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Toward low-energy drying: Analysis of current processes and energy reduction potential utilizing heat pumps

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Abstract

Industrial drying is among the most energy-intensive processes, accounting for approximately 10 – 25% of total industrial energy consumption across various sectors. Despite its critical role in industries such as food processing, chemicals, paper, and textiles, drying operations often suffer from low thermal efficiency and significant energy losses, particularly through the discharge of low-temperature waste heat. Heat pumps offer a promising solution by recovering and upgrading waste heat, reducing primary energy consumption, and enhancing overall process efficiency. The advantages of integrating heat pumps into drying systems were explored in depth in the IEA HPT Annex 59 project “Heat Pumps for Drying”, whose findings are presented in this study. This paper presents a comprehensive analysis of existing drying processes, examining key performance indicators, including specific energy consumption, drying efficiency, and product quality. A central focus is identifying opportunities to reduce energy demand through heat pump integration strategies. Based on the analysis of current drying processes, the potential for improving efficiency through various heat recovery measures, such as recirculation, heat exchangers, and heat pumps, is evaluated. Additionally, several case studies are presented, demonstrating successful industrial applications of heat pumps in drying. These real-world examples illustrate both the practical and operational challenges encountered, as well as the energy savings and operational benefits that have been achieved. By combining detailed process analysis with real case studies, the paper highlights the significant technical and economic potential of heat integration measures to transform conventional drying operations into more energy-efficient and sustainable processes. These findings offer valuable insights for engineers, plant operators, and scientists seeking to enhance the energy efficiency of drying systems.

Keywords: drying process; energy efficiency; heat recovery; heat pump; use cases

1. Introduction

Drying is a fundamental unit operation across numerous industries, including food processing, pharmaceuticals, pulp and paper, and chemical manufacturing. It is estimated that drying accounts for 10 – 25% of industrial energy consumption globally [1], making it one of the most energy-intensive processes in production chains. Traditional drying methods, such as convective hot air drying, often rely on fossil fuels or inefficient heat sources, leading to high energy consumption and significant greenhouse gas emissions. With increasing energy costs and stricter environmental regulations, there is a pressing need for more sustainable and energy-efficient drying technologies. Heat pumps (HPs) have emerged as a promising alternative, offering the potential to reduce energy consumption in drying processes by up to 80% [2]. By recovering and upgrading

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low-grade heat, HPs can achieve high coefficients of performance (COP) and significantly lower the carbon footprint of drying operations. This paper presents a comprehensive analysis of current drying processes, building upon the findings of the IEA HPT Annex 59 "Heat Pumps for Drying" project [3]. The project investigates the application of HPs across a range of drying processes, with the primary objective of assessing the potential for energy savings in various industrial, commercial, and residential applications. The study assesses the technical feasibility of HP integration, identifies key opportunities and challenges for widespread adoption, and quantifies the potential energy reduction through case studies and energy modeling. The results are synthesized to provide actionable recommendations for industry stakeholders, aiming to facilitate the transition toward more sustainable and energy-efficient drying technologies.

2. Analysis of drying processes

Industrial drying processes exhibit significant variability in terms of operating temperature, residence time, and product conveying methods, each of which is tailored to the specific requirements of the material being processed. The energy required for water evaporation is typically supplied through hot surfaces (as in contact drying), radiative sources (such as microwave or infrared), or by preheating the drying medium. In most cases, air serves as the primary drying agent, absorbing the moisture evaporated from the product. The advantages and limitations of the most widely employed industrial drying technologies are summarized in Table 1. Generally, higher drying temperatures result in reduced residence times and enable the use of more compact dryer designs.

Table 1. Overview of dryer technologies

Dryer technology	Advantages	Disadvantages
Tunnel dryer Material is placed on trays and moved through a long tunnel with hot air flowing either concurrently or counter-currently.	+ Simple design + Suitable for large particles + Can handle various materials	- Large space requirement - Uneven drying if airflow is not uniform - Labor-intensive
Belt dryer Materials are continuously loaded onto a belt that passes through multiple drying zones. Hot air is circulated through the material on the belt or through the belt itself.	+ Energy efficient + Mechanically gentle product manipulation + Versatile for different particles, including big ones	- Higher initial investment cost - Requires complex and regular maintenance (moving parts) - Limited flexibility in precise moisture control (dead zones) - Not suitable for fine particles
Rotary dryer Materials are tumbled inside an inclined, long drum or cylindrical shell that rotates slowly. Materials are in direct contact with a heated gas.	+ Can handle large capacities + Can accept high flue gases + Less sensitive to particle size	- High energy consumption - Can cause particle degradation - Can cause dryer degradation (abrasion) - Noisy operation - Possible excessive entrainment losses, especially with fine particles - Potential for attrition and agglomeration
Fluidized bed dryer High-velocity hot air is passed vertically upwards through the material, causing solid particles to become suspended and mixed intensely.	+ High heat transfer rate + Fast and uniform drying + Suitable for small particles	- Not suitable for sticky and abrasive materials - High pressure drop - Potential for attrition and agglomeration
Spray dryer Liquid feed is atomized into fine droplets and sprayed into a hot drying chamber, where it rapidly dries into a powder.	+ Rapid drying + Ideal for heat-sensitive liquids + Produces uniform powder	- High energy use - Large footprint - Limited to pumpable liquids
Flash dryer Wet materials are rapidly dispersed into a high-velocity stream of hot air or gas. The drying agent removes moisture from the particles.	+ Very fast drying + Compact design + Suitable for fine particles	- Not suitable for sticky materials - Dust generation - Requires good feed dispersion - Thermal sensitivity (requires careful control for heat-sensitive products) - Particle size limitation (large/irregular particles may not dry uniformly)

