Commissioning and operation for first of its kind large steam generating heat pump under commercial conditions

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1 Introduction

The European industrial sector stands at an inflection point: the increasingly stringent decarbonisation mandates embedded in EU climate policy and the persistent volatility of fossil fuel markets are reshaping the energy strategies of manufacturing companies across the continent. These factors have exposed the vulnerability of industrial processes dependent on natural gas for their heat supply. The pulp and paper industry is a good example of this double pressure. Paper manufacturing is inherently heat-intensive. Steam is the backbone of the drying process, and process stability in the drying section has a direct and measurable impact on product quality. For decades, this requirement for absolute reliability made the sector deeply conservative in its approach to energy supply. Gas-fired boilers, with their well-understood performance envelope and rapid response characteristics, have been the technology of choice.

Yet the economics and the regulatory environment are shifting decisively. Carbon pricing mechanisms, EU and national energy transition programmes are pushing towards the industrial heat electrification. Meanwhile, advances in heat pump technology have expanded the range of temperatures achievable through electrically driven thermodynamic cycles, penetrating territory that was, until recently, considered the exclusive domain of combustion. High-temperature heat pumps (HTHPs) capable of delivering steam are now attracting serious industrial attention. Sectors including chemicals and pharmaceuticals, food and beverage, district heating networks, and pulp and paper have all identified significant potential for HTHP deployment. The market is nascent but growing rapidly, with project pipelines expanding across Northern and Central Europe. Within this context, the project developed for delfort group at their Tervakoski mill in Finland (Figure 1) occupies a special position. It is a genuinely pioneering system, combining a large-scale hydrocarbon-cycle heat pump with a steam compressor in a novel series configuration, capable of supplying 12 MW of thermal power in the form of high-quality steam. Designed, engineered, supplied, installed, and commissioned by Turboden, the system has been started up in the summer of 2025 and has since accumulated nine months of operational data which allow for a meaningful assessment of its real-world performance.

This article documents the project from start to finish: the industrial context and the client's specific requirements, the engineering approach and system architecture, the challenges encountered during commissioning and the performance results achieved in operation. The goal is not merely to celebrate

Fig. 1. External view of the delfort heat pump.

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a technical achievement, but to draw lessons that can inform future projects in what promises to become an increasingly important segment of the industrial energy market.

2 The market context: Heat pumps and the industrial decarbonisation imperative

2.1 The case for high-temperature heat pumps

Heat pumps operate on a well-established thermodynamic principle: by consuming electrical work, they transfer thermal energy from a lower-temperature source to a higher-temperature sink, delivering more heat energy than the electrical energy consumed. The ratio of heat delivered to electrical energy consumed — the Coefficient of Performance (COP) — is the key measure of efficiency and economic viability. For decades, heat pumps were associated primarily with low-temperature applications: space heating in residential and commercial buildings, and low-grade industrial process heat. The technical challenge of achieving high output temperatures while maintaining acceptable COPs limited their industrial applicability. However, utilization of new refrigerants, advanced compressor design, and system integration have steadily extended the operational envelope. Modern high-temperature heat pump systems can now deliver heat at temperatures above 150 °C, and, as this project demonstrates, can generate steam at conditions suitable for demanding industrial processes.

2.2 Turboden's role in the large heat pump market

Headquartered in Brescia, Italy, the company has built its industrial identity around the integration of complex thermodynamic systems in demanding industrial environments. Widely known for its Organic Rankine Cycle (ORC) technology for waste heat recovery and renewable energy applications, has in recent years extended its expertise into the heat pump domain, recognising the fundamental thermodynamic complementarity between the two technologies and the growing industrial demand for electrified heat solutions. The deployment of large-scale industrial heat pumps is not simply a matter of procuring a unit from a catalogue. Each industrial site presents a unique combination of heat source characteristics, process requirements, existing infrastructure, and operational constraints. Successful HTHP projects require a system integrator capable of bridging the gap between thermodynamic performance models and the reality of industrial process environments. This project represents the most ambitious heat pump deployment to date, and a significant demonstration of this system integration capability.

