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Overcoming system complexity: dynamic simulation of heat pump integration in paper drying

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Abstract

High-temperature heat pumps (HTHPs) are emerging as a key technology for industrial decarbonization and are particularly promising for steam-intensive processes such as paper drying. However, integrating HTHPs into existing steam networks remains challenging due to strong process dynamics, tight control requirements, and uncertainties regarding economic feasibility. This study investigates these aspects through a dynamic system simulation that couples a detailed drying-section model with a combined closed-loop compression heat pump (CLCHP) and mechanical vapor recompression (MVR) unit. The system generates 5.9 MW of steam at 5 bar using moist exhaust air at 86 °C as the heat source and achieves a global COP of 2.1. A techno-economic analysis (TEA) is performed for major European paper-producing countries, while particular emphasis is placed on evaluating transient behaviour and control strategies under disturbances such as rapid steam-demand reductions during paper breaks. Results demonstrate that while the HTHP is economically competitive under dynamic price scenarios, steady-state analysis alone is insufficient for assessing feasibility. Dynamic simulations reveal significant control challenges, including strong coupling between pressure and superheat regulation and the risk of compressor limit violations during paper breaks. A cascade-control strategy is shown to improve stability but still approaches operational boundaries. The findings highlight the necessity of dynamic simulation and control-oriented design in future industrial HTHP deployments and provide guidance on robust integration strategies for paper drying applications.

Keywords: high temperature heat pumps; paper drying; dynamic behaviour; control strategies; techno-economic analysis

1. Introduction

Decarbonizing industrial heat supply is fundamental for meeting global climate targets. Approximately 70 % of industrial energy demand in the EU is used for process heat, the majority of which is supplied by fossil fuels [1], [2]. Steam-intensive processes represent particularly attractive opportunities for electrification. High-temperature heat pumps (HTHPs) offer a renewable pathway to replace natural-gas boilers and achieve efficient steam generation from waste heat and electricity. While heat pumps below 100 °C are widely deployed, applications above this temperature remain limited due to technological immaturity and integration challenges [3].

The paper industry is one of the most energy-intensive manufacturing sectors. Drying alone can account for up to 40 % of production costs [4], and the Confederation of European Paper Industries aims to reduce CO_2 emissions by 80 % by 2050 compared to 1990 levels [5]. The drying section of a paper machine uses steam-heated multi-cylinder dryers, making HTHPs particularly relevant for this application. Furthermore, the moist exhaust air from the hood offers a valuable waste-heat source that can be upgraded through an HTHP to produce steam.

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This work develops a dynamic simulation environment to evaluate the technical, economic, and operational feasibility of HTHPs for steam supply in paper drying. A detailed model of the drying section is coupled with a closed-loop compression heat pump (CLCHP) using R-600 and a downstream mechanical vapor recompression (MVR) stage. The model is used to evaluate steady-state performance, techno-economic feasibility, and—most importantly—the dynamic behaviour of the integrated system under realistic disturbances such as paper breaks. While techno-economic analysis provides insight into long-term cost competitiveness, only dynamic simulation can reveal whether an HTHP can maintain stable operation during rapid load changes, which are inherent in paper-machine operation [6]–[9].

The main contribution of this study is the systematic analysis of the control requirements and transient performance of an HTHP integrated into a drying section. The results provide guidance for the design and operation of HTHP systems in pulp and paper production and highlight the need for control-oriented integration strategies to ensure industrial feasibility.

2. Methodology

This section describes the modelling framework developed to analyse the integration of a high-temperature heat pump (HTHP) into a paper-machine drying section. The overall system is modelled using a component-oriented, physics-based approach implemented in Modelica. The drying section and heat pump models are formulated as lumped-parameter 0D/1D representations capturing mass and energy balances, phase change and dominant thermal storage effects. Spatially resolved phenomena such as detailed flow fields, moisture gradients within the paper web or local heat transfer coefficients are not resolved. Instead, the modelling focus lies on capturing the coupled dynamic behaviour between the paper machine, the steam system and the heat pump under transient operating conditions. This level of detail is sufficient for analysing control interaction, disturbance propagation and operational stability, which are the primary objectives of this study

2.1. Modelling of the drying section supplied by an HTHP

The drying section is implemented in Modelica using the TIL Suite libraries (TLK-Thermo, TLK Energy), which provide component-based models for humid-air flows, heat exchangers, steam systems and rotating machinery. The model setup is based on the PM7 paper machine, a large-scale industrial paper machine located in Husum, Sweden, which offers one of the most complete experimental datasets available for a single machine, including temperature profiles, steam pressures and hood-air conditions [8], [11].