The selection of an appropriate drying technology depends not only on product-specific properties, such as particle size and conveying requirements, but also on the drying temperature and the required drying capacity. Fig. 1 illustrates the ranges of drying temperatures and corresponding heating capacities, the latter being a function of drying capacity and dryer efficiency, as described in [1] and [6]. The turquoise-shaded region indicates applications that commercially available high-temperature HPs can serve. Conventional vapor compression cycles have a temperature limit of approximately 160°C due to the thermal stability and performance constraints of standard refrigerants and compressor lubricants at elevated temperatures [4][4]. However, higher temperatures may be achieved using alternative HP technologies, including Joule or Stirling cycles and mechanical vapor (re)compression (MVR). With respect to heating capacity, piston and screw compressors are most suitable for small- to medium-scale applications, whereas turbo compressors are preferred for larger heating capacities in the MW range as this technology is currently not fully developed for the smaller capacities. A comprehensive overview of market-ready and near-market-ready high-temperature HP technologies can be found on the homepage of IEA HPT Annex 58 [5].

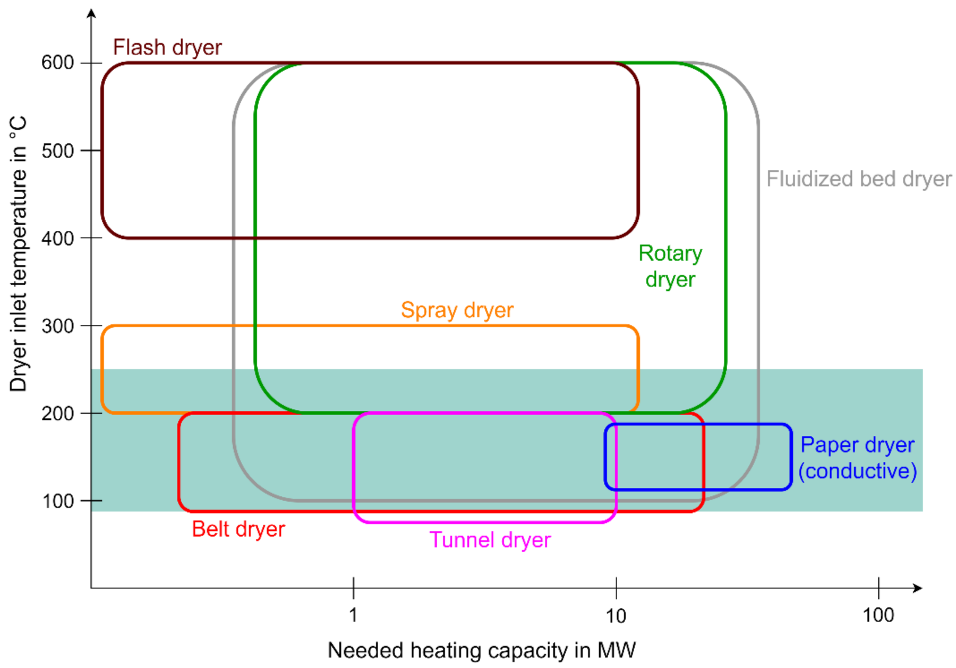

Figure 1. Dryer technology overview: Required heating capacity and drying temperature

3. Energy efficiency potential

Regarding a standard drying process, energy is consumed for heating the product and the drying agent, evaporating water and losses, with the majority being attributable to evaporation. The moisture leaves the dryer as water vapor mixed with the drying agent (exhaust air). For this reason, when improving energy efficiency, the focus lies on heat recovery using the dryer's exhaust.

3.1. Important factors for heat recovery

The primary focus in improving energy efficiency during drying processes is on heat recovery, utilizing the latent energy contained in the exhaust gases that would otherwise be released from the dryer. Heat recovery can substantially reduce overall energy usage, and several factors play a role to determining the potential for energy savings.

- Exhaust air temperature:
  The exhaust air temperature plays a critical role in heat recovery systems. High exhaust temperatures have a high potential for direct heat recovery (DHR), whereby exhaust heat is directly used to preheat a colder medium in a heat exchanger (HEX), such as fresh air, for the drying process. However, the exhaust air temperature should not be too high, as excessive heat reduces the overall energy efficiency of the drying process.