3 Project specifications: The paper mill's requirements and the "heat upgrade" concept

Delfort group is a global manufacturer of specialty papers, with production facilities across Europe. Their mill in Finland produces a range of high-quality specialty paper products and relies on a continuous and stable supply of steam for its drying processes as the quality of the final product is strongly influenced by the uniformity and consistency of this process. Temperature fluctuations, pressure transients, or flow interruptions in the steam supply can propagate into product defects or production losses. This sensitivity to steam supply stability creates demanding specifications for any heat supply system. The installation must deliver steam at the required temperature, pressure, and mass flow rate with a degree of consistency that matches or exceeds what a conventional gas-fired boiler provides. Meeting this requirement with a large-scale heat pump, a technology whose operating behaviour is inherently more complex than a simple combustion system, was the central engineering challenge of the project. One of the enabling features of this project was the availability of significant quantities of waste heat at the mill site. Paper manufacturing generates low-grade thermal energy at multiple points in the process, and this thermal energy has historically been partly recovered and partly rejected to the environment.

The key insight that made the project viable was the recognition that this distributed, variable waste heat resource could serve as the heat source for a large-scale heat pump. Rather than treating waste heat as a disposal problem, the project reframes it as a valuable input, an energy resource that, when upgraded through a thermodynamic cycle, can supply a significant fraction of the mill's steam demand. The concept is described as a "Heat Upgrade" system: a configuration that captures waste heat streams at multiple temperature levels, consolidates them, and transforms them into high-quality steam. The variability of the waste heat resource was a significant design challenge as the system must be capable of operating effectively across a wide range of input conditions, maintaining stable steam output even as the heat source fluctuates with changes in the upstream production process.

3.1 System architecture

The heat upgrade system developed consists of two primary subsystems working in coordination. The first is a large-scale heat pump operating on a hydrocarbon refrigerant cycle. This machine recovers waste heat from the paper mill process through a pressurised hot water loop, upgrades it thermodynamically, and delivers heat at a temperature level suitable for steam generation. The choice of hydrocarbon refrigerant reflects both thermodynamic performance requirements and environmental considerations, as natural refrigerants have negligible global warming potential. The second is a steam compressor operating in series with the heat pump. The steam compressor takes lower-pressure steam and mechanically compresses it to the pressure and temperature levels required by the paper mill process. By combining the heat pump and the steam compressor in series, the system achieves output conditions that neither machine could reach independently, while maintaining acceptable efficiency.

The connection between the paper mill's waste heat streams and the heat pump is made through a pressurised hot water loop. This intermediate circuit acts as a buffer and aggregator, collecting thermal energy from the distributed waste heat sources and delivering it to the heat pump evaporator at a controlled and stable temperature. The design of this loop was a critical element of the system engineering, directly influencing the heat pump's operating stability and efficiency. The system also includes an electric boiler, which operates in parallel with the heat pump and steam compressor combination. The two heat generation systems operate simultaneously, together replacing the gas-fired boilers as the primary steam supply under normal operating conditions. The gas boilers are retained in the plant and can be brought online rapidly if needed, providing a safety net that was an important element in securing the client's commitment to the project.

The combined system delivers a total thermal output of approximately 12 MW, equivalent to around 18 tonnes per hour of steam. This output is fed into the mill's steam distribution network which aggregates supply from all sources and distributes it to the various process consumers.

4 Commissioning: Challenges and solutions

Commissioning any large industrial system is a complex undertaking. Commissioning a system that is genuinely novel, one for which there is no established operational blueprint, no fleet of reference installations, and no accumulated operational knowledge to draw upon, is an order of magnitude more demanding. This heat pump system is, by any reasonable definition, a first-of-a-kind installation. While the individual technology components are based on established engineering principles, their combination in this configuration, at this scale, and in this operational context, had no precedent. The commissioning team was operating at the frontier of available knowledge, required to make real-time engineering judgements in situations that had not been anticipated during the design phase.

