15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Increased efficiency through flexible design and operation of a heat pump system in paper drying

Sabrina Dusek[a,*], Sophie Knöttner[a], Peter Prinz[b], Thomas Strauss[c]

[a] AIT Austrian Institute of Technology GmbH, Giefinggasse 2, 1210 Vienna, Austria
[b] Heinzel Steyrermühl GmbH, Fabriksplatz 1, 4662 Laakirchen, Austria
[c] Laakirchen Papier AG, Schillerstrasse 5, 4662 Laakirchen, Austria

Abstract

The use of heat pumps in industrial processes offers great potential for increasing efficiency. Often, high temperature lifts are required leading to a low Coefficient of Performance (COP) and thus high operating costs. Additionally, requirements on the heat supply (e.g. steam pressure) may change depending on the product (e.g. paper type). To reduce operating costs, achieving the highest possible COP at every operating point is crucial. Consequently, a flexible design of the heat pump system can be essential to ensure economical operation.
So-called cylinder dryers are often used in paper manufacturing. In these dryers, the energy required for drying is supplied by steam-heated cylinders over which the paper web is transported. This process produces moist exhaust air with a high relative humidity of nearly 100%. A heat pump can be integrated in these processes to utilize the humid exhaust air to provide steam for the steam cylinders. In these drying systems, the steam requirements (pressure and mass flow) and the available waste heat (temperature, mass flow, and moisture content) generally vary depending on the actual product. If a heat pump is used, the heat pump system should be designed in a way that it can be operated as efficiently as possible at different operating points.
In this contribution, different heat pump system designs are compared with each other based on typical operating points of a paper machine. The results are compared in terms of energy saving potential. Moreover, it will be shown how flexible operation in response to electricity prices can affect economic efficiency of the system. For this analysis, a second technology, biomass boilers, is considered for periods with high electricity prices. The aim is to show that both a flexible design and flexible operation of a heat pump system offer advantages for economic feasibility.

Keywords: paper drying; heat pump application; flexibility; steam generating heat pump

1. Introduction

Industry is facing increasingly competitive economic frame conditions and at the same time dynamic operating environments, e.g. due to volatile markets but also internal variations in demand requirements. Thus, not only efficient, but also flexible energy supply is becoming more and more a relevant success factor for maintaining operational competitiveness.

For several sectors, e.g. pulp and paper production, heat pumps represent a promising technology option for industrial applications due to their high energy efficiency. However, they are typically not considered as highly flexible supply options. Industrial heat pumps are typical base load technologies and become especially attractive for transforming and decarbonizing industrial heat supply when having high coefficients of performance (COP) that enhance their economic attractiveness compared to conventional heating systems. Furthermore, their capital-intensity makes careful consideration of high full-load hours and efficient design necessary.

* Corresponding author. Tel.: +43 664 8251 411
E-mail address: Sabrina.Dusek@ait.ac.at

The application of heat pump technologies in paper drying to increase efficiency and for electrification is being discussed in different scientific contributions. In the course of the EU-funded project SPIRIT, Gollasch et al. [1] investigated the application of a steam compressor (mechanical vapor recompressor) in the steam network of a paper mill. The focus of their contribution was modelling the steam compressor system and developing a start-up procedure including a control strategy.

In this work, a simulation-based analysis was conducted to determine the optimal design and integration of heat pumps for steam provision in paper drying, accounting for varying operational conditions and system configurations. Moreover, due to the high temperature lift, a cascade system consisting of a closed heat pump and at least one steam compressor was considered in all investigated concepts. Chosing such a system design is based on findings, e.g. by a working group of EHPA and CEPI members [2] and also studied by Wilk et al. [3] for the application in a paper dryer. Various heat pump concepts for generic steam generation were also studied in Wilk et al. [4]. Here, also the combination of a closed heat pump and steam compressor promised the highest COP for the assumptions made.

To evaluate the economic performance of the investigated concepts, a static comparison of the operational cost-effectiveness of heat pumps versus an alternative decarbonization option—a biomass boiler—was performed. The findings from this analysis were subsequently used to determine the number of hours in 2024 during which heat pump operation would have been economically attractive under dynamic and volatile electricity market conditions.