- Dew point:
  If a larger share of the energy needed for drying is to be recovered, the moisture in the exhaust air is important. To recover latent heat, the exhaust air needs to be cooled below its dew point. This process condenses the water vapor.
- Exhaust air contamination:
  Exhaust air contamination, such as dust or particulates, can hinder the performance of heat recovery systems. These particles can clog heat exchangers, resulting in reduced efficiency and increased maintenance costs. Furthermore, contamination in the condensed water can complicate water recovery systems.

The temperature levels of the heat source and sink define the thermodynamic performance of a heat pump-assisted drying system. The Coefficient of Performance (COP) of an ideal (Carnot) HP can be expressed as

$$COP_{Carnot} = \frac{T_H}{T_H - T_C} \tag{1}$$

where T_H and T_C represent the absolute temperatures in K of the high- and low-temperature reservoirs, respectively. The Carnot efficiency η_{Carnot} is a metric to compare the real system to the ideal Carnot cycle:

$$\eta_{Carnot} = \frac{COP}{COP_{Carnot}} \tag{2}$$

Lower sink temperatures T_H and higher source temperatures T_C both decrease the effective temperature lift and thus improve the COP, as indicated by Eq. (1). In the case of a drying process, the sink temperature is linked to the needed dryer inlet temperature and the source temperature is determined by the exhaust conditions. For sufficient heat recovery cooling of the exhaust below the dew point is typically needed. Once the temperature has fallen below the dew point and condensation has started, a significant amount of energy is available without decreasing the temperature much further. Thus, regarding drying processes, the dew point is a good estimate for the source temperature.

To visualize these relationships, Fig. 2 illustrates the effect of exhaust air dew point and dryer inlet temperature on the COP. The plot represents the attainable COPs for various drying configurations, assuming a Carnot efficiency of 0.5 and a pinch point of the HEX of 5 K on both the source and sink sides.

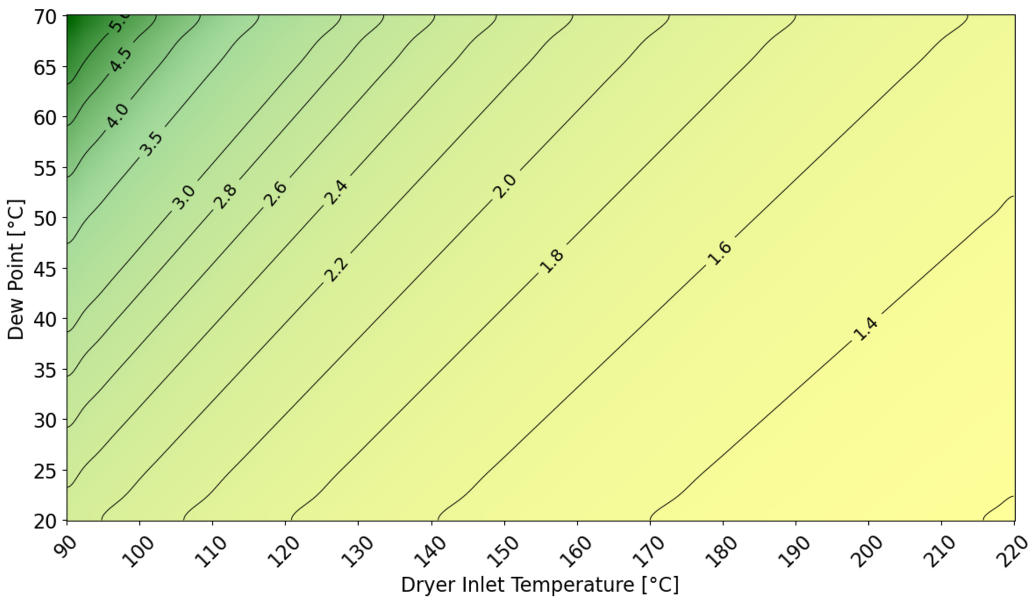

Figure 2. COP as a function of exhaust air dew point and dryer inlet temperature

3.2. Investigated heat recovery measures

To estimate the potential of energy efficiency improvement, the following heat recovery measures are investigated in this study:

- Product cooling: The dry product is fed into a cooling zone to recover sensible heat.
- Air recirculation: By increasing the circulation rate, the needed amount of fresh air, which has to be preheated, can be decreased while keeping the air flow through the dryer itself constant. Furthermore, air recirculation increases the moisture of the exhaust air, which is beneficial for heat recovery.
- DHR: Via DHR, energy is transferred directly from the exhaust air to the fresh air. Obviously, the exhaust air temperature needs to be sufficiently higher than the fresh air temperature.
- HP: The moist exhaust air can serve as a source for a HP. The HP raises the temperature level of the energy recovered from the exhaust air, allowing it to be reused for driving the drying process.

A possible implementation of all these heat recovery measures is illustrated in Fig. 3. The fresh air required for the drying process is preheated by multiple heat sources at varying temperature levels. An air-air HEX for DHR with the exhaust air follows the preheating in the product cooler. After mixing with the airflow of the outer recirculation, the air is further preheated by the sink of the HP using a water cycle. The preheated air is finally mixed with the inner recirculation and heated to the desired dryer inlet temperature using electric heating elements or natural gas. In the dryer, water is evaporated from the product and moist exhaust air is formed. The air-air HEX for DHR first cools the moist exhaust air and then the exhaust serves as a source of heat for the HP. Regarding different drying processes and their requirements, some of the suggested heat recovery measures may not be beneficial or even possible.