4.2 Cold commissioning

Cold commissioning focused on validating the mechanical and electrical installation, verifying instrumentation, testing safety systems, and confirming the logic of the control system in a controlled environment. This phase confirmed the mechanical integrity of the pressurised hot water loop, verified the operation of all isolation and control valves, and validated the sensor configuration and signal routing throughout the system. The control system architecture was particularly important to validate at this stage. The heat pump and steam compressor operate as an integrated system, with the control logic responsible for managing the interaction between the two machines, responding to changes in heat source conditions, and maintaining stable steam output. The complexity of this control task, particularly in the face of the variable waste heat input from the paper mill, required careful programming and validation before thermal operation could begin.

4.3 Hot commissioning: Confronting real conditions

Hot commissioning, when the system is brought to operating temperature and thermal performance is progressively established, is where a first-of-a-kind installation reveals its true character. Inevitably, the real conditions at the site differ, in ways both anticipated and unanticipated, from the conditions modelled during the design phase. Here, a primary challenge encountered during hot commissioning was the management of variability and transients in the waste heat input to the heat pump. The paper mill's production process generates waste heat streams whose quantity and temperature are not constant, they vary with production rate, product type, machine settings, and a host of other operational factors. While this variability had been anticipated in the design, its actual character at the specific operating conditions of the mill required adaptation both in the configuration of the heat recovery system upstream of the heat pump and in the heat pump's own control strategy.

The engineering team worked to stabilise the thermal spikes in the heat pump's input as sudden increases or decreases in the temperature or flow rate of the waste heat stream, through a combination of adjustments to the upstream heat recovery configuration and refinements to the heat pump control logic. The goal was to ensure that fluctuations in the waste heat source were absorbed and buffered before they could propagate into the heat pump's operating cycle in ways that would compromise performance or stability.

4.4 Managing process transients: The paper break challenge

Among the transient events that a paper mill heat pump installation must manage, the paper break is perhaps the most significant. A paper break occurs when the paper sheet, running continuously through the machine at high speed, tears. This is a relatively common occurrence caused by defects in the sheet, tension imbalances, or other process disturbances. When a paper break occurs, the machine must be stopped or significantly slowed while the sheet is re-threaded. This has an immediate and significant consequence for the mill's heat balance: the thermal loads in the drying section drop sharply, and the waste heat streams feeding the heat pump's input loop undergo a sudden and substantial reduction.

This rapid reduction in heat input creates a dangerous operating condition. The heat pump compressor at the heart of the system is susceptible to surge, a phenomenon in which the flow through the compressor reverses in an uncontrolled manner, causing severe mechanical stress and potentially damaging the machine. Surge typically occurs when the compressor is asked to maintain a pressure ratio that exceeds its capability at the available flow rate, precisely the condition that arises when the heat pump's thermal input collapses suddenly. Managing this surge risk in the context of real paper mill operations was one of the most demanding technical challenges of the commissioning phase. The solution developed by the engineering team involved two complementary approaches.

First, the control system was refined together with the Customer to have an effective communication between the pressurised hot water loop and the heat pump control logic. This gave the heat pump system the ability to adjust operating conditions in a controlled manner and avoid surge. Second, the heat pump and steam compressor control strategies were refined to manage the transition through partial load conditions more effectively, maintaining the machine's operating point within safe boundaries even as conditions changed rapidly. This required detailed analysis of the compressor's operating map and careful calibration of the control response. The successful resolution of this challenge, one of the most technically demanding problems in the heat pump field, while maintaining the system's steam delivery capability, represents a significant achievement of the project commissioning programme.

4.5 Trial run and handover

Following the resolution of the major commissioning challenges, the system entered the trial run phase: a defined period of monitored operation under commercial conditions, during which performance was verified against contractual guarantees and the operational team at the mill gained experience in managing the new system. The trial run confirmed that the system was capable of stable, sustained operation under the full range of conditions encountered at the mill, including the transient events that had required the most significant adaptation during hot commissioning. With the trial run successfully completed, the system was handed over for commercial operation in the summer of 2025.

