Thermal Energy Storage (PTES) – 15000 m^3 water-based reservoir built on top of BTES,
- Air-to-water heat exchanger (AtW) for ambient heat recovery providing up to 1,4 MW low temperature thermal output,
- Short-term buffer tank for network balancing – 100 m^3 pressurised steel water tank,
- 1.6 MWp photovoltaic (PV) farm and hybrid PVT collectors,
- SCADA-based monitoring system for temperatures, flows, and power consumption.

The system is based on 48 small heat pumps to easily adapt to rapidly changing conditions in PV electricity generation. The ability to gradually increase electricity consumption allows for maximising PV yield consumption while lowering the risk of having to draw electricity from the national grid. The heat produced in this way can be stored in three ways: short-term in a buffer and seasonally in BTES or PTES. Furthermore, by using multiple heat pump units, we can easily adapt to the demand of the heating network.

Thermal and electrical energy balances were calculated from logged data (1-min resolution) over a full operating year (May 2024 – April 2025). Fig. 2 presents the conceptual annual energy flow diagram, showing interactions among sources, storages, and the district network.

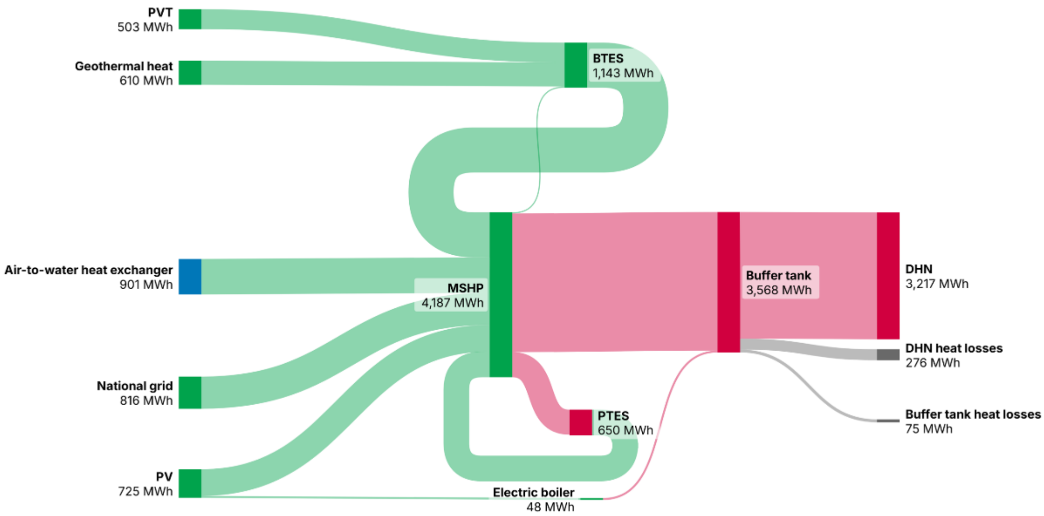

Figure 2. Energy flow diagram in HPF system.

Electricity from PV and PVT systems is prioritised for on-site consumption by heat pumps, air-to-water heat exchangers and circulation pumps. Only surplus less than 50 kW can be exported to the national grid due to connection constraints.

Instantaneous and seasonal COP values were derived from measured heat and power data. Separate COPs were determined for each operating mode:

- Air-source mode: summer operation when ambient air temperature is higher than BTES return temperature.
- BTES mode: summer regeneration and winter extraction.
- PTES mode: summer charging; discharging during heating season peak demand.

Numerical reference values were obtained from pre-implementation TRNSYS 18 simulations for comparison.

3. Results and Discussion

3.1. Annual energy balance

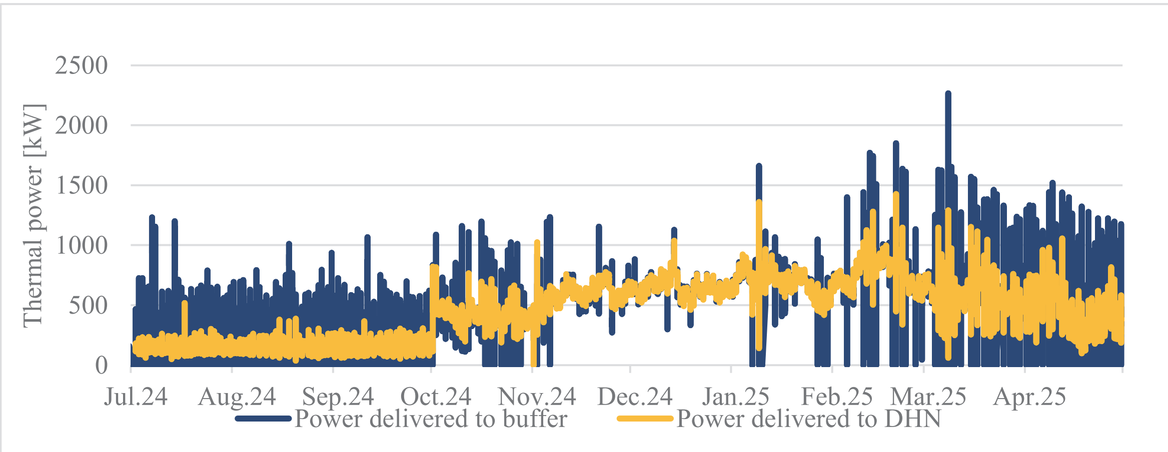

Figure 3. Overview of thermal power outputs to buffer and DHN.