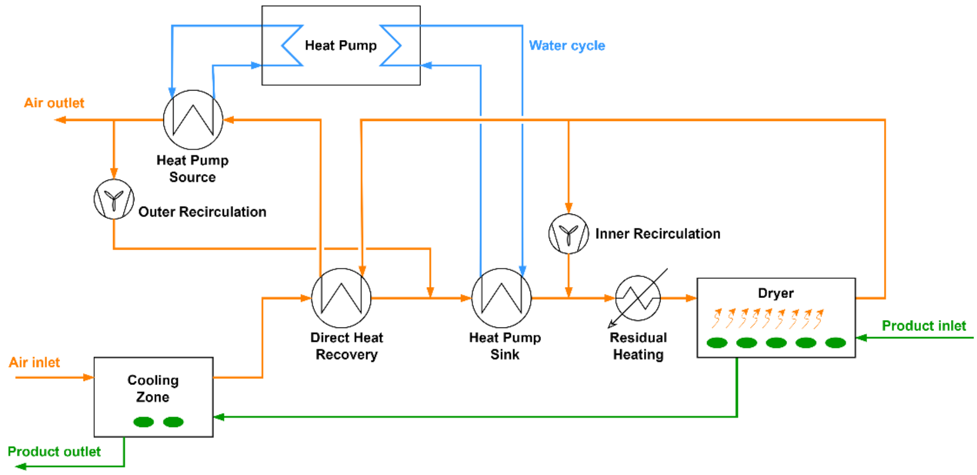

Figure 3. Integration of heat recovery measures into a drying process

3.3. Energy saving potential of drying processes

To support the analysis of heat recovery potential, the online tool Drying Toolbox is created [7]. The Drying Toolbox is a mathematical model designed for a simplified drying system, with a focus on heat recovery measures. It enables the application of the heat recovery options depicted in Fig. 3, allowing for the quantification of the theoretical potential for energy savings. The submodel of the drying chamber does not include drying kinetics, making the tool ideal for users who can define the material and heat balance of the drying chamber and only wish to evaluate heat recovery alternatives. The Drying Toolbox features an input panel where users can define main parameters and select heat recovery options. It provides a schematic of the process, including the selected heat recovery devices and key process parameters and generates Sankey diagrams for each calculated alternative, offering a visual representation of energy flows to facilitate analysis and understanding of their interactions. Additionally, the Drying Toolbox identifies logical inconsistencies or errors in input parameters (e.g., reversed heat flows) and alerts users with a message explaining the issue and suggesting possible solutions. The Drying Toolbox was developed in the Dymola/Modelica environment, which is suitable for interdisciplinary modelling [8].

In this study, the Drying Toolbox [7] is utilized to assess the energy savings potential and CO2 savings potential of four generic drying processes. To determine realistic parameters for the drying processes, literature and manufacturer data are utilized, and any missing data are supplemented based on the authors' experience. Table 2 gives an overview of the investigated drying processes.

Table 2. Investigated generic drying processes

Dryer technology	Product	Product mass flow dry	Product moisture in/out	Product temperature in/out	Fresh air mass flow	Air temperature dryer inlet	Inner/outer recirculation reference
		kg/s	kg water/kg wet solid	°C	kg/s	°C	% of fresh air mass flow
Spray dryer	Starch derivatives	0.25	0.75/0.03	70/90	27.2	160	0/0
Tower dryer	Corn	0.6	0.3/0.15	25/60	9.5	85	0/0
Belt dryer	Petfood	2.5	0.25/0.08	70/80	9.5	125	272/0
Tunnel dryer	Ceramics	3	0.25/0.02	25/75	41.4	120	0/0

In the reference scenario, the residual heating demand is calculated by entering the values provided in Table 2 into the Drying Toolbox and turning off all heat recovery measures. Stepwise heat recovery is added, starting with the product cooler, followed by DHR, and then the HP. The scenario DHR thereby also includes the product cooler and the scenario HP includes the product cooler as well as the DHR. Regarding the belt dryer and the spray dryer, two HP configurations are investigated: a lower temperature HP preheating the air to 125°C (scenario HP 125°C) and a higher temperature HP preheating the air to 160°C (scenario HP 160 °C) or 180°C (scenario HP 180°C). For all scenarios, including an HP, the Carnot efficiency, as defined in Eq. 2, is set to 0.5. The minimum temperature difference between the hot and cold side of the HEX (pinch point) for DHR is set to 20°C. Furthermore, for all cases, it is assumed that the inlet air is 25°C and is completely dry and that the product is cooled to 35°C when the cooling zone is used.