4.6 Warm start capability and load flexibility

One of the practical requirements that emerged clearly during the commissioning programme was the need for the system to be capable of returning to full operation quickly after a planned or unplanned stop, a so-called warm start, performed when the plant's thermal mass is still partially at temperature. In a paper mill environment, where production scheduling is continuous and steam demand cannot easily be deferred, a heat pump system that requires hours to reach full output after a shutdown would impose unacceptable constraints on operational flexibility. The commissioning team devoted significant attention to optimising the warm start sequence. By exploiting the residual thermal energy stored in the pressurised hot water loop and in the heat pump circuit itself, the system was demonstrated to be capable of returning to stable steam delivery within a few minutes of restart, a performance characteristic that is directly comparable to that of a conventional electric boiler and well within the operational expectations of the paper mill.

This rapid restart capability, validated during the trial run under real plant conditions, was a significant result. It demonstrated that a large steam-generating heat pump of this complexity is not condemned to the slow, carefully managed starts characteristic of some large thermal machines, but can instead exhibit the operational agility that industrial processes demand. Equally important was the demonstration of the system's ability to modulate its steam output continuously and stably across a wide operating range. The heat pump and steam compressor combination was shown to follow variations in the mill's steam demand smoothly, adjusting output without the step changes or oscillations that would be detrimental to paper quality. This load-following capability is a prerequisite for the system to function as a genuine primary heat source rather than a base-load supplement, and its successful demonstration during commissioning was a key milestone before handover.

5 Operation and performance

5.1 Performance, availability and reliability against contractual guarantees

The most fundamental measure of any industrial energy system's success is its performance in commercial operation relative to the guarantees provided at the time of sale. For a first-of-a-kind installation, this comparison carries particular significance. The system has, in the first nine months of commercial operation, demonstrated performance that meets and in several operating conditions exceeds the contractually guaranteed values (as a reference the guaranteed steam flowrate was 18 t/h and the system is delivering between 20 and 21 t/h, with a COP between 1.9 and 2 in different operating conditions). The system has consistently delivered the required steam output at the specified temperature and pressure, confirming the validity of the engineering approach and the thermodynamic models on which it was based.

Beyond raw thermal performance, the operational availability of the system is a critical metric for an industrial client whose production process depends on a continuous steam supply. The system has demonstrated availability performance in line with contractual commitments, operating continuously over extended periods with planned and unplanned outages both within the expected parameters for a system of this type in its first year of operation. The engineering team has maintained close engagement with the plant operation throughout, using data from the system's instrumentation network to identify and implement improvements on a continuous basis.

5.2 Continuous improvement: From operational data to enhanced performance

One of the distinguishing features of this project is the systematic use of operational data to drive continuous performance improvement. The system is equipped with comprehensive data logging capabilities, capturing parameters across all major subsystems at high temporal resolution. Analysis of the first nine months of commercial operation has provided the engineering team with a detailed picture of system behaviour across the full range of conditions encountered at the mill, identifying opportunities to enhance efficiency and operating flexibility beyond the already-above-guarantee baseline. This iterative approach is characteristic of how genuinely novel technologies mature in industrial service. The project is not simply a static demonstration of a technology concept; it is an evolving engineering programme that is progressively refining the performance of a complex system in its natural operational environment.

6 Operational evidence: A representative day of plant data

The operational characteristics described above are well illustrated by Figure 2, which presents logged plant data from a representative day of commercial operation (30 December 2025). The figure plots three key

