From Waste Heat to Value: Pinch Analysis, Process Integration and Heat Pump Design in Super-Absorbent Polymer Drying

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Abstract

Industrial drying is among the most energy-intensive operations in manufacturing and remains heavily dependent on fossil-based thermal utilities. As industry moves toward electrification, heat exchangers and industrial heat pumps are emerging as key technologies for reducing energy consumption, recovering waste heat, and lowering emissions. At the same time, many drying processes still reject substantial amounts of recoverable thermal energy, creating significant opportunities for internal heat recovery and process integration.

Originally developed in the late 1970s in response to the energy crises of that era, Pinch analysis provides a systematic framework for maximizing heat recovery within industrial processes. Today, it is increasingly relevant for integrating electrified technologies and low-carbon utilities into modern thermal systems.

This paper investigates energy use in an industrial drying application for super-absorbent polymer production and identifies major consumption areas and heat recovery opportunities. It introduces key efficiency metrics and applies process integration and Pinch analysis to evaluate the thermal performance of the system. Using a representative drying case, the study illustrates hot and cold streams, composite curves, and the role of Pinch-based targeting in the design of direct heat recovery and heat pump solutions.

Results indicate that fossil fuel use can be reduced by more than 80% in the analyzed case. In the configuration maximizing fuel reduction, the integrated heat pump achieves a COP of 2.3 and demonstrates to be attractive at energy price ratios of 1.7 or below. However, lower delivery temperatures can substantially increase COP, thereby improving economic viability at higher electricity-to-gas price ratios. The system also remains net beneficial in terms of CO2 emissions up to an electricity emission factor of 0.75 kgCO2/kWh; this threshold corresponds to a payback-optimized configuration with higher COP than the case delivering maximum fuel reduction. Overall, the greatest benefit will be achieved when Pinch analysis is combined with process expertise and upstream optimization measures, including composition optimization, pre-dryer moisture reduction, die and extruder design, particle-size control, and digital dryer control. These measures reduce thermal demand, improve temperature matching, and enhance the feasibility and value of heat recovery and heat pump integration.

Keywords: Sustainability; Industrial drying; Process optimization, Heat-pumps; Energy recovery

1. Introduction

Industrial energy use is changing fast, driven by cost pressure, new technology, and stronger environmental constraints. In the past, cheap fossil fuels powered most plants, so efficiency was not a focus. Today, companies aim to cut emissions, use less energy, and move to more sustainable production [1]. Drying is one of the most energy-hungry steps in many sectors, including food, pharmaceuticals, textiles and wood. In many cases, drying takes a large share of total process energy, so it is a key target for improvement [2]. Studies report that drying can represent about 10–25% of a country's industrial energy use, making optimization a clear priority [2, 3].

A core strategy is to recover and reuse waste heat. Many processes release around 70% of their input energy as residual heat [4, 5]. With the right solutions, this low-temperature heat can be captured and reused. Industrial heat pumps and well-designed heat exchanger networks can lift and route this heat back into the process, cutting fuel use and emissions [6, 7]. This shift also treats "waste" as a resource: in the circular economy, by-products such as CO_2, organic residues, and other streams are reused in the plant or in other value chains. In food and drink, common examples include CO_2 capture from fermentation, anaerobic digestion of organic waste to produce biogas, and converting biowaste into higher-value products [8, 9]. The result is a move away from a linear "take-make-dispose" model toward integrated, circular systems that lose less energy and material while improving long-term sustainability.

2. Energy Conservation in Industrial Drying

2.1 Historical Perspective on Industrial Energy Use

In the early industrial era, energy was cheap and loosely managed. Heat-intensive steps relied on fossil fuels, and waste heat and material streams were often released without reuse. The oil crises of the 1970s and later environmental policies changed this: industry began to focus on energy saving and process integration to find heat recovery options in complex plants. Pinch analysis, developed in the late 1970s, changed how we design energy systems. It provides a clear method to find the minimum heating and cooling a process needs and shows how hot and cold streams can exchange heat inside the plant before using utilities, cutting fuel use and operating cost [10, 7]. A cold stream is one which needs heating, and a hot stream is one which contains potential waste heat (such as exhaust air from drying) or requires cooling.

For drying, progress has mainly come from better heat recovery and more efficient heat supply. Conventional and condensing heat exchangers can recover sensible and latent heat from hot, humid exhaust, while industrial heat pumps can upgrade this low-temperature heat to more useful levels for air or product preheating [6, 11]. Across industry, the direction is clear: balance cost, efficiency, and sustainability by recovering heat, applying pinch analysis in design, and using digital monitoring and control to keep systems efficient.

2.2 Energy Flows in the Drying Process

In drying, most of the energy goes into evaporating water (latent heat), while a smaller but important share heats the wet product and moisture to the operating temperature (sensible heat). Additional energy is used to heat and move the drying medium (such as air or steam), and further losses occur with hot, humid exhaust as well as through walls, ducts, and leaks [2, 3]. These pathways explain why hot and saturated exhaust often carry a large fraction of the input energy out of the system, making them prime targets for recovery [11]. Opportunities for saving usually start with reducing the water load before thermal drying, then minimizing unnecessary heating of air and solids, and finally recovering heat from the exhaust. Preheating inlet air with exhaust heat and preheating the wet feed with recovered heat can cut the external heating duty. Where exhaust temperatures are low or humidity is high, condensing heat exchangers and industrial heat pumps can recover latent heat and upgrade it to useful temperature levels for the process [11, 6]. Good insulation, tight seals, and controlling exhaust humidity and temperature help avoid over-venting lowering losses [11].