2. Method

The basis for the investigations in this contribution is formed by three operating points (OPs) derived from real operating conditions of a paper machine, which are summarized in Table 1. In general, exhaust air flows occur in several zones of the paper machine, which have been simplified and combined into a single exhaust air flow. It was also assumed that heat recovery via heat exchangers, for example preheating of the dryer supply air, had already taken place. This means that the resulting exhaust air with the specified conditions is available purely for use by the heat pump. The composition of the exhaust air was determined as follows, with water and nitrogen content adjusted depending on the relative humidity at each OP: Argon 0.93 vol%, CO_2 0.04 vol%, O_2 20.04 vol%. A temperature of 80 °C was assumed for the condensate to be evaporated. In this application, steam is required at different pressure levels depending on the OP. For simplicity, it was assumed that saturated steam is required, although in real applications slightly superheated steam is often needed to compensate losses to the consumer. Furthermore, different steam mass flows are generated for each OP. Evaporating 70 t/h of water from 80 °C to 134 °C (saturation temperature at 3 bar_a) requires 46 MW heat capacity of the steam supply system. This is the OP with the lowest heating capacity required. For the investigations, it was therefore determined that the heat pump system has a maximum heating capacity of 50 MW and thus covers approximately the base load. The remaining share in the other two OPs is covered by an additional supply technology, e.g. a gas boiler or electric boilers, etc. For the analysis in this work it is not further investigated how the residual amount of steam is provided. The reference technology assumed for calculating annual energy savings is a natural gas fired steam boiler with an efficiency of 90%.

Table 1. Use Case

	OP 1 Low grammage	OP 2 Medium grammage	OP 3 High grammage
Steam demand, t/h	70	85	90
Steam pressure, bar_a	$p_l = 3$	$p_m = 4$	$p_h = 5$
Thermal capacity, MW	47	57	61
Exhaust air temperature, °C	52	65	61
Relative humidity exhaust air, %	88	99	91
Dew point temperature, °C	49	65	59
Exhaust air mass flow, t/h	665	606	628
Occurrence d/a,	108	123	30

Three different heat pump concepts were modeled and simulated using IPSEpro (Integrated Process Simulation Environment) [5] to assess the ecological impact in terms of final energy and CO_2 emission savings. The modeling is based on mass and energy balances and uses steady-state simulations.

The investigated heat pump concepts are shown in Fig. 1, Fig. 2 and Fig. 3. All concepts include an intermediate water cycle on the source side of a closed loop heat pump, into which heat from the exhaust air is fed via a heat exchanger, with a minimum pinch temperature of 10 K. The heat exchanger was modeled as a counterflow heat exchanger, using a heat transfer coefficient and a logarithmic mean temperature difference.

The closed loop heat pump is modeled based on the specification of a second law efficiency and the steam compressor based on the specification of an isentropic efficiency. On the source side of the closed loop heat pump a cooling of 10 K of the water intermediate cycle is assumed. A minimum temperature difference of 3 K was assumed for both the difference between the source outlet temperature and the evaporation temperature and between the condensation temperature and sink outlet temperature. The increase in pressure in the steam compressors is modeled in a single-stage, with condensate being injected at the outlet to obtain saturated steam. Any additional pumps required (e.g. intermediate water cycle) are not included in the model. Furthermore, heat pump system losses (e.g. electrical efficiency) were considered by a system efficiency factor of 0.92.

In the first heat pump concept, shown in Fig. 1, a closed heat pump generates saturated steam at 1 bar_a. This steam is then compressed in a steam compressor to the highest required steam pressure (5 bar_a) and then, depending on the OP, expanded in a valve to the respective pressure. To ensure saturated steam water is injected after expansion. In the model, isenthalpic expansion was assumed for the valves.

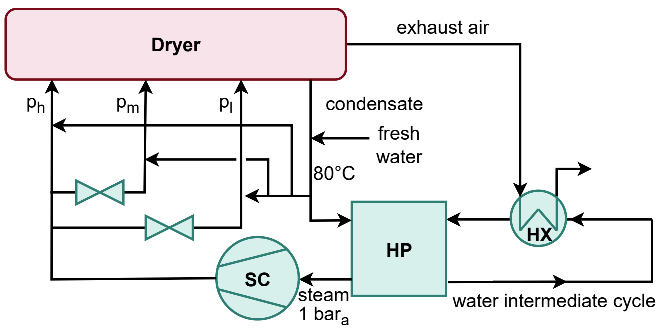

Figure 1. Heat pump concept 1 (SC … steam compressor, HP … heat pump, HX … heat exchanger, p_h … high pressure, p_m … medium pressure, p_l … low pressure).

Compared to the first concept, in the second concept shown in Fig. 2, saturated steam is generated at the lowest required pressure level (3 bar_a) using the closed loop heat pump and then compressed to either 4 bar_a (second compressor not in operation) or 5 bar_a (both compressors in operation) using two steam compressors connected in series.