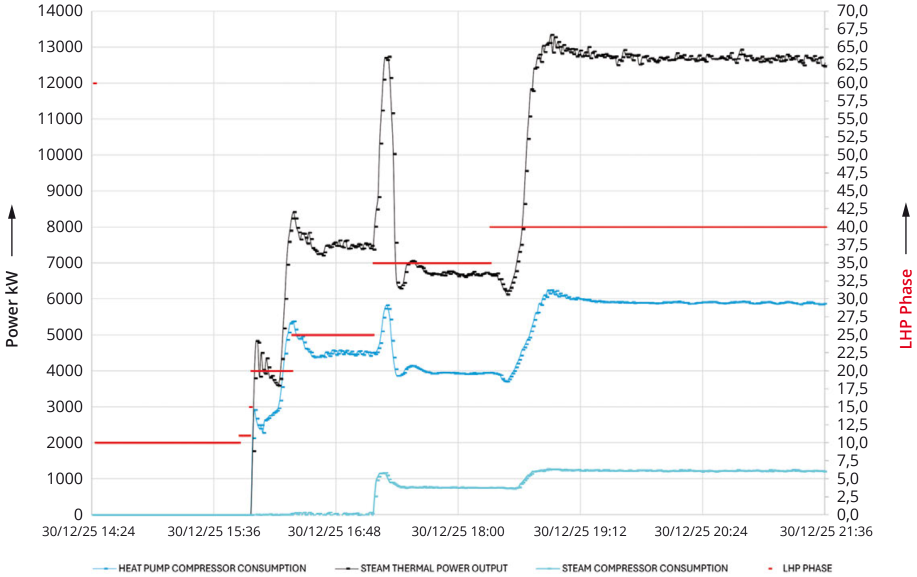

Fig. 2. Operational data from the heat upgrade system, 30 December 2025.

operational variables against time across a seven-hour window: the total thermal power delivered as steam (Steam Total Thermal Power, black curve), the electrical consumption of the heat pump compressor (light blue dashed curve), and the electrical consumption of the steam compressor system (cyan curve). The right-hand axis indicates the LHP operating phase, marked in red to allow correlation between the machine's control state and the measured power values. The chart (Figure 2) captures a complete operational sequence, from a warm start in the early afternoon through progressive load steps to sustained full-load operation in the evening hours. What is immediately apparent is the speed and smoothness of the start-up sequence. From the moment the system is brought online, the total steam thermal power ramps upward in a controlled progression through a series of distinct operating phases, each corresponding to a step increase in the LHP phase value shown on the right axis. The transition between phases is orderly and rapid, with the system reaching stable intermediate output levels within minutes of each step change, a direct illustration of the warm start agility described in Section 4.6.

The most operationally revealing feature of the chart is the sharp transient visible around 16:45. At this point, the total steam thermal power surges briefly to a peak of approximately 12,500 kW before dropping rapidly to around 7,500 k, a reduction of roughly 40 % in thermal output occurring within a few minutes. This transient is characteristic of a process disturbance in the upstream paper mill, most likely a paper break or a sudden reduction in machine load. The system's response, absorbing the disturbance, traversing partial-load operation without tripping, and then stabilising at a new lower output level, is a direct validation in commercial operation of the surge management strategies developed and tested during hot commissioning. Following this transient, the system can be seen re-stabilising progressively, with the LHP phase stepping upward again as the heat input recovers and the control system advances the operating point through successive load stages. By approximately 18:30, the plant has reached and sustained its maximum thermal output, delivering steam at power levels in excess of 12,000 kW, close to the full rated capacity of 12 MW.

The heat pump compressor electrical consumption (light blue dashed curve) tracks closely with the thermal output, as expected for a machine whose electrical load is proportional to the mechanical work input to the thermodynamic cycle. The steam compressor electrical consumption (cyan curve) rises and stabilises in a pattern consistent with the steam compressor operating at its design point during full-load operation. The alignment between these three traces (thermal output, heat pump compressor power, and steam compressor power) across the full operating day provides a coherent and internally consistent picture of a system performing as engineered. Taken together, the data presented in Figure 2 capture in a single operational snapshot the key attributes that were the objectives of the commissioning programme: rapid warm start, stable load following, resilience through process transients, and sustained full-load efficiency. The fact that this performance was recorded not during a controlled test but during a routine day of commercial operation underlines that these are genuine operational characteristics, not artefacts of a favourable test condition.

6 Conclusions and outlook

6.1 Technical significance

The successful commissioning and commercial operation of this heat pump system represents a significant milestone for the industrial heat pump sector. For the first time, a large-scale steam-generating heat pump of this configuration has been demonstrated under sustained commercial conditions in a real industrial environment. The challenges overcome during commissioning have generated engineering knowledge and validated control strategies that did not exist before this project. This knowledge now resides within the company's engineering organisation, enriching its design models, simulation tools, and operational expertise.