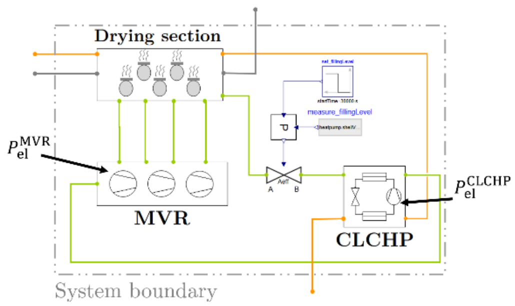

Figure 1. Model of the drying section supplied by a HTHP with steam.

Figure 1 illustrates the coupled drying section and heat pump system. The heat source of the CLCHP is the moist exhaust air from the drying hood at approximately 86 °C, while the heat sink corresponds to the condensate stream supplying the steam system. Downstream of the CLCHP, mechanical vapour recompression raises the steam pressure to 5 bar, corresponding to the operating conditions of the drying cylinders. The indicated temperature and pressure levels represent nominal steady-state operation and serve as reference points for the subsequent dynamic analysis.

The drying section consists of multiple steam-heated cylinders arranged in groups. The paper web is guided over the cylinders at high speed, evaporating moisture until a dry-solid content of above 90 % is reached [6], [9]. Each drying group is supplied by a dedicated steam header. The steam pressure increases stepwise between groups to maintain an adequate temperature gradient and heat-transfer rate.

Inside each cylinder, steam condenses on the inner surface, releasing latent heat to the cylinder shell. Condensate is extracted via siphon systems and collected in a condensate header. The condensation phenomena and heat-transfer coefficients are represented using the correlations implemented in TIL.

The drying section is enclosed by a hood that controls humidity, temperature and airflow. Moist exhaust air leaves the hood at around 86 °C and contains a significant amount of recoverable thermal energy. The moist-air flow is modelled using TIL's humid-air library, including humidity ratio, dewpoint and latent-heat interactions. This exhaust-air stream serves as the main heat source for the HTHP.

Since the coefficient of performance of the heat pump depends strongly on the temperature levels of the heat source and sink, variations in exhaust air temperature and steam pressure are captured dynamically in the model, including the resulting temperature glides across the heat exchangers.

The combined hood and drying-group model was validated against PM7 measurement data from Husum. Cylinder surface temperatures, pressure levels and exhaust-air states show good agreement with the measurements reported in Ekvall [8], confirming the model's ability to represent both stationary and transient conditions.

2.2. Modelling of the HTHP system and control loops

The steam supply is provided by a high-temperature heat pump consisting of a closed-loop compression heat pump (CLCHP) operating with R-600 (n-butane) and a downstream mechanical vapour recompression (MVR) unit. Such hydrocarbon-based HTHPs have been demonstrated to reach sink temperatures around 120–130 °C at acceptable compressor pressure ratios [3], [17].

The CLCHP comprises an evaporator, compressor, internal heat exchanger (IHX), condenser, and thermostatic expansion valve. The evaporator extracts heat from the moist exhaust air of the drying section at 86 °C. The condenser upgrades the condensate stream leaving the drying cylinders (107 °C, 1.3 bar) to produce steam at 5 bar, supplying 5.9 MW back to the drying section.

Downstream of the CLCHP, an MVR stage compresses part of the steam to reduce the required thermal lift in the condenser and to increase the overall system COP. The flow split and recompression scheme follow the concept described in Gobbers [18].

Two primary control loops govern CLCHP operation:

(1) Superheat control:

A PI controller adjusts the valve opening area to maintain a small but positive superheat at the compressor inlet, preventing liquid carry-over.

(2) Condenser pressure (steam saturation temperature) control:

A PI controller modulates compressor speed to achieve the desired steam pressure at the condenser outlet.

These two loops interact weakly but maintain stable operation under steady conditions. This structure aligns with standard industrial HTHP concepts for steam generation [3], [12], [17].