The moisture content of the exhaust air of the generic tower dryer and spray dryer is relatively low, so recirculation could be an option. The energy saving potential of recirculation is calculated without considering other heat recovery measures. In the scenarios "recirc 50%" and "recirc 100%", the inner recirculation is set to 50% and 100%, respectively, and the fresh air mass flow is reduced accordingly to maintain a constant air mass flow through the dryer.

In the generic belt dryer, a multiple of the fresh air is recirculated inside the dryer (inner recirculation), which is very common for industrial belt dryers. This configuration poses a significant disadvantage to the implementation of a HP, as the subsequent installation of HEX inside the dryer is not feasible for a retrofit. In order to replace the residual heating completely, the fresh air is heated to a much higher temperature than would be actually needed for the drying process to reach the required drying temperature after mixing with the inner recirculation.

The resulting specific energy consumption (SEC), see Eq. (3), for residual heating (red) and electricity (turquoise) for all scenarios is shown in Fig. 4. Additionally, the specific moisture extraction rate (SMER), see Eq (4), for the reference and the best case for each dryer technology is provided in Fig. 5. Furthermore, the specific CO_2 emissions per kg evaporated water for the reference and the best case for each dryer technology are compared in Fig. 5, as well ($EU_{electricity}$: 195 g_{CO2}/kWh, gas: 215 g_{CO2}/kWh (2025) [9]). All results of the generic drying processes are summarized in Table 3.

$$SEC = \frac{energy\ demand}{mass\ of\ evapotated\ water} \tag{3}$$

$$SMER = \frac{mass\ of\ evapotated\ water}{energy\ demand} = \frac{1}{SEC} \tag{4}$$