2.3 Quantifying Dryer Efficiency

We define dryer heat efficiency with a simple example (see Figure 1). Fresh air at a humidity ratio of 7.5 g/kg dry air is heated from 20°C to 120°C at a flow of 5 kg/s (dry air basis) to dry a product. To simplify, we assume no wall losses. In this ideal view, the added heat ends up in the exhaust as hot air and water vapor.

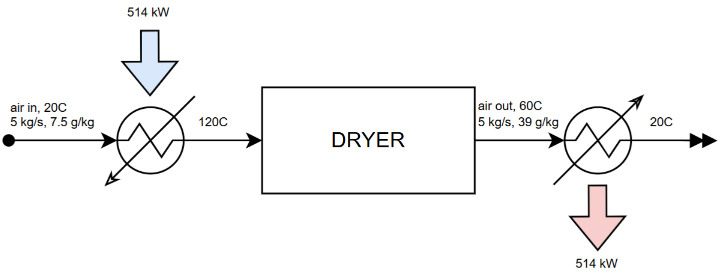

Figure 1. Simple dryer with inlet fresh air and exhaust.

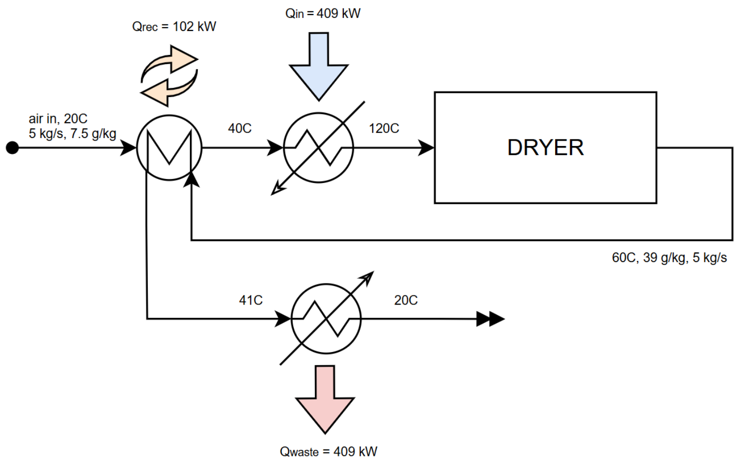

Figure 2. Dryer with direct heat recovery from the exhaust via a heat exchanger.

Heating 5 kg/s of air from 20°C to 120°C needs about 514 kW of boiler heat (assuming 100% boiler efficiency). In an ideal case, you could recover the same 514 kW by cooling the exhaust from 60°C down to 20°C and fully condensing the steam. We define the heat recovery efficiency as the fraction of total heat covered by recovery:

$$\eta = \frac{Q_{rec}}{Q_{in} + Q_{rec}} \tag{1}$$

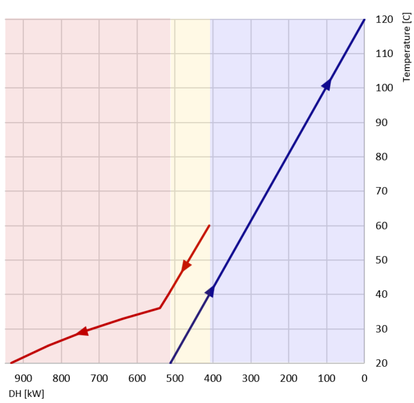

Figure 3. Composite Curve of the dryer with exhaust-to-inlet heat recovery (preheating).

Here, Q_{rec} is the recovered heat and Q_{in} is the remaining boiler heat after recovery. With no recovery, $\eta = 0$. Now add a heat exchanger to preheat the inlet air using the exhaust (see Figure 2). In this setup, about 102 kW can be recovered by cooling the exhaust to 41°C, which preheats fresh air to 40°C. The Composite Curve (CC) in Figure 3 shows temperatures of fresh air and exhaust across the heat exchanger. Orange is recovered heat, blue is remaining boiler heat, and red is waste heat left in the exhaust.

Using Equation 1, the heat recovery efficiency is about 20%. In the next sections, we use Pinch Analysis to see how to increase this efficiency further, for example by combining multiple heat exchangers and, where appropriate, industrial heat pumps.

3. Pinch Methodology and its Applications

3.1 Overview of the Pinch Methodology

Pinch methodology (pinch analysis) is a practical way to cut energy use by matching process heat sources and sinks at the right temperature levels. The core idea is simple: recover as much heat as possible inside the process before using external utilities.

The method emerged in the late 1970s and early 1980s in the chemical industry, with early applications in heat exchanger network design. It quickly demonstrated large savings in refineries, petrochemicals, and other thermally intensive plants, and later expanded to utility systems, site-wide integration, and to mass and water pinch [10, 7, 1]. To perform a general Pinch Analysis, one must collect all of the streams (water, air, ...) in the process which need heating or cooling. For each stream, one needs the inlet temperature and the end temperature, along with the corresponding energy requirement, which can be calculated from other properties such as mass flow and heat capacity of the fluid. This list of streams is the only requirement to get a heat recovery estimation of the process, meaning the heat which can potentially be recovered through direct hot/cold exchange of streams. This is the first step of making a process more sustainable, as direct heat exchange is typically more efficient than technologies requiring additional power or heat input.

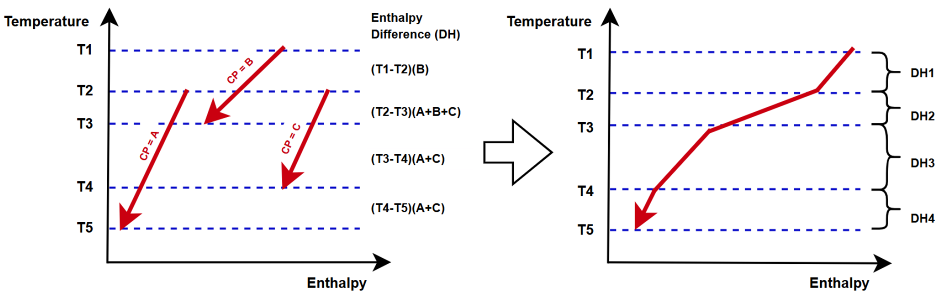

Figure 4. Construction scheme of the hot stream part of the Composite Curve using the heat capacity (CP) of the streams.