During a paper break, the drying section no longer removes energy from the steam via the paper-web evaporation process. As a result, cylinder surface temperatures rise rapidly. Industrial practice reduces the steam pressure to a uniform level of about 1.8 bar to avoid overheating [8]. This behaviour is implemented via a boolean switch in the model, which transitions the system between normal-operation and break-operation control structures.

The resulting dynamic interaction between the drying section and the HTHP is one of the main focuses of this study.

2.3. Techno-economic modelling

A techno-economic analysis (TEA) evaluates the competitiveness of the HTHP against a natural gas boiler, which represents the standard steam-generation technology used in paper mills. The boiler efficiency is taken as 0.9, typical for modern installations [12], and is referenced to the lower heating value (LHV).

The techno-economic assessment is based on the net present value (NPV) of total system costs, consisting of investment costs (CAPEX) and discounted annual operating expenses (OPEX) over the assumed lifetime. Operating expenses include electricity and fuel costs derived from annual operating hours and country-specific energy price trajectories, as well as maintenance costs represented by a fixed fraction of CAPEX. These cost components are combined to calculate the levelized cost of heat (LCOH), which enables a consistent comparison between the heat pump system and the reference gas boiler.

The economic comparison is based on the levelized cost of heat (LCOH):

$$LCOH = \frac{|NPV|}{\sum_{t=1}^{n} \Delta t \; \dot{Q}_{steam} \frac{(1+r)^t}{(1+i)^t}} \qquad (1)$$

with:

- $n = 15$years lifetime
- discount rate $i = 5\,\%$
- inflation rate $r = 2\,\%$
- operating hours $\Delta t = 8400\,\text{h/a}$
- steam demand $\dot{Q}_{\text{steam}}$

Investment costs include CLCHP and MVR units, scaled via established specific cost correlations [12]. To reflect planning and integration efforts, a multiplication factor of 3 is applied. Maintenance costs are modelled as 6 % of CAPEX per year [12].

Electricity and natural-gas prices, as well as grid emission factors, are taken from the ENTSO-E/ENTSOG TYNDP “National Trends” scenario for 2025–2039 [14]–[16]. Prices are interpolated linearly between annual values. CO_2 certificate prices follow the same scenario. The five largest paper-producing countries in the EU are considered: Germany, Sweden, Italy, Spain and the EU average [14], [15].

2.4. *Model validation and scope of applicability*

Model validation focuses on reproducing steady-state operating points and the qualitative dynamic response of the drying section during disturbances. Deviations in the timing of fast transients between measurements and simulation are expected due to the use of lumped thermal capacities and simplified representations of machine internals. Nevertheless, the model reliably captures the dominant interactions between steam pressure, cylinder temperature and heat pump operation, allowing robust conclusions on control behaviour and system integration.

3. Techno-economic Results & Discussion

This section compares the economic performance of the proposed HTHP concept—consisting of a closed-loop compression heat pump (CLCHP) using R-600 and a downstream mechanical vapour recompression (MVR)—with a conventional natural gas boiler. The comparison uses country-specific energy prices and CO_2 certificate costs from the ENTSO-E/ENTSOG “National Trends” scenario [14]–[16].

3.1. Results

The CLCHP achieves a COP of 2.9, and the combined CLCHP–MVR system reaches a global COP of 2.1, values consistent with current high-temperature hydrocarbon heat pump demonstrations [17]. Maximum refrigerant pressure and temperature (20.1 bar, 126.1 °C) remain within allowable limits for R-600. The compressor pressure ratio of 3.9 indicates feasible operation.

The exhaust air leaves the evaporator at 64.9 °C, providing a recoverable exergy potential of 10.2 MW. The specific electricity demand is 336 kWh per tonne of produced steam, which aligns with reported values for comparable HTHPs [3]. The integration of the MVR increases the global COP by approximately 0.1 due to partial steam recirculation [18].

Table 1 summarises the levelized cost of heat (LCOH) for the evaluated countries. The HTHP outperforms the gas boiler in all cases, with cost reductions ranging from 0.1 ct/kWh (IT) to 5.7 ct/kWh (SE).

Table 1. LCOH in ct/kWh for the countries DE, ES, IT, SE and EU for the natural gas boiler and the CLCHP & MVR.