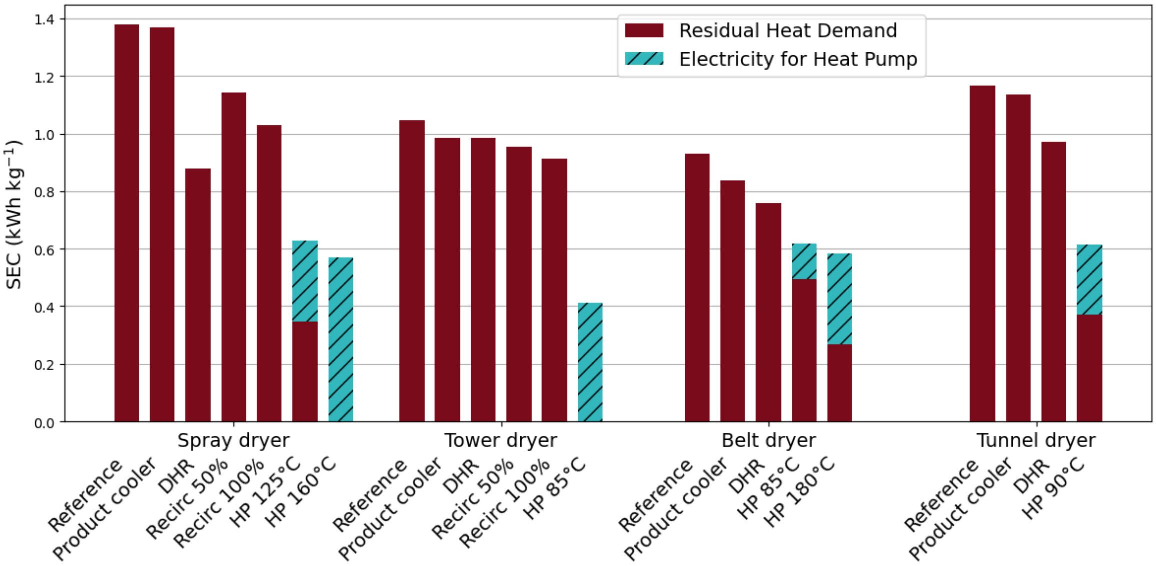

Figure 4. Energy savings potential for different drying processes

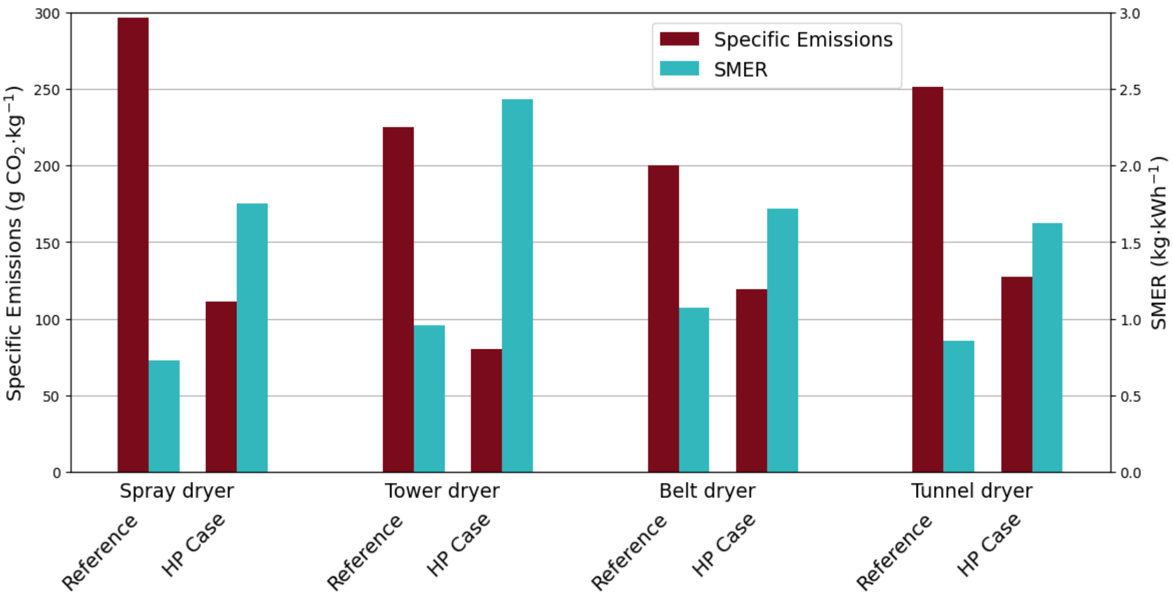

Figure 5. CO_2 emissions and SMER

Table 3. Results of different scenarios for generic drying processes

Dryer technology	**Scenario**	**Share of SEC for residual heat demand**	**Share of SEC for electricity**	**SEC$_{total}$**	**SMER**	**CO_2**
		kWh/kg	kWh/kg	kWh/kg	kg/kWh	g/kg
Spray dryer	Reference	1.38	-	1.38	0.72	296.7
	Product cooler	1.37	-	1.37	0.73	294.55
	DHR	0.88	-	0.88	1.14	189.2
	Recirc 50%	1.14	-	1.14	0.88	245.1
	Recirc 100%	1.03	-	1.03	0.97	221.45
	HP 125°C	0.35	0.28	0.63	1.59	129.85
	HP 160°C	-	0.57	0.57	1.75	111.15

Tower dryer	Reference	1.05	-	1.05	0.95	225.75
	Product cooler	0.98	-	0.98	1.02	210.7
	DHR	0.98	-	0.98	1.02	210.7
	Recirc 50%	0.95	-	0.95	1.05	204.25
	Recirc 100%	0.91	-	0.91	1.10	195.65
	HP 85°C	-	0.41	0.41	2.44	79.95
Belt dryer	Reference	0.93	-	0.93	1.08	199.95
	Product cooler	0.84	-	0.84	1.19	180.6
	DHR	0.76	-	0.76	1.32	163.4
	HP 125°C	0.50	0.12	0.62	1.61	130.9
	HP 160°C	0.27	0.31	0.58	1.72	118.5
Tunnel dryer	Reference	1.17	-	1.17	0.85	251.55
	Product cooler	1.13	-	1.13	0.88	242.95
	DHR	0.97	-	0.97	1.03	208.55
	HP 90°C	0.37	0.24	0.61	1.64	126.35

3.4. Superheated steam drying using MVR

Steam drying plays an important role in reducing CO_2 emissions compared to hot-air drying. Even with fossil-based heating, recirculating slightly superheated steam offers efficiency gains, while integrating open steam compression enables further improvement in the energy balance and CO_2 reduction. Since drying processes at or above atmospheric pressure operate above 100 °C, steam drying eliminates the need for a low-temperature stage HP, as required in most hot-air systems, making it particularly suitable for HP integration. [10], [11]

In this study, a system with multi-stage turbo steam compression was assumed, see Fig. 6, as those compressors can handle high volume flow rates. The maximum pressure ratio was set to 2, and the isentropic efficiency was set to 75%. Typical losses for auxiliary systems and drying are also considered. The MVR-system is equipped with an intercooling using condensate (4). As additional electrical power is added to the system's energy balance, a fraction of the low-pressure steam can be used as an additional heat source (5). The ratio between electric energy consumption and recuperated steam (ΔQ_{rec}) is higher as the temperature lift increases. The example processes refer to [10] and were calculated using a stationary simulation tool in a Python environment accessing fluid properties from CoolProp [12]. The most important process parameters, the pressure (p_{dry}) and the temperature (T_{SHS}) of the superheated steam can be found in Table 4. Table 4 also displays the CO_2-reduction compared to using natural gas ($EU_{electricity}$: 195 g_{CO2}/kWh, gas: 215 g_{CO2}/kWh (2025) [9]) and the temperature level (T_{rec}) where the additional latent heat could be used. Significant potential for CO_2-reduction, waste heat recovery and improvement of SEC is derivable.