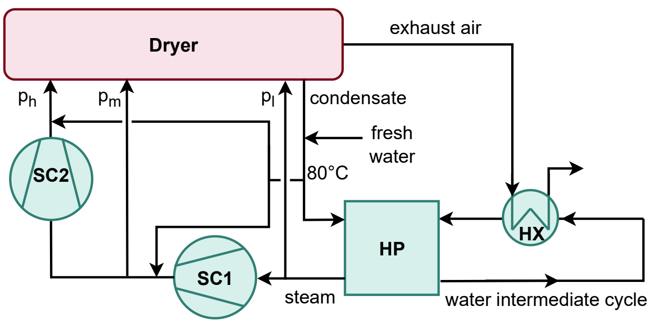

Figure 2. Heat pump concept 2 (SC … steam compressor, HP … heat pump, HX … heat exchanger, p_h … high pressure, p_m … medium pressure, p_l … low pressure).

Fig. 3 shows the third concept studied. Here, as in the first concept, the closed loop heat pump generates 1 bar_a of saturated steam. Subsequently, a maximum of three steam compressors are used in series to provide the steam pressures depending on the OP.

The three heat pump concepts were compared in terms of system COP and yearly final energy savings, with both the second law efficiency and the isentropic efficiency being varied from 0.4 to 0.6 and from 0.6 to 0.8, respectively. The variation ranges were derived based on selected manufacturer specifications published as part of the IEA HPT Annex 58 project [6] for on the one hand side direct steam-generating compression heat pumps operating in the subcritical range and on the second hand side steam compressors.

For the economic evaluation, first, average day-ahead electricity prices for Austria in 2024 [7] with average fees of 45 €/MWh (assumption based on Austrian fees) were related to average prices for biomass as energy carriers. For 2024, depending on the type of energy source – pellets, wood chips, or logs – costs were reported between 40 and 70 €/MWh [8]. These data points – specific average electricity prices incl. fees and biomass costs – were related to the maximum COPs reached with one of the configurations for the three OPs. In a second step fluctuating electricity prices incl. fees were considered, and it was derived in how many hours of the year the operation of a heat pump would have been beneficial for every OP from an operative point of view compared to a biomass boiler (with an assumed efficiency of 90%) with different costs of biomass.

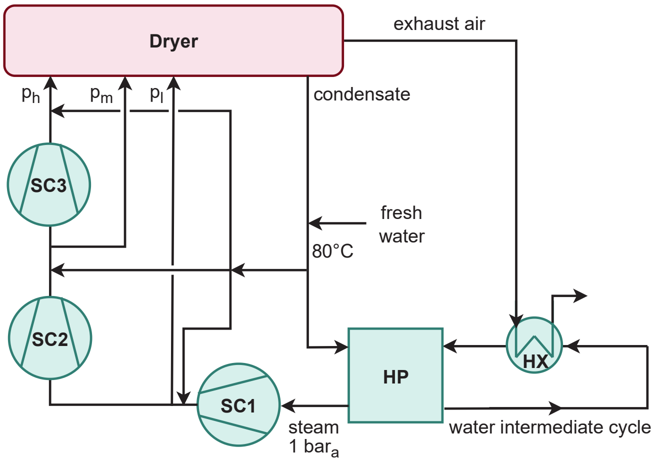

Figure 3. Heat pump concept 3 (SC … steam compressor, HP … heat pump, HX … heat exchanger, p_h … high pressure, p_m … medium pressure, p_l … low pressure).

3. Results and Discussion

In general, the use of a 50 MW heat pump system can save 61 kilo tons of direct CO_2 emissions and 76 kilo tons of CO_2 emissions annually when indirect emissions are considered. This result is based on the assumption of CO_2 emission factors for natural gas burning (efficiency of 90%) of 201 $g_{CO2,eq}$/kWh for direct emissions and 249 $g_{CO2,eq}$/kWh for indirect emissions [9]. In the case of electricity, green electricity was assumed, therefore neither direct nor indirect emissions are emitted.