The heat recovery potential can be visualized by what is called the Composite Curve (CC), an example of which was already shown in Figure 3. This figure is constructed from the list of process streams and contains an ensemble of all hot (in red) and cold (in blue) streams in the process. In Figure 4, one can observe how the red line of the CC is constructed from all the hot streams of the process; the same steps apply for the blue line.

Another important graph, usually obtained after the initial direct heat recovery estimation, is the Grand Composite Curve (GCC), an example of which is shown in Figure 5. This curve shows the remaining heat demand and waste heat, respectively above and below the pinch point, the latter being the minimum temperature difference in the heat recovery potential. This value is very determining in the final size of the heat exchangers, as lower temperature differences require larger areas, so the heat recovery potential is tightly dependent on this value.

Additionally, in Figure 5, one sees a sharp and narrow spike in the center. This is indicative that a heat-pump has a lot of potential, as the temperature lift between waste heat and remaining heat sink is minimal, leading to an efficient heat-pump. Obtaining the CC and GCC of a process is therefore key to understanding the potential of making the process more efficient.

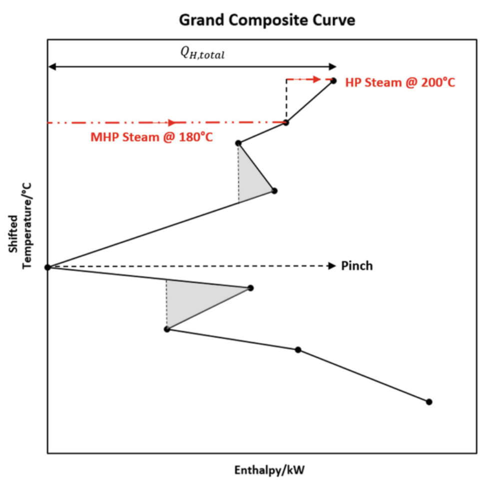

Figure 5. Grand Composite Curve example showing heating demand and waste heat remaining after direct heat recovery, the heat demand being satisfied by steam at 180°C and 200°C.

3.2 Process Integration Approach: Drying Systems

As presented in Figure 1, the drying process is a very simple case for Pinch Analysis, as it usually only has two streams: fresh air which needs heating (cold stream), and hot exhaust containing waste energy in the form of sensible heat and water vapor (hot stream). The CC and GCC of many drying processes are therefore quite similar; an example of the CC and GCC is shown in Figure 3 and Figure 6 respectively.

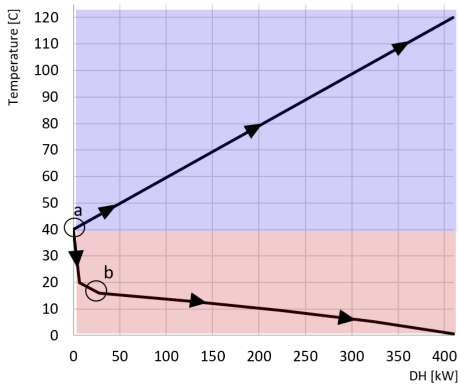

Figure 6. Grand Composite Curve of an example drying process showing heating demand (blue) and waste heat (red) remaining after direct heat recovery (a=pinch point, b=dew point of exhaust) (ΔT_{min}=20°C).

In Figure 6, we can observe the two streams of the drying process. Above the pinch point, we have the fresh air at 40°C (since it has been previously pre-heated directly by exhaust in Figure 3), needing heating to 120°C, and the exhaust air which still contains energy and can potentially be cooled down even further. To graph the GCC, the temperatures of either the hot or cold streams must be shifted so that the minimum temperature difference becomes zero. In this figure, the hot streams are all shifted by minus the ΔT_{min}, equal to 20°C. The temperatures below the pinch point (40°C) in Figure 6 are therefore displayed 20°C lower than initially; this is just to make the GCC easier to interpret.

One can note how the fresh air is a straight line, as there is no change of phase involved in the heating of the air, while the exhaust is a curved line. When the exhaust reaches 100% relative humidity, water starts to condense, continuously changing the heat capacity of the air, which then produces a curved line when the exhaust air is cooled down. Because this temperature is much lower than the temperature of the pre-heated fresh air, it is impossible to recover this heat through the use of heat-exchangers alone, since heat only flows from higher to lower temperatures. This is where the heat-pump comes in.

Let's take a look at the Pressure-Temperature (PH) diagram of the R1233zd(E) refrigerant in Figure 7. Simply said, a heat-pump is able to "upgrade" the temperature of this energy. Essentially the exhaust air can be used to evaporate a refrigerant with a lower boiling point (1⟶2), then upgrade this vapor to higher temperatures through a compressor (2⟶3). The refrigerant, which now has a higher temperature than the fresh air, can be used to heat the latter through condensation (3⟶4). The refrigerant is then passed through an expansion valve to decrease its pressure back to the starting point, hence completing the cycle.