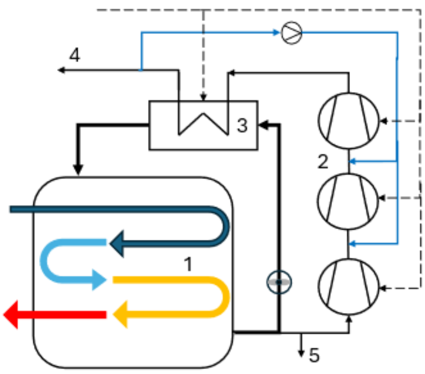

Figure 6. Superheated steam drying with MVR-system: dryer (1), MVR (2), heat exchanger (3), condensate (4), auxiliary steam (5)

Table 4. Process parameters of superheated steam drying for commonly used products

Product	p_{dry}	T_{SHS}	SEC	SMER	COP	CO_2	ΔCO_2	ΔQ_{rec}	T_{rec}
	bar	°C	kWh/kg	kg/kWh		g/kg	%	%	°C
Beet pulp	1	150	0.17	5.88	4.63	32.9	-77.5	10.5	100
Paper	1	250	0.31	3.23	1.85	59.7	-59.2	46.8	100
Wood chips	2	200	0.21	4.76	3.34	40.3	-71.8	23.3	120

4. Use cases of dryers with integrated HPs

This section summarizes several case studies of industrial drying processes in which HPs have been successfully implemented [3], including applications in biomass, animal feed, fish meal, and brick production. Heat recovery is achieved through the sensible heat of exhaust air, condensation of latent heat from superheated steam dryers, or by recompressing, superheating, and recycling wet steam. Table 5 presents key figures for the cases, highlighting energy savings, efficiency improvements, practical implementation challenges, and the energy savings and operational benefits achieved with HP applications across different industries.

Case 1: Biomass drying with an MVR heat pump

As part of the DryFiciency project [13], an innovative superheated steam dryer was installed at a test site in Drammen, Norway, for drying biomass, including bio-sludge, wood chips, and garden compost. A two-stage MVR heat pump, based on automotive turbo-compressor technology adapted by Rotrex, was later integrated to recover and reuse excess steam from the dryer. During full-scale testing, start-up heat losses caused a drop in steam pressure, leading to system instability. An auxiliary heater was added to address this, but the project ended before full integration could be tested. Nonetheless, lab tests of the MVR system showed up to 75% energy savings and COP values ranging from 4.5 to 8.7, demonstrating high efficiency and potential for fossil-free operation.

Case 2: Animal feed drying with a steam-generating heat pump

In Trondheim, Norway, Felleskjøpet implemented a high-temperature HP developed by Aneo Industry to reduce energy use in animal feed production [14]. The HP recovers waste heat from the air used in pellet cooling and drying with a secondary heat transfer loop. It then upgrades the heat to generate process steam at 130°C for hygienization and heat treatment. The HP system uses a cascade with an ammonia HP in the first stage and an MVR in the second stage. The first stage heats and evaporates make-up water, while the second stage compresses saturated steam to 2 bar_a. The system's capacity is two tons of steam per hour. It achieved energy savings of over 65% and annual power savings of 5.4 GWh, with a COP of 3.1 to 3.4. Since the HP system replaced electric boilers, the electrical peak load has been reduced, enabling expansion of animal feed production. Project challenges included retrofitting the system into the existing plant and ensuring flexible operation.

Case 3: Heat pump for dryer exhaust recovery in fish meal production

A 4.4 MW steam-generating HP, developed by Aneo Industry and EPCON Evaporation Technology, has been integrated into the cooking process at one of Pelagia's fish meal and oil production facilities [15]. The system recovers waste heat from two sources: wet steam from a superheated steam dryer and contaminated condensate from an evaporative separation process used to remove water from fish meal before drying. This excess heat is upgraded to produce seven tons of process steam per hour at pressures between 1.5 and 4.5 bar. The heat from the condensate is recovered using cascaded ammonia HP and MVR systems, while the wet steam from the dryer exhaust is condensed in a heat exchanger that generates steam. The same MVR system then upgrades this low-pressure steam. With this system configuration, boiler-generated steam was replaced, and the cooking process was electrified. This achieved over 70% energy savings, offering a COP of around 3.2.

Case 4: Heat pumps for bricks drying

Wienerberger has partnered with AIT Austrian Institute of Technology GmbH in the GreenBricks project [16] to implement an electrified brick plant, integrating three compression HPs into the brick drying process. Installed in 2025, this system utilizes the HPs to compensate for the reduced exhaust air in the absence of flue gases from the electrified kiln. The HPs recover latent heat from the dryer's exhaust air via an air scrubber, which is then used to preheat ambient air and power internal heating elements in the dryer. The system operates with a heating capacity of 3.5 MW and a flow temperature of 90 °C. The dryer itself, extended in length, allows for longer drying times at lower temperatures. With this innovative setup an efficiency increase is expected compared to a conventional fossil fuelled dryer. The SEC is expected to decrease by up to 54%. Assuming green electricity and considering the electrified kiln at the site, a fully decarbonised brick drying process is obtained.

Table 5. Overview of realized case studies of industrial drying processes in which heat pumps have been successfully implemented, including applications in biomass, animal feed, fish meal, and brick production.