6.2 De-risking the next projects

This project has significant implications for the broader development of the industrial HTHP market. Its primary contribution is to de-risk the category for future clients and investors. Until recently, the absence of reference installations for large steam-generating heat pumps in industrial service was a significant barrier to new project development. Prospective clients and their financing partners faced a fundamental uncertainty: while the engineering principles were sound and the performance models credible, there was no operational evidence that a system of this type would perform as designed in real industrial conditions, over sustained periods, while coping with the full range of process dynamics that characterise actual manufacturing environments.

This heat pump project provides that evidence. It demonstrates that a 12 MW steam-generating heat pump can be successfully engineered, commissioned, and operated in a real paper mill; that it can cope with the process transients inherent in paper manufacturing; and that it can deliver performance over an extended operational period. This demonstration fundamentally changes the risk profile of similar projects, making them more credible to clients, more attractive to investors, and more financeable on competitive terms. The engineering knowledge accumulated through this project also has direct economic implications. The design models, control algorithms, and operational insights developed for this plant can be applied directly to the next HTHP projects, reducing the engineering effort required, shortening commissioning timelines, and improving the confidence with which performance guarantees can be made. Future projects benefit from the fact that they are no longer first-of-a-kind installations.

6.3 Large heat pumps as flexible grid assets

The operational experience gained in managing the heat pump's response to the variable thermal loads of the paper mill process has direct relevance to a broader challenge in the energy system: the management of flexibility in electricity grids characterised by high penetrations of variable renewable generation. Large industrial heat pumps consume significant quantities of electrical power. Their ability to modulate their consumption, increasing it when renewable generation is abundant and electricity prices are low, reducing it during periods of scarcity, makes them natural candidates for participation in demand response and grid flexibility services. The experience accumulated in managing the heat pump's response to rapid changes in process conditions, absorbing transients, maintaining output stability, and operating efficiently across a wide range of partial load conditions, is directly applicable to the challenge of grid-responsive operation. The project, while developed primarily as an industrial energy solution, points toward a future in which large industrial heat pumps serve a dual function: supplying heat to the process and providing flexibility to the grid.

6.4 Looking forward

The knowledge, validated models, and operational experience accumulated through the project provide a strong foundation for the implementation of future industrial HTHP projects for the company. The sectors with the greatest near-term potential (pulp and paper, food and beverage, chemicals, district heating) share many of the characteristics that made this project both challenging and rewarding as variable heat sources, demanding process requirements, and a strong economic case for electrification given the current trajectory of energy prices and carbon costs.

For industrial clients in these sectors considering HTHP deployment, the project offers both a technical reference and a message of practical encouragement: the technology works, it can be engineered to meet demanding process requirements, and it can be operated reliably at scale. The challenge of the first-of-a-kind has been met. The path to the next generation of projects is clearer and less risky than it was before.

Kurzfassung

Inbetriebnahme und Betrieb der ersten großen Dampferzeugungs-Wärmepumpe ihrer Art unter kommerziellen Bedingungen

Hochtemperatur-Wärmepumpen (HTHPs) zur Bereitstellung von Prozessdampf gewinnen in der Industrie zunehmend an Bedeutung. Vor diesem Hintergrund nimmt das von Turboden für die delfort-Gruppe realisierte Projekt eine besondere Stellung ein. Die Anlage kombiniert erstmals eine großtechnische Kohlenwasserstoff-Wärmepumpe mit einem Dampfkompressor in Reihenschaltung und stellt 12 MW thermische Leistung in Form von hochwertigem Prozessdampf bereit. Nach der Inbetriebnahme im Sommer 2025 ermöglichen umfangreiche Betriebsdaten eine belastbare Bewertung unter realen Bedingungen. Der Beitrag beschreibt das Projekt von der Konzeption bis zum Betrieb und stellt Systemarchitektur, Inbetriebnahme sowie erste Betriebsergebnisse vor. Im Mittelpunkt steht die Nutzung dezentral anfallender Abwärmeströme als Energiequelle. Durch ihre thermodynamische Aufwertung kann ein erheblicher Teil des Dampfbedarfs des Werks gedeckt werden.