LCOH [ct/kWh]	EU	DE	ES	IT	SE
Ref: natural gas boiler	5.6	6.2	4.4	5.4	9.8
HTHP: CLCHP & MVR	5.2	5.7	3.2	5.3	4.1

Energy costs dominate the LCOH for both systems. For the boiler, they account for 98.8 %, while the HTHP allocates 83.4 % of its LCOH to electricity, with CAPEX and maintenance making up the remainder.

Table 2. Normalized cost breakdown of the LCOH into CAPEX, energy and maintenance cost for both steam supply concept, averaged across all countries.

Cost category [%]	Ref: natural gas boiler	HTHP: CLCHP & MVR
CAPEX per LCOH	0	13.4
Energy costs per LCOH	98.8	83.4
Maintenance costs per LCOH	1.2	3.2

3.2. Discussion

The results indicate that the CLCHP–MVR concept is economically competitive in all examined countries. Two cases illustrate the main drivers:

- **Spain:** low energy prices lead to generally favorable LCOH values across technologies.
- **Sweden:** high gas prices and comparatively low electricity prices create particularly favorable conditions for HTHPs.

The CLCHP-only configuration becomes viable only in Sweden, consistent with the sensitivity analysis in [18]. Furthermore, the study confirms that static 2025 prices would not yield feasible results; only dynamic energy-price trajectories maintain competitiveness.

Potential cost reductions through renewable integration (e.g., PV) remain modest, reducing LCOH by about 0.1 ct/kWh [18], suggesting that operational efficiency and robust control strategies are more critical for improving economic performance.

4. Dynamic Behaviour and Control Strategy Assessment

The integration of a high-temperature heat pump (HTHP) into a paper-machine drying section introduces strong dynamic coupling between the steam supply and the drying process. While steady-state operation can be stabilised reliably, real paper-machine operation is dominated by fast disturbances—especially paper breaks—that trigger abrupt changes in steam demand, condensate return and hood-air conditions. These disturbances propagate directly into the heat pump cycle and challenge the control system, which must maintain safe operation despite rapidly shifting boundary conditions.

4.1. Disturbances and Their Propagation into the HTHP

When the paper web tears, evaporation on the cylinder surfaces stops immediately, removing the dominant heat sink of the drying section. Cylinder-shell temperatures rise rapidly unless the steam pressure is reduced. Industrial practice, and the approach implemented here, lowers all group pressures to a uniform safety level of about 1.8 bar to avoid overheating [8]. The simulated responses during such events match the PM7 measurement data from Husum [8], confirming that the model reproduces the relevant thermal dynamics of the drying section.

Figure 2 illustrates the transient response of selected cylinder groups and the corresponding internal steam pressures following a web break. The pressure and temperature signals are evaluated inside a representative drying cylinder, denoted as cyl.33, which is located in the later part of the drying section and is therefore particularly sensitive to disturbances in steam supply. The pressure response is significantly faster than the temperature response, as the latter is governed by the large thermal capacity of the cylinder shell and surrounding machine structure. The temperatures of the cylinder shells drop to the safety level of approximately 116.9 °C within a short period, while the internal steam pressures converge simultaneously toward the uniform 1.8 bar setpoint. This behaviour corresponds closely to both the operational strategy at the PM7 machine, and the trends observed in the validation measurements.