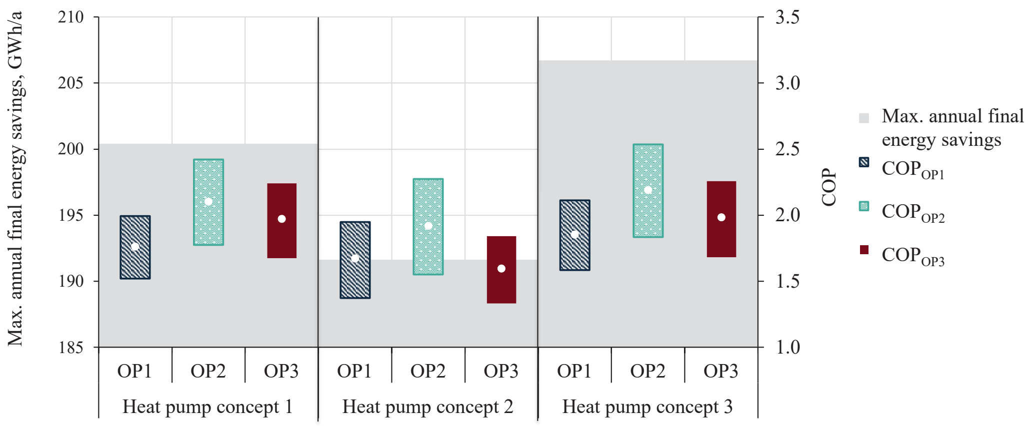

Figure 4. Annual energy savings and COP for the heat pump concepts and OPs evaluated.

Fig. 4 presents the results in terms of max. annual final energy savings and COP for the three heat pump concepts. The COP is also shown for each OP. The investigations have resulted in COPs between 1.33 and

2.54 depending on the operating point and heat pump concept. In general, OP2 provides the highest COPs (1.55 – 2.54) for all concepts, as this is where the source temperature and the dew point are highest. Moreover, the third heat pump concept delivers significantly better COPs (1.58 – 2.54) and annual final energy savings (162 – 207 GWh/a) than the other two heat pump concepts. Heat pump concept 2 delivers the lowest results, as the closed loop heat pump generates steam at 3 bar_a instead of 1 bar_a and therefore must overcome a significantly higher temperature lift. This result shows the positive influence of heat pump cascading in reducing the temperature lift for the individual stages.

In addition to saving energy and reducing CO_2 emissions, the use of a heat pump system also has the advantage that water is condensed from the exhaust air, which can be reused, thereby reducing fresh water consumption. In heat pump concept 3, a maximum of up to 249 kilo tons of water per year can be condensed from the exhaust air and reused in the production process.

In Fig. 5 the analysis of the static economic assessment of biomass boilers vs. industrial heat pumps systems for the best COPs reached in all three OPs is shown. Biomass boilers are more cost-effective in the upper-left region with comparably cheap biomass, while heat pumps become economically advantageous in the lower-right region where the electricity-to-biomass price ratio is lower, particularly when heat pumps operate at higher efficiency levels (steeper diagonal lines). The red diamond marks show, that for an average electricity price incl. fees in 2024 biomass prices between 50 and 60 €/MWh lead already to an operational economic advantage for heat pumps (excluding investment costs).

When considering a fluctuating time series for day-ahead electricity prices (see [7]) and evaluating the operational benefit compared to a biomass boiler the results summarized in Table 2 can be found when varying the biomass prices between 40, 60 and 80 €/MWh and assuming the best found COPs for all three operating points. While for low biomass costs of 40 €/MWh economically efficient heat pump operation is possible less than 30% of the time (1470 hours for OP1 and up to 3008 hours for OP3). However, already for 60 €/MWh, a significant change can be observed. The biomass boiler would have been economically preferred between 957 and 2697 hours. For 80 €/MWh for all operating points the biomass boiler is less than 500 hours per year economically advantageous.

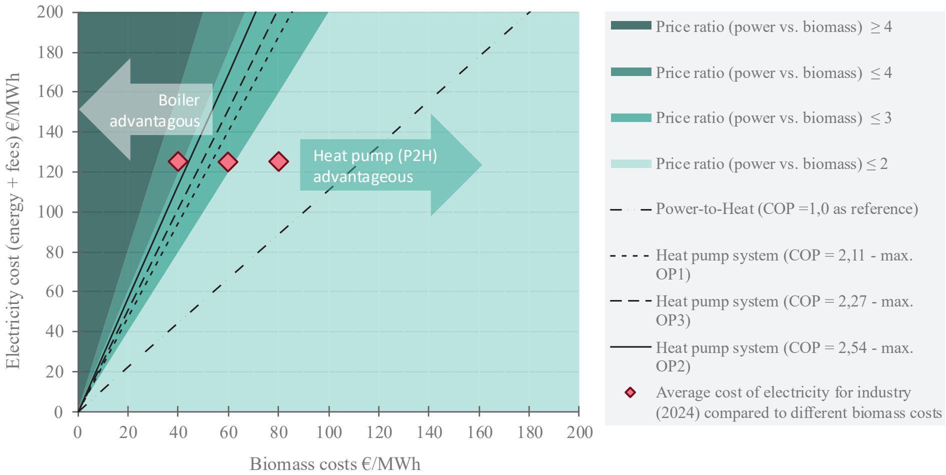

Figure 5. Static assessment of feasibility of heat pumps for decarbonization vs. biomass boilers. Price ratios between electricity and biomass are shown as different areas in the plot. Diagonal lines represent heat pump systems with varying COPs (2.11 to 2.54), indicating break-even points between the two technologies. Red diamonds mark average 2024 industry electricity costs at different biomass price levels.