Case	Biomass	Animal feed	Fish meal	Bricks
Technology provider	Rotrex, Epcon	ANEO Industry, EPCON	ANEO Industry, EPCON	Wienerberger AG
Dryer type	Super-heated steam dryer (paddle), with steam jacket	Packed bed, counterflow chiller/dryer	Steam dryer (paddle)	Tunnel dryer
Drying product(s)	Dried biomass (bio-sludge, wood chips, garden compost with original MC around 70%)	Bulk solids, typically feed or food	Powder, sludge	Bricks
Drying medium	Superheated steam	Air	Steam	Air
Operation	Batch, discontinuous	Continuous	Continuous	Continuous & discontinuous
Product conveying	Paddle	Gravity	Paddle	Carts
Heating medium temperature	125 to 140°C superheated steam at 1 bara	To the dryer/cooler: ambient air. To the hygienizer: 130 °C	N.A.	70 to 200 °C
Heat sources	Boiler steam, heat pump	Ambient air, heat pump	Boiler steam, heat pump	Heat pumps, kiln exhaust air
Heat pump capacity	0.5 MW	1.5 MW	4.5 MW	3.5 MW
Supply temperature	142 °C (condensation temperature at 4.2 bara)	120 to 130 °C	143 °C (steam condensation)	90 °C
Refrigerant	R 718 (water)	Ammonia (R717) and water (R718) (cascade HP)	R 718 (water)	Ammonia (R717)
Drying time	~ 10 h	30 min	1 to 2 h	1 to 2 days
Start of operation	2020	2024	2024	2025
Capacity (water evaporation)	~ 160 kg/h (from 70% to 15 % MC)	2'000 kg/h	7'000 kg/h	3'000 kg/h
Dryer dimensions	N/A	4 x 4 x 5 m length	4 x 8 length (estimation)	70 m length
Outlet condition drying medium	~ 100 °C saturated steam	65 °C 35% r.h.	85 to 95 °C 90 to 98% r.h.	40°C 90% r.h.
Direct heat recovery	Yes	Yes	Yes	No
Heat source	Outlet of the dryer	Excess heat from chilling/drying air	Exhaust from the dryer	Scrubber using exhaust air

5. Discussion

In this section a brief comparative discussion is provided to link the theoretical savings potential identified by the Drying Toolbox with the actual savings achieved in the case studies. In addition, the described approach to estimate the COP of the implemented HP is applied to the use cases.

5.1. COP of installed HP

Based on Fig. 2 the COP for the cases 2, 3 and 4 can be estimated. Comparison of the estimated COP and the measured values reveals a good fit for the production of fish meal (case 3), when the figure is extrapolated to higher dew points a little bit. Regarding the drying of bricks (case 4) Fig. 2 indicates a COP of around 3. Although in this case there are no long-time measurements available yet, the estimated COP of 3 is matching the expectations based on manufacturer data. Inputting the data of the steam-generating HP for drying of animal feed (case 2) into Fig. 2 results in a significantly lower COP of around 2.2 compared to the values presented in Chapter 4. The reason for this mismatch is that the HP is also providing hot water at 85°C for other processes, which significantly improves the COP of the overall system, see [14].

5.2. Total energy savings

The drying of bricks (case 4) allows for the best comparability between theoretical potential and actual achieved savings, because the theoretical case matches the real-world application. As the product cooler already existed before the rebuilt of the tunnel dryer the theoretical potential for energy savings amounts to 46%, which is expected to be met (or even outperformed due to decreasing of the drying temperature) in reality. Regarding the drying of animal feed (case 2) the achieved savings clearly outperform the theoretical potential of the belt dryer. In contrast to the theoretical calculations, in the real-world application the whole drying process is optimized to increase the efficiency. The theoretical potential for energy savings is the highest in case of superheated steam drying, presented in Chapter 3.4. Based on the applied temperature and pressure the drying of biomass (case 1) is comparable with the calculated values for beet pulp, see Table 4. The realizability of the theoretical potential is demonstrated in laboratory scale only.

6. Conclusion

This analysis shows that industrial drying, despite its high energy demand, offers considerable energy efficiency potential through heat integration measures. The evaluation of various drying processes and heat recovery options - such as air recirculation, direct heat recovery, product cooling, and heat pump integration - indicates that significant reductions in SEC (specific energy consumption) are achievable without altering the dryer itself and thus impacting on product quality. Besides dryer inlet and exhaust temperature, the exhaust moisture is found to impact the efficiency of heat recovery the most. Using the Drying Toolbox, an online tool that evaluates heat integration measures for dryers, it is shown that a combination of measures - product coolers, direct heat recovery (DHR), and heat pumps - reduces SEC by around 40% to 60% to approximately 0.4–0.6 kWh/kg. In general, drying processes with high exhaust air temperature provide a high potential for DHR, while a heat pump benefits from a high exhaust dew point and low dryer inlet temperatures. Regarding the investigated drying processes, the potential of a product cooler and air recirculation was found to be moderate. Even larger energy savings can be achieved by using superheated steam as a drying agent and an MVR-system.

Heat pump drying case studies from different industrial sectors, including biomass, animal feed, fish meal, and brick production, support these findings. All of them confirm measurable energy savings and efficiency improvements. Overall, the study highlights the technical and economic potential of heat recovery and heat pump technologies to enhance the energy performance of industrial drying systems.

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