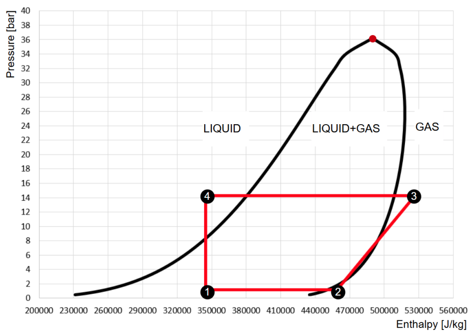

Figure 7. Pressure-Temperature diagram of the R1233zd(E) refrigerant along with an example heat-pump cycle.

It is also possible to visualize heat-pumping in the GCC, as shown in Figure 8. Notice how the exhaust, which at some point passes through its dew point, gives its heat to the refrigerant which evaporates and heats up above boiling point (blue line). After passing through the compressor, the refrigerant then condenses, heating up the fresh air until a certain point. This way, more heat from the exhaust is recovered for a relatively small additional power input. The latter depends heavily on the temperature lift, meaning the difference in temperature between the evaporation and condensation temperature of the refrigerant.

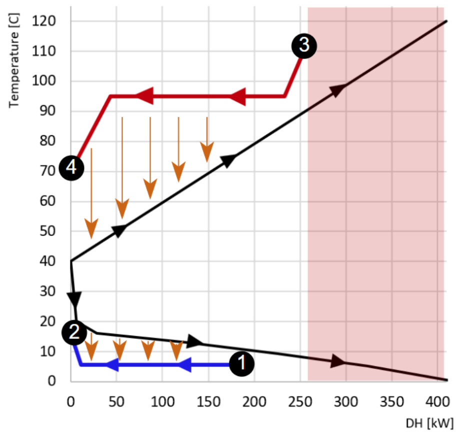

Figure 8. Grand Composite Curve of an example drying process with integrated heat-pumping, the region highlited red being the remaining heat demand after direct heat exchange and heat recovery through heat-pumping and the orange arrows indicating the direction of heat flow (ΔT_{min}=20°C and $\Delta T_{min,hp}$=5°C).

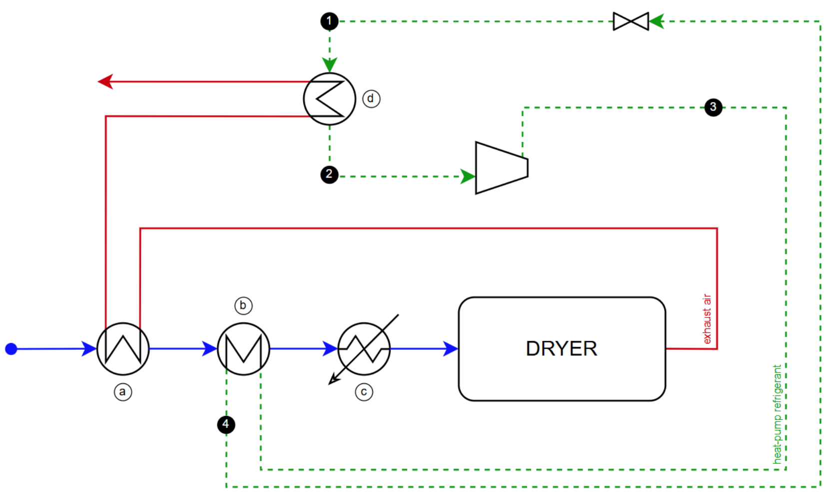

Figure 9. Process flow diagram of a dryer with integrated heat exchanger and heat-pump for energy efficient drying.

The whole system seen until now (dryer, heat exchanger, heat-pump) is fully represented in Figure 9. To summarize, the fresh air is pre-heated by the exhaust air until a certain temperature (a), then by the condensing refrigerant of the heat-pump (b) which has been initially evaporated using the exhaust (d) then compressed. Finally, if the final temperature of the fresh air has not been attained yet, the remaining heat demand of the air is satisfied by external utilities (c) (e.g. steam, gas boiler, electric heating). One can have a full overview of the heat-pump cycle by putting together Figure 7, Figure 8 and Figure 9 and connecting steps 1 to 4 of the cycle.

4. Pinch Methodology Applied to super-absorbent polymer drying process

4.1 Process Description and Stream Definition

Figure 10. Representation of the chosen drying process with fresh air (blue) and exhaust air (red).

For clarity of exposition, we do not consider here the detailed features of industrial drying process for super-absorbent polymer production, such as air recirculation, multiple drying zones, or humidity-dependent operating modes. Instead, we focus on a simplified representation: fresh ambient air is heated to the required inlet temperature, and hot, moisture-laden exhaust air leaves the dryer carrying recoverable thermal energy.

This reduced model is chosen to make the principles of Pinch Analysis easier to illustrate without the added complexity of numerous interacting streams and control strategies. However, it is important to emphasize that this simplification is only for a demonstration purpose. In a rigorous industrial Pinch Analysis, all relevant process streams must be identified and represented—including recirculated air, intermediate zone exhausts, make-up air, condensate streams, and any auxiliary heating or cooling utilities. Only by systematically accounting for every hot and cold stream in the actual drying system can we ensure that no heat recovery opportunities are overlooked and that the resulting energy targets and Heat Exchanger (HEX) network truly reflect the practical potential of the process.

Based on the simplified process diagram of Figure 10, there are two streams we need to consider, one hot and one cold stream. The flux table necessary for a heat recovery estimation can be found in Table 1. This table is the only requirement for us to obtain the two most important tools for heat recovery estimation, as mentioned in Section 3: the Composite Curve (CC) and Grand Composite Curve (GCC), shown respectively in Figure 11 and Figure 14 and further discussed in Section 4.2.1 and Section 4.2.3.

Table 1. Flux table of the considered drying process, temperatures in °C, humidities in kg/kg dry, and mass flows in kg/s.