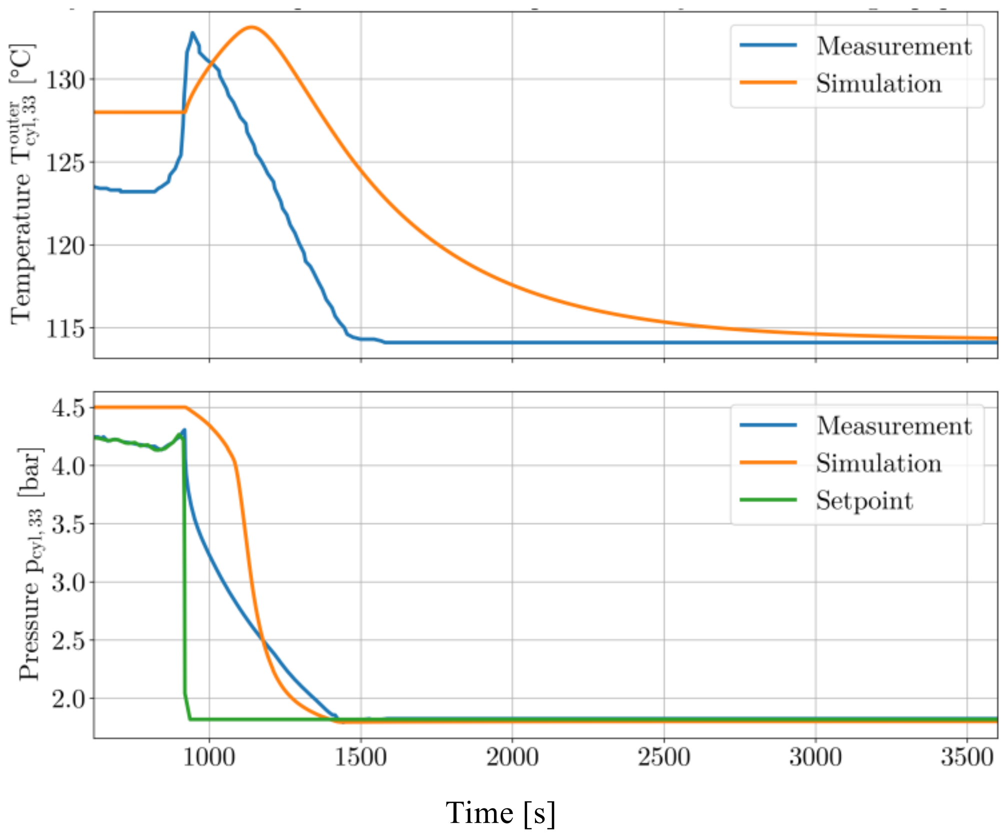

Figure 2. Transient progression of cylinder surface temperature and internal steam pressure during a paper break. The pressure of all drying groups is reduced to 1.8 bar to prevent overheating, leading to a corresponding drop in cylinder temperature to approximately 116.9 °C.

A paper break affects both the condenser and evaporator of the HTHP simultaneously. The sudden drop in steam demand reduces the thermal load on the condenser, causing the condenser pressure to fall. At the same time, the hood exhaust air cools because evaporation ceases, weakening the evaporator's heat source. With the evaporator load collapsing, the refrigerant tends to superheat excessively, which prompts the superheat controller to close the expansion valve. Meanwhile, the lower condenser duty causes the pressure controller to reduce the compressor speed. These competing actions, closing the valve and slowing the compressor, reinforce each other negatively. Neither loop can stabilise its controlled variable, leading to oscillatory evaporator pressure, unstable superheat and repeated shifts in compressor speed, consistent with the behaviour observed in previous studies [18].

4.2. Evaluation of Alternative Control Strategies

A first modification to improve robustness consists of regulating the evaporator pressure using an on–off strategy that maintains the pressure within a predefined safety band. While this prevents the pressure from collapsing during a break, the discrete valve movement introduces abrupt jumps in refrigerant mass flow, which propagate through the cycle and hinder superheat control. As a result, the on–off strategy improves safety margins but does not ensure smooth or reliable operation during real disturbances.

A more effective solution is a cascade control structure. In this approach, the evaporator pressure is regulated by an outer loop, which provides a dynamically adjusted setpoint to an inner superheat controller. This coordinated response reduces the interaction between valve and compressor and leads to significantly smoother pressure and superheat trajectories. During paper breaks, the cascade controller maintains control authority even when the boundary conditions change abruptly and avoids the large oscillations observed with PI or on–off control. However, the controller tends to drive the compressor closer to its upper operating limits during recovery, which remains within acceptable ranges for hydrocarbon compressors [17] but highlights the need for careful tuning.

