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High-Temperature Large-Scale Heat Pumps for Industrial Process Heat and District Heating

Design and Integration of Two Industrial Case Studies

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Abstract

The decarbonization of industrial heat demand is a central challenge of the energy transition, as many energy-intensive processes still rely on fossil fuels to supply high-temperature thermal energy. Electrification through high-temperature large heat pumps (HTHPs) enables the valorization of low-grade waste heat and its upgrade to temperature levels suitable for district heating and industrial processes. This paper presents the design, industrial integration, and operational concept of two large-scale applications. The first case study is a 6 MWth heat pump integrated in an Italian steel plant to recover continuous waste heat from the electric arc furnace cooling circuit and supply hot water to a district heating network up to 120 °C. The second case study is a 12 MWth heat pump coupled with mechanical vapor recompression (MVR) in a paper mill, producing superheated steam at 170 °C from wastewater-derived heat at approximately 18 °C; due to confidentiality constraints, only high-level process information is disclosed for this installation. The case studies illustrate that multi-megawatt HTHP systems can be integrated in complex industrial environments, complementing existing heat recovery solutions and enabling substantial reductions of fossil heat use and associated greenhouse gas emissions.

1. Introduction

Achieving net-zero greenhouse gas emissions requires a profound transformation of industrial energy systems. Industrial process heat contributes substantially to global final energy consumption and CO_2 emissions, particularly in sectors such as steel and pulp & paper. The electrification of heat, supported by an increasingly decarbonized power grid, is therefore a key pathway to reduce emissions while maintaining process performance and reliability.

High-temperature heat pumps (HTHPs) can recover low-grade waste heat and upgrade it to useful temperature levels with high efficiency. Comprehensive reviews highlight technological progress and remaining challenges related to refrigerant selection, compressor technology, and process integration at elevated sink temperatures. Arpagaus et al. surveyed commercial and near-market HTHP solutions and their operating domains for industrial heat supply [1]. More recently, Jouhara et al. reviewed HTHP fundamentals, modelling approaches, and applications, and emphasized the need for further industrial deployment and integration studies [2].

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Beyond hot-water applications, electrified steam generation is increasingly discussed for industrial decarbonization. Bless et al. compared steam generation pathways in terms of energy, CO_2 emissions and cost, including heat pump-based options [3]. Works from the OST Buchs research group (Arpagaus, Bertsch) further address HTHP design and integration for industrial heat and steam supply, including turbocompressor concepts enabling large temperature lifts [4]. International RD&D activities (e.g., IEA HPT TCP Annex/Project work on high-temperature heat pumps) also underline the relevance of large-scale demonstrations and process integration concepts [5].

Despite these advances, the number of publicly documented, continuously operated, multi-megawatt installations reaching high temperature levels and integrated into complex industrial systems remains limited. This paper addresses this gap by presenting two industrial case studies: (i) a 6 MWth HTHP integrated in a steel plant for district heating supply, and (ii) a 12 MWth HTHP combined with MVR for 170 °C superheated steam generation in a paper mill. The contribution of this work lies in the description of real-scale integration concepts, operating strategies, and key performance indicators under industrial conditions.

2. Methods/Approach

2.1. Heat Pump in Steel Mill

The HEATLEAP project (European Commission LIFE programme) was implemented at the ORI Martin electric arc furnace (EAF) steel plant in Brescia, Italy, in collaboration with industrial and research partners. The objective is to demonstrate real-scale recovery of low-grade waste heat in an energy-intensive industry and its use in a district heating (DH) system.

A 6 MWth large heat pump (LHP) was designed and installed to recover thermal energy from the EAF cooling circuit, where hot water is typically available at about 70–75 °C and was previously dissipated via cooling towers. The LHP upgrades this heat to supply pressurized hot water to the DH network, with a maximum delivery temperature of 120 °C. The system is designed for flexible operation, including variable sink temperature to match DH requirements and variable source conditions associated with batch steelmaking.

The plant already operates an Organic Rankine Cycle (ORC) system (in operation since 2014) that recovers high-temperature waste heat from EAF off-gases for electricity generation and/or district heating supply depending on seasonal demand. The ORC and the LHP address different waste-heat quality levels: the ORC valorizes high-temperature streams, whereas the LHP valorizes a continuously available low-temperature stream from the cooling circuit. Electricity generated by the ORC is not used to drive the LHP; instead, the two systems operate in a complementary manner within the site energy system.

Operational data and performance indicators (thermal output, electricity consumption, operating hours, and DH supply conditions) were collected within the project monitoring framework to assess efficiency, flexibility, and integration robustness under industrial conditions.

2.2. Heat Pump in Paper Mill

Due to confidentiality agreements with the end user, only general information about the paper mill installation can be disclosed. The system integrates a 12 MWth large heat pump with mechanical vapor recompression (MVR) to recover low-grade heat from process wastewater and related low-temperature streams at approximately 18 °C.

The heat pump generates low-pressure saturated steam (≈1.6 bar). The produced steam is subsequently compressed by an MVR unit to approximately 3.4 bar and superheated to about 170 °C to meet the process steam requirements. This configuration enables electrified steam generation at industrial scale and represents a first-of-its-kind installation in the pulp and paper sector in terms of both capacity and temperature level.

The heat pump cycle is implemented with large centrifugal compression stages and industrial heat exchangers. Key performance indicators and operating data are monitored; detailed component specifications and contractual performance data are not disclosed due to NDA constraints.