Stream Name	Temperature In	Temperature Out	Humidity In	Humidity Out	Mass Flow
fresh air	28.90	120.00	15.70	15.70	70.30
exhaust air	56.70	25.00	39.60	sat.	70.30

4.2 Thermal Analysis Tools and Optimization

4.2.1 Composite Curves (Hot and Cold)

The CC obtained from Table 1 shows us the fresh air of the drying process which needs heating from 28.90°C to 120.00°C (cold stream), as well as the exhaust which can potentially be cooled down from 56.70°C to 25.00°C (hot stream), the latter temperature being arbitrary as it is not an actual cooling requirement, just a potential source of energy.

The ΔT_{min} was chosen here as 20°C, since such an exchange is often done through an air-water-water-air heat exchange system, shown in more detail in Section 4.2.2. Such a system requires a large enough temperature difference for a good heat exchange driving force as we have relatively more heat exchange interfaces (two HEXs required), otherwise the HEXs would be too big, and therefore expensive. An optimization can of course be made between the investment of the HEXs and the resulting energy savings; this will be presented in later sections.

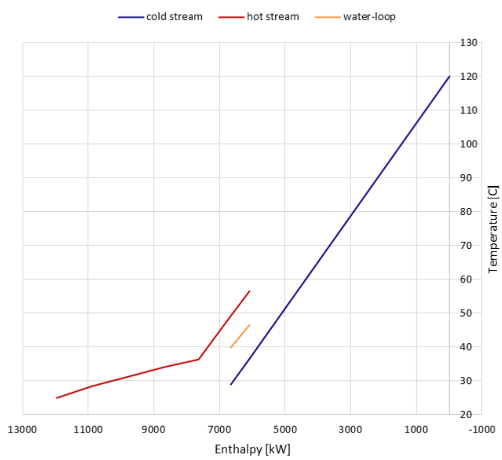

Figure 11. Composite Curve resulting from Table 1 with integrated water-loop for the heat exchange.

The CC shows a heat recovery potential between the cold and hot stream of our drying process equal to approximately 567 kW, retrieved from the overlap between the red and blue lines. In a nutshell, the region on the graph where the temperature of the hot stream is + ΔT_{min}°C larger than the temperature of the cold stream represents the region where heat can move from the exhaust to the fresh air.

The point where the red line becomes curved instead of a straight line is the moment the exhaust air cools down past its dew point, at which time it starts to condense and release sensible as well as latent heat from the previously evaporated water in the drying process. The orange line in the CC represents the water stream in the water-loop system, acting as an intermediate heat transfer medium between the exhaust and fresh air, discussed in more detail in Section 4.2.2.

4.2.2 Heat Exchanger Basics

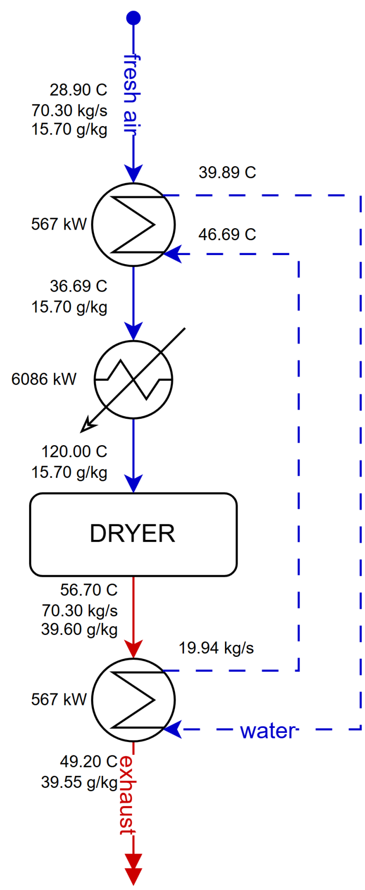

Figure 12. Dryer with water-loop heat exchange (ΔT_{min} = 20°C).

Heat exchangers are central to process integration because they enable the recovery and reuse of thermal energy between process streams. By transferring heat from hot streams to cold ones, they reduce the need for external heating and cooling utilities and support more sustainable process design.

Figure 12 shows our example dryer with a water-loop heat exchanger system to achieve our heat recovery potential of 567 kW, with a ΔT_{min} of 20°C. An air-water-water-air water-loop heat exchange system offers distinct advantages over an air-air heat exchanger. By utilizing water as an intermediary heat transfer medium, this system provides more flexible heat exchange network as water-loops are easier to integrate into a system as the location of the inlet fresh air and exhaust becomes less critical.

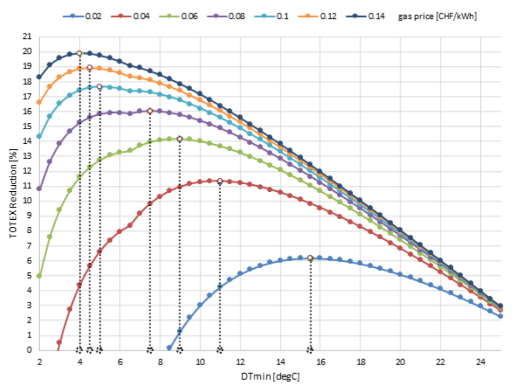

Figure 13. Total cost reduction ratio for different natural gas prices in CHF/kWh for the installation of a heat exchanger for direct heat recovery (expected lifetime=30.00 y, interest rate=6%.

One can note the difference between the direct heat recovery system shown in Figure 12 (water-loop), and Figure 9 (direct air-air heat exchanger): a water-loop adds water as an intermediate heat transfer medium between the fresh air and the exhaust.