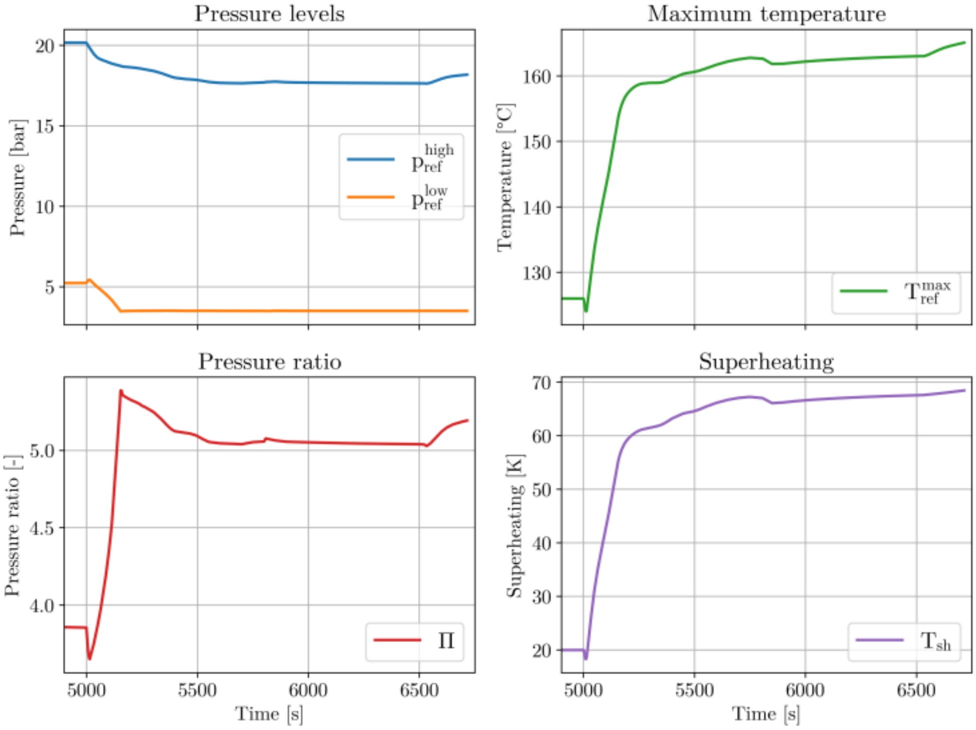

Figure 3. Dynamic response of the HTHP during a paper break using the cascade control strategy. Evaporator pressure, refrigerant mass flow, and superheat remain stable despite rapid changes in boundary conditions, avoiding the oscillations observed with on–off con

4.3. Implications for the CLCHP–MVR System and Industrial Operation

The hybrid CLCHP–MVR configuration adds further dynamics. Under normal conditions, the MVR increases the global COP through steam recirculation. During break events, however, the reduced steam mass flow lowers the recompression benefit and temporarily reduces MVR effectiveness. The coordinated cascade control of the CLCHP stabilises the system sufficiently to prevent unsafe MVR operation, but the interaction confirms that the MVR must be integrated explicitly into the control strategy rather than treated as a static add-on.

Overall, the results show that the central challenge of HTHP integration in paper drying is not the thermodynamic performance in steady state, but the ability to maintain stable operation during fast transients. Paper breaks impose simultaneous disturbances on both sides of the heat pump, and classical PI control structures cannot manage these interactions. Cascade control provides a substantial improvement, but further optimisation—such as predictive control or adaptive setpoint strategies—may be required for industrial application. Dynamic simulation thus plays a crucial role in derisking HTHP deployment and developing control strategies suitable for real paper-machine operation.

5. Conclusion

This study assessed the technical, economic and dynamic feasibility of supplying a paper-machine drying section with a high-temperature heat pump (HTHP). The coupled model of the drying process and a CLCHP–MVR system achieved stable steady-state operation at 5.9 MW and 5 bar steam with a global COP of 2.1, remaining within the reported limits for hydrocarbon-based HTHPs [17], [18]. The techno-economic analysis showed that the concept can outperform a natural-gas boiler in levelized heat costs across major EU paper-producing countries when future electricity, gas and CO_2 price trends are considered. The techno-economic assessment indicates levelized costs of heat between 3.2 and 5.7 ct/kWh for the CLCHP–MVR system across the investigated countries, consistently below those of the reference natural gas boiler.

The dynamic simulations revealed that transient behavior, especially during paper breaks, is the critical challenge for industrial implementation. Sudden changes in steam demand and hood-air conditions lead to strong interactions between the pressure and superheat control loops, which conventional PI control cannot stabilize. An on–off strategy improves safety but remains insufficient. A cascade controller coordinating evaporator pressure and superheat significantly enhances stability and keeps the hybrid CLCHP–MVR system operable during disturbances, although compressor loads approach upper limits during recovery.

Overall, the findings demonstrate that robust control strategies are essential for successful HTHP integration in paper drying. Dynamic modelling proves indispensable for identifying operational risks and guiding the development of suitable control architectures, enabling the broader deployment of high-temperature heat pumps in energy-intensive industries.

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