Table 2. Hours of the year when biomass boilers are economically advantageous compared to heat pumps for the respective OPs of the best heat pump system design and a sensitivity analysis of different biomass prices.

	OP 1	OP 2	OP 3
	COP = 2.11	COP = 2.54	COP = 2.27
Biomass price 40 €/MWh	7290	5752	6818
Biomass price 60 €/MWh	2697	957	1870
Biomass price 80 €/MWh	495	140	274

4. Conclusion

In this contribution, three different heat pump concepts with a heat capacity of 50 MW are compared with each other based on three selected operating points of a paper machine. The analysis has shown that the concept that is most cascaded and tailored to the requirements at each operating point delivers the highest COP values and thus the highest final energy savings. This concept can achieve theoretical final energy savings of up to 206 GWh/a. The heat pump concept, in which steam is generated at the highest required pressure and then expanded to lower pressure levels depending on the operating point, in approximately 6 GWh/a less final energy savings in the maximum case. The result shows that a heat pump system design that is flexible to operating conditions and only supplies what is needed at the respective pressure level can provide significantly higher energy savings, although the investment costs must also be considered subsequently.

The operational economic assessment of the best heat pump design revealed, that high economically feasible full load hours would be possible already for biomass prices around 50-60 €/MWh. Within this range the evaluation of hours, where biomass boilers are advantageous indicate that flexibility is possible with such a proposed system configuration in combination with optimized operation schedules and paper production (furthermore OPs) aligned to market conditions feasible heat pump operation is becoming more realizable in the future.

Acknowledgements

This contribution is part of the research project DEEP (FO999924229). This project is funded by the Climate and Energy Fund and the FFG (www.ffg.at). The FFG is the central national funding agency and strengthens Austria's innovative capacity.

References

[1] Golasch J., Kriese M., Siegel J., Kabat N., Walden J. Numerical investigation of a heat pump demonstrator for partial electrification of the steam supply for paper drying. *Applied Thermal Engineering* 2025, **278**, https://doi.org/10.1016/j.applthermaleng.2025.126941.

[2] Confederation of European Paper Industries (CEPI) and European Heat Pump Association (EHPA). Heat Pumps. Solutions for the decarbonisation of the pulp and paper industry. [Online]. Available: https://www.cepi.org/wp-content/uploads/2024/04/EESF-Heat-pumps-factsheet.pdf. [Accessed 05 01 2026].

[3] Wilk V., Knöttner S., Drexler-Schmid G., Barz T., 2023. "Superheated steam drying for paper production: process efficiency assessment," 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Las Palmas de Gran Canaria, Spain.

[4] Wilk V., Helminger F., Dusek S., Lauremann M., Fleckl T., 2019. "Steam generation from waste heat with heat pumps [in German: Dampferzeugung aus Abwärme mit Wärmepumpen]," DKV-Tagung. Ulm, Germany.

[5] Perz E. A Computer Method for Thermal Power Cycle Calculation. *Journal of Engineering for Gas Turbines and Power* 1991; **113**:2, p. 184.

[6] IEA HPT Annex 58. Task 1 – Technologies. [Online]. Available https://heatpumpingtechnologies.org/annex58/task1/. [Accessed 10 07 2026].

[7] ENTSO-E Transparency Platform. Balancing Zone AT for 2024. [Online]. Available: https://newtransparency.entsoe.eu/market/energyPrices?permalink=690901df135786160298e822. [Accessed 03 11 2025].

[8] Austrian Biomass Association. [Online]. Available: https://www.biomasseverband.at/wp-content/uploads/Energietraegerverlauf_2025_01.pdf. [Accessed 03 11 2025].

[9] Fritz D, Gössl M, Hatzl E, Kranzl S, Poupa S, Pölz W, Schreiber H. Harmonized Austrian direct and upstream GHG emission factors for relevant energy sources and technologies. Data status 2024 (in German: Harmonisierte Österreichische direkte und vorgelagerte THG-Emissionsfaktoren für relevante Energieträger & Technologien. Datenstand 2024), Umweltbundesamt GmbH, Vienna, 2025.