The heat recovery potential is linked to the chosen ΔT_{min}. As mentioned in Section 4.2.1, a trade-off exists between ΔT_{min} and the investment associated with the heat exchangers. Figure 13 shows the reduction in total cost associated with different ΔT_{min} values. One can see a global maximum for each chosen natural gas price. The higher the latter is, the more beneficial lower ΔT_{min} values (e.g. bigger HEXs) become, since monetary savings associated with heat recovery increase. For more details on the construction of Figure 13, see Appendix A. To keep the analysis general, 20°C will still be chosen as the ΔT_{min}.

4.2.3 Grand Composite Curve

The GCC of our example dryer is shown in Figure 14. Such a figure represents the state of the system after direct Heat Recovery (HTR) (e.g. after the installation of the water-loop). The fresh air, which has been pre-heated to 36.69°C through direct HTR, still needs heating up to 120.00°C, which corresponds to 6086 kW. This information can be directly visualized on the GCC.

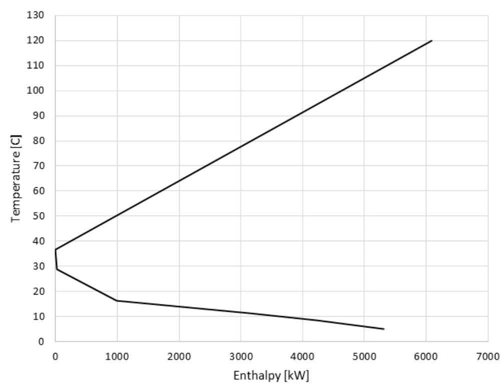

Figure 14. Grand Composite Curve resulting from Table 1.

The pinch point is located here at approximately 36°C. It is the point where we cross the value of the ΔT_{min}. Above this point is the residual heat demand of the system (heat which must be provided after direct HTR), and below it is the waste heat still available in the exhaust after direct HTR. For the construction of the GCC, all the temperatures of the exhaust had to be shifted to -ΔT_{min}, meaning that on the graph said temperatures below the pinch point are in reality +20°C higher. This shift is done to visualize the pinch point clearly. As already mentioned in section 3, the narrower the GCC looks, the more promising the integration of a heat-pump is, since a narrow GCC means that the temperature lifts required to go from the temperature of the exhaust to that of the fresh air are low, which would lead to a more efficient heat-pump.

We will now integrate a heat-pump to showcase its benefits. Heat-pump integration is usually the next step of process integration after choosing where to place the HEX. A key choice is the heating temperature of the heat-pump. The higher this temperature, the larger the recovery, but the more electricity we have to put into the system to achieve higher lifts, and the larger the heat-pump will be (and therefore the investment). This optimal heating temperature will depend mostly on the electricity to natural gas price ratio.

Figure 16, similar to Figure 13, shows the reduction in total yearly cost with increasing target air temperature, for different electricity to natural gas price ratios, with a designed heat-pump of COP (Coefficient Of Performance) equal to 2.32. For this particular example, we notice a global maximum for some of those ratios. For a ratio below 1, the heat-pump will always be beneficial since electricity is cheaper than gas, whilst for very high ratios, almost no benefits can be observed no matter the target air temperature of the Heat Pump (HP), because of the high price of electricity as compared to resulting gas savings.

For now, let us choose a heating temperature of the heat-pump of 112.00°C + 8°C, with 112.00°C being the target temperature of the fresh air after the heat-pump, and 8°C the ΔT_{min} we allow for both the condensing and evaporating side of the heat-pump. The evaporating and condensing refrigerant of the HP can be visualized on the GCC, as shown in Figure 15, where we observe that about 82.64% of the heating requirements are now satisfied by the HP, with 588 kW remaining which must be provided by external utilities. The heat-pumping cycle can be visualized in a Pressure-Enthalpy (PH) diagram, shown in Figure 23. Finally, the full dryer-HTR system can be visualized in Figure 17 with all relevant process parameters.

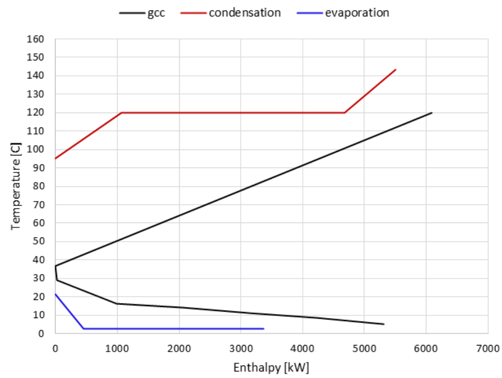

Figure 15. Grand Composite Curve with integrated heat-pump cycle ($\Delta T_{min,hex}$=20°C) and integrated heat-pump ($\Delta T_{min,hp}$=8°C).

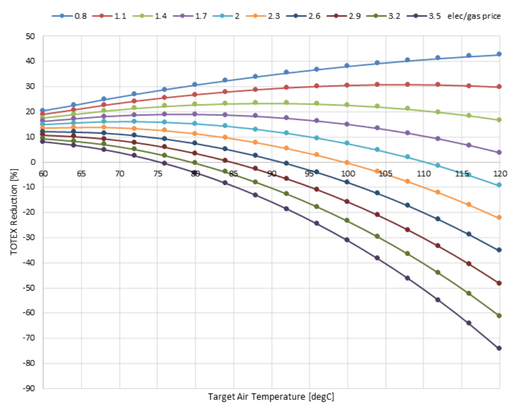

Figure 16. Total cost reduction ratio for different elec / gas price ratios in CHF/kWh, with increasing target air temperature for a heat exchanger-heat pump combined system (same heat exchanger as in Figure 13, expected lifetime=30.00 y, interest rate=6%, base gas cost=0.06 CHF/kWh).