3. Results and discussions

3.1. Heat Pump in Steel Mill

Methodology and baseline: Reported energy and CO_2 savings are evaluated against the pre-installation baseline in which low-temperature heat from the EAF cooling circuit was dissipated through cooling towers and district heating (DH) demand was supplied by conventional heat generation. Results refer to the reference year 2023. Thermal energy delivered to the DH network and the electricity consumed by the heat pump were monitored within the project framework; associated emission reductions were calculated using the DH-specific substitution approach. Additional benefits related to reduced auxiliary electricity demand (e.g., ventilation and cooling) were estimated from site operating data.

Heat Pump performances and parameters can be summarized as follow:

Table 2. Heat Pump Performances

Heat Source	Value
Type	Electric Arc Furnace cooling circuit
Temperature profile	75-70°C
Heat Sink	
Type	District heating water
Heat sink inlet temperature	65°C
Heat sink outlet temperature	95°C (up to 120°C)
Heat Pump Performances	
Thermal power delivered	6 MW
COP	8.2
LHP Fluid	HFO R1233ZD

The implemented large heat pump (LHP) system is capable of supplying up to 85% additional heat to the district heating (DH) network. Full integration with the DH network enables the system to avoid the release of waste heat to the environment, reduce the power demand of the cooling system, and significantly lower the overall carbon footprint.

The application of this innovative LHP system has resulted in the following key outcomes:

Reduction of Greenhouse Gas Emissions:
The system enables an annual reduction of 5,750 tonnes of CO_2 emissions for the connected DH network, primarily due to the increased efficiency of heat exchange provided by the LHP. Over the heating season (October to April), the steel plant supplies a total of 22,000 MWhth to the DH network during approximately 3,890 operating hours per year.

Additional CO_2 Savings:
An extra reduction of 803 tonnes of CO_2 per year is achieved through the decreased use, or complete elimination, of the air ventilation system previously required to maintain the electric arc furnace (EAF) at a constant temperature of 65–70°C. This corresponds to an expected energy saving of 622 MWh/year, equivalent

to 251 tonnes of CO_2. The environmental benefits from these CO_2 savings substantially offset the electricity consumption associated with the LHP operation.

Reduction of HFC-Related Emissions: The adoption of a new refrigerant fluid has led to a 99.7% reduction in greenhouse gas emissions from hydrofluorocarbons (HFCs), corresponding to approximately 250 tonnes of CO_2 equivalent per year.

Additional environmental and operational benefits include:

Significant reduction of air pollutants from heating sources, with annual decreases of 1,952 kg NO_x, 989 kg SO_x, and 84 kg particulate matter.

Decreased reliance on fossil fuels, resulting in a reduction of natural gas consumption for heating by approximately 230,000 Nm³ per year.

Near-zero water consumption, as the system operates with a closed-loop water circuit that recirculates and cools the process water.

These results collectively demonstrate the substantial environmental and operational advantages of integrating large heat pump technology into industrial and district heating applications.

3.2. Heat Pump in Paper mill

As the paper mill project is currently subject to a non-disclosure agreement with the client, comprehensive process and performance details cannot be provided at this time. In compliance with confidentiality requirements, only the main system characteristics reported in the Methods section are included in this paper; additional results and operational findings will be presented at the conference.

Table 2. Heat Pump Performances

Heat Source	Value
Type	Process waste water
Temperature profile	18-8°C
Heat Sink	
Type	Steam for process application
Heat sink inlet temperature	104°C
Heat sink outlet temperature	>170°C – 2.5 barg
Heat Pump Performances	
Thermal power delivered	12 MW
COP	2
LHP Fluid	R600a

4. Conclusions

The decarbonization of industrial processes through electrification represents a pivotal strategy in the global effort to mitigate climate change and achieve sustainable development goals. Electrification enables the substitution of fossil fuels with renewable electricity, thereby reducing greenhouse gas emissions and enhancing overall energy efficiency. As industries account for a significant share of global energy consumption and CO_2 emissions, the deployment of advanced electrification technologies is essential to realize the ambitious climate targets set by the European Union and other international frameworks.

In this context, this paper has presented two innovative projects that exemplify the application of high-temperature heat pumps in industrial settings. The first project, implemented in a steel plant, demonstrates the practical valorization of otherwise unused waste heat. By integrating a large-scale heat pump, low-grade thermal energy from the furnace cooling circuit is upgraded and supplied to a district heating network, raising water temperature from 60°C to 120°C. This approach not only improves the overall energy efficiency of the steelmaking process but also enables the integration of industrial facilities within urban environments. Such synergy between industry and community supports the vision of future European energy systems, where industrial waste heat recovery plays a central role in decarbonizing urban heating and fostering resilient, interconnected energy infrastructures.

The second project, realized in a Northern European paper mill, will be discussed in greater detail at the upcoming conference. Nevertheless, it is important to highlight that this installation is the first of its kind worldwide in terms of both capacity and temperature for the pulp and paper sector. The project is pioneering in its use of centrifugal compressors with natural refrigerants to achieve high-temperature heat pump operation. This technological advancement underscores the feasibility and scalability of electrification in energy-intensive industries, particularly in the paper sector, which has traditionally relied on fossil-based steam generation. The successful implementation of this project provides a concrete demonstration that large-scale, high-temperature heat pumps can be effectively deployed in industrial applications, paving the way for future replication and broader adoption.

In summary, the projects presented herein illustrate the transformative potential of electrified heat in industrial decarbonization. By leveraging advanced heat pump technologies, it is possible to unlock new synergies between industry and society, contribute to the realization of European climate objectives, and set a benchmark for future developments in sustainable industrial energy systems.

Looking ahead, further advancements are anticipated in the deployment of large heat pump systems, including the exploration of alternative solutions for future installations. Ongoing research and development efforts will focus on the adoption of novel refrigerants, as well as the integration of advanced control strategies and process integration schemes. These future developments are expected to further enhance the performance, flexibility, and sustainability of industrial heat pump applications.

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