The total annual thermal energy delivered to the DH network almost aligned 3500 MWh, with 90% originating from renewable sources. Peak heating demand reached 1.5 MW (Fig. 3). Renewable electricity covered the entire system consumption either directly (self-consumption of locally generated electricity) or via certified green supply from the national power grid. The unevenness of the power supplied to the buffer compared to the DHN is the result of self-consumption of electricity from the local PV farm and storage of the heat generated in this process. During the day, when PV yield is available, short-term heat storage is charged. Then the entire system is shut down to save energy, and the heat stored in the buffer is released into the DHN.

The PTES and BTES storages played complementary roles: PTES covered medium-temperature operation (10-55 °C), while BTES acted as the low-temperature source (3-12 °C). The short-term buffer (up to 90 °C) enabled demand-side flexibility.

3.2. Monthly energy delivery by source and mode

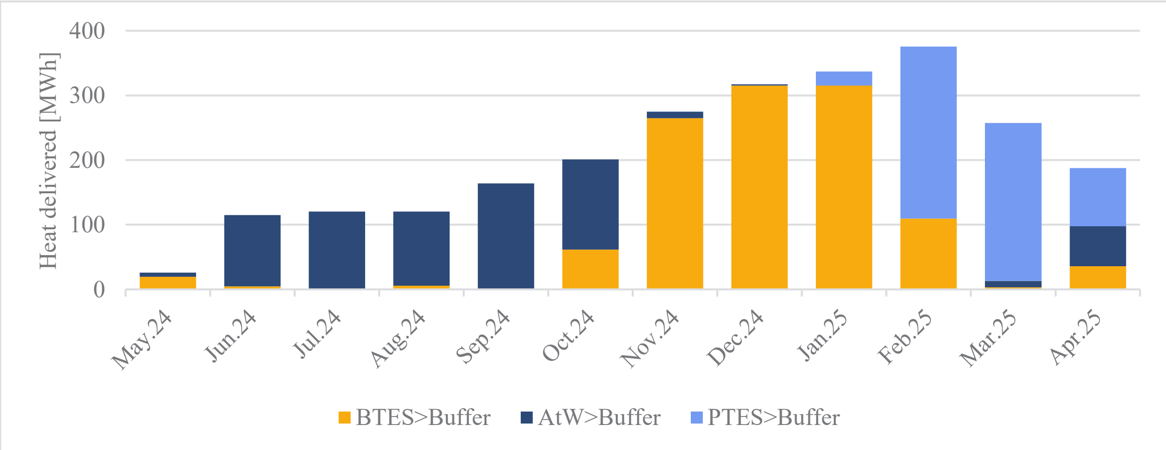

Figure 4. Monthly energy delivered to DHN by specific source.

Monthly data (Fig. 4) reveal that air-source operation dominated during summer months (May–October), while BTES/PTES contributions increased in mid- and late- heating season.

Solar-driven charging of PTES occurred mainly between June and September, supported by excess PV/PVT electricity utilised by heat pumps extracting heat from surrounding air.

Measured seasonal COP values were within expected ranges:

Table 1. Measured COP rangers for each operation mode in HPF system.

Heat pump source	Heat pump load	Typical Supply Temp. (°C)	COP range	Notes
BTES	Buffer	58-70	2.6–3.2	Stable performance without significant variation
Air-to-water heat exchanger	Buffer	58-75	2.0–3.5	COP strongly depending on air temperature and buffer temperature
Air-to-water heat exchanger	BTES	10-25	4.0–4.3	Highest COP; stable performance
Air-to-water heat exchanger	PTES	10-60	2.8-4.2	Decrease in COP with increasing temperature in the storage
PTES	Buffer	58-65	2.8–3.8	Decrease in COP with decreasing temperature in the storage

Overall SCOP ≈ 3.1, consistent with TRNSYS predictions. The PTES average temperature reached 55 °C, slightly below the 65 °C design target due to delayed full-power operation in early 2024. BTES temperatures peaked at 12 °C, confirming effective passive charging via PVT collectors.

3.3. System reliability and operational issues

The system achieved 100 % availability of heat supply. Minor technical issues included:

- Need for manual control of the system from May to July due to the process of fine-tuning of a complex automatic system
- A single heat pump unit failure (no impact due to redundancy),
- Temporary communication errors in automation cabling (resolved),
- Overheating in electrical cabinets under high load (mitigated by added ventilation).

No significant fouling were observed in hydraulic circuits. The modular design and redundancy were key to maintaining continuous operation.

3.4. Discussion

The first year of operation demonstrated that MSHP with seasonal thermal energy storage systems can meet high renewable heat shares in northern European climates. The dual-layer configuration (PTES above BTES) significantly reduces land requirements.

The main performance drivers identified were:

- Continuous operation with flexible source switching,
- High self-consumption of PV electricity,
- Accurate numerical pre-design using TRNSYS models,
- Robust control algorithms ensuring proper stratification and source sequencing.

4. Conclusions

Operational data matched numerical predictions within ±5 % for total heat output and ±0.1 for seasonal COP, validating the model accuracy. This confirms that numerical simulation played a crucial role in system design, optimisation, and risk mitigation. The HPF operated according to design, delivering ca. 3.5 GWh/yr of heat with almost 90 % renewable share. Dual-layer seasonal thermal energy storage (BTES and PTES) integration ensured flexible operation across seasons. System reliability exceeded expectations, confirming scalability of MSHP technology for district heating. High-resolution modelling and simulation were key enablers of the project’s success, reducing uncertainty and enabling optimal control strategies.

The results demonstrate that large-scale multi-source heat pump systems can replace conventional DH plants, accelerating the decarbonisation of urban heat supply.

Acknowledgements

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