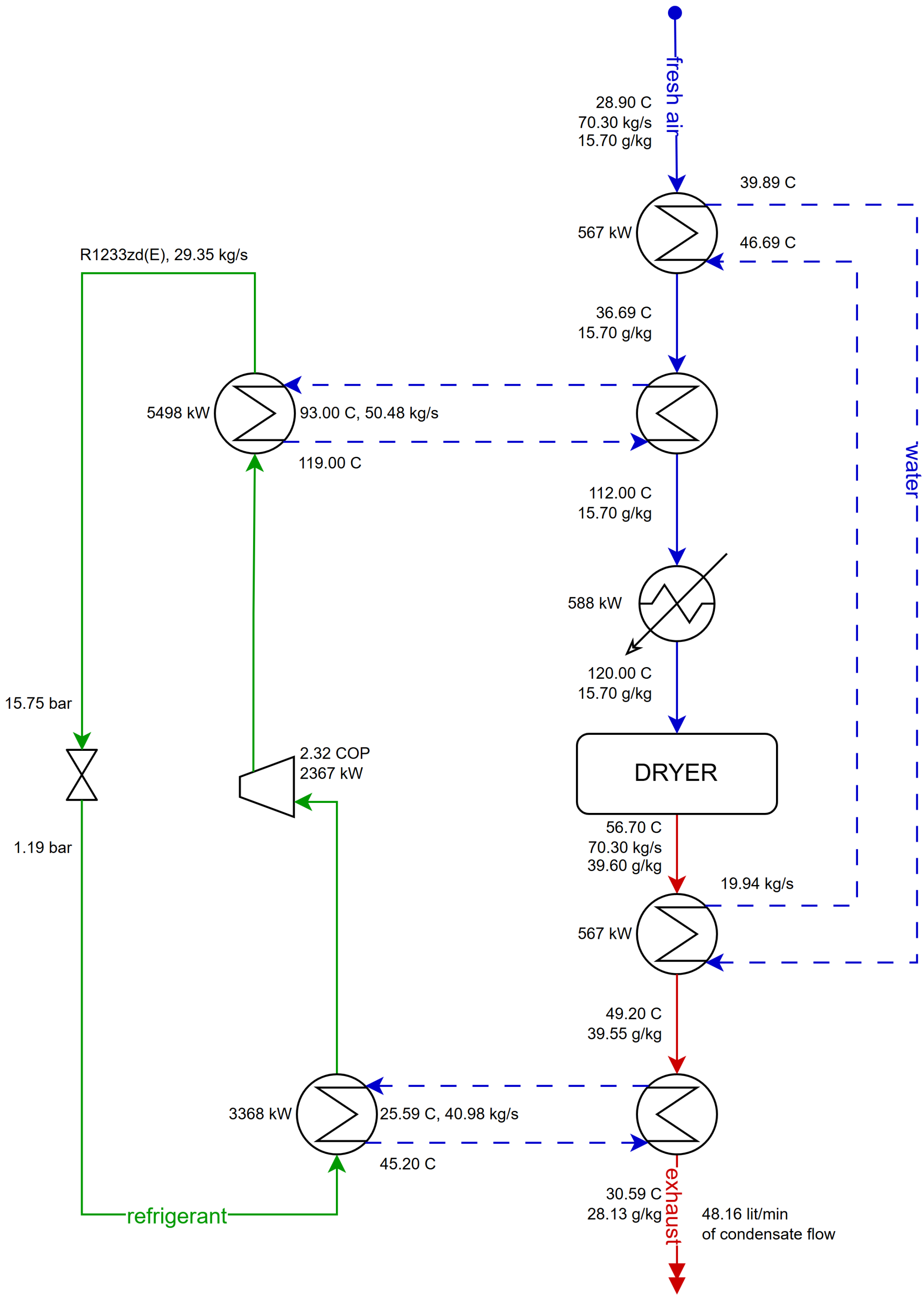

Figure 17. Dryer with water-loop heat exchange ($\Delta T_{min} = 20°C$) and integrated heat-pump ($\Delta T_{min} = 8°C$).

5. Business and Strategic Implications

5.1 Economic Evaluation

This section summarizes the economic attractiveness of the proposed energy recovery concepts with direct heat recovery through a water-loop heat exchanger system, and the additional integration of a heat-pump for the industrial dryer described in the previous section. The objective is to translate the thermal performance indicators established in the previous sections (e.g. recovered heat, residual utility demand, compressor power) into financial metrics that support decision-making.

The direct heat recovery system provides an instantaneous reduction of purchased heating duty of approximately 567 kW. After this integration step, the remaining heating demand is approximately 6086 kW. When a heat-pump is added, a fraction of the remaining demand can be supplied using electricity, which in this case corresponds to about 82.64% of the heating requirements, leaving approximately 588 kW to be provided by external utilities. The required compressor power is 2367 kW, for an achieved coefficient of performance of COP = 2.32.

In practice, the economic value of these integrations is driven by: (i) avoided fuel consumption (typically natural gas), (ii) additional electricity consumption (for the heat-pump), and (iii) investment. A simple annualized operating cost difference can be expressed as:

$$\Delta\text{OPEX} = -\left(\dot{Q}_{\text{saved,gas}}\right)\, c_{\text{gas}} + \left(P_{\text{el,HP}}\right)\, c_{\text{el}} \qquad (2)$$

where c_{gas} and c_{el} denote energy prices (in CHF/kWh). The payback period then follows from:

$$\text{Payback} = \frac{\text{CAPEX}}{\Delta\text{OPEX}} \qquad (3)$$

The pinch-based workflow naturally leads to a CAPEX/OPEX compromise: a lower ΔT_{min} increases recoverable heat but typically requires more heat transfer area and therefore higher investment. This behavior is illustrated by Figure 13, which shows a cost reduction optimum for different assumed fuel prices. The same logic applies to the heat-pump: increasing the target supply temperature (i.e., increasing temperature lift) can increase recovered heat, but at the expense of lower COP and higher compressor sizing, thus affecting both OPEX and CAPEX (see Figure 16).

From an industrial perspective, the economically optimal design is therefore not the thermodynamically maximum recovery, but the configuration that minimizes total annualized cost under realistic operating conditions. In addition, operational constraints such as minimum exhaust outlet temperature (corrosion risk, plume visibility) and hygiene constraints on air streams can impose tighter bounds than pure economics.

Choosing arbitrary gas and electricity prices of respectively 0.08 CHF/kWh and 0.11 CHF/kWh (ratio=1.40), and using Figure 13 and Figure 16, we find an optimal $\Delta T_{min,hex}$ of 7°C for the direct HTR HEX, and an optimal heating temperature of 88°C for the heat-pump ($\Delta T_{min,hp}$ = 20°C). The savings resulting from the latter are summarized in a bar chart shown in Figure 18.

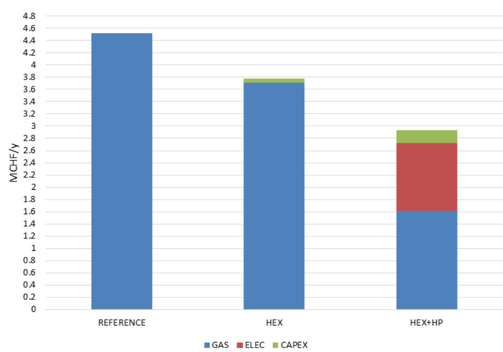

Figure 18. Bar chart showing the total yearly cost in MCHF/y for three systems (dryer alone, dryer+hex and dryer+hex+hp) broken down into gas, electricity and capex costs (expected lifetime=30.00 y, interest rate=6%, gas price=0.08 CHF/kWh, electricity price=0.11 CHF/kWh).

5.2 Sustainability and Corporate Responsibility

Beyond economics, heat recovery and heat-pump integration support sustainability targets by directly reducing the demand for high-carbon thermal utilities. In the present case, direct heat recovery reduces the required external heating duty while maintaining process performance. With the heat-pump integrated, a significant share of the heating demand is met via electrically driven upgrading of waste heat, which decreases the need for combustion-based heat and therefore reduces on-site emissions.

Energy efficiency improvements through waste heat recovery are commonly recognized measures in industrial decarbonization pathways and can contribute to compliance with emerging energy-audit requirements, best-available-technique benchmarks, and internal corporate roadmaps. Pinch analysis provides an auditable, engineering-based justification for the chosen measures, supporting both regulatory documentation and internal governance processes.

The reduction in greenhouse gas emissions depends on the displaced fuel and the emissions intensity of electricity. In simplified terms, the change in emissions can be written as:

$$\Delta CO_2 \approx -E_{\text{gas,saved}} \cdot EF_{\text{gas}} + E_{\text{el,added}} \cdot EF_{\text{el}}, \quad (4)$$

where EF_{gas} and EF_{el} denote gas and electricity emission factors respectively. Consequently, heat recovery is almost always beneficial, and heat-pumps become increasingly impactful as the electricity mix decarbonizes (or when supplied by low-carbon power procurement). From an ESG viewpoint, these measures typically contribute to: (i) reduced Scope 1 emissions (less fuel combustion), (ii) potentially increased Scope 2 (electricity) but often with a net reduction depending on the grid emission factor, and (iii) improved energy intensity KPIs (kWh per unit product), which are frequently tracked in sustainability reporting.

Using the same case used to generate Figure 18, we can examine how annual CO_2 savings in tons/y evolve as a function of the electricity emission factor in kg/kWh, with the gas emission factor assumed constant at 0.20 kg/kWh. Results are shown in Figure 19, where one can note that for our optimized dryer-hex-hp system, CO_2 is being saved annually for all cases up until an electricity emission factor of 0.75 kg/kWh.

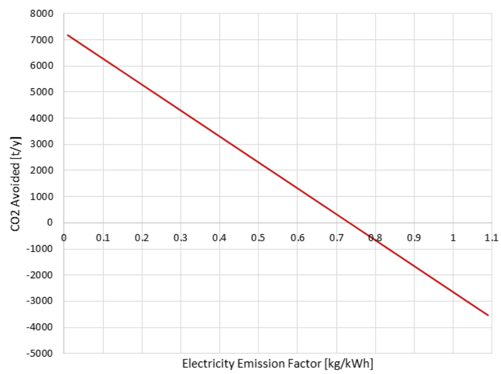

Figure 19. Evolution of CO_2 annual savings in tons per year as a function of the electricity emission factor for a full dryer-hex-hp heat recovery system ($\Delta T_{min,hex}$=7°C, optimal HP heating temperature=88°C, $\Delta T_{min,hp}$=20°C).

5.3 Empowering Clients with Pinch-Based Solutions

Pinch methodology is most effective when implemented as a structured workflow that industrial stakeholders can repeat across sites and processes. The approach is transparent: it links measured plant data to thermodynamic targets (CC/GCC), then to technical concepts (heat exchanger placement, heat-pump feasibility), and finally to an investment decision supported by cost and sustainability metrics.

A pragmatic implementation roadmap for stakeholders can be summarized as follows:

1. **Data collection and validation:** Define system boundaries, identify hot/cold streams, and establish reliable operating envelopes (temperatures, humidities, mass flows, availability). For drying systems, special attention should be given to condensation behavior and the associated latent heat release, since it strongly affects the shape of the CC and the magnitude

of recoverable heat.

2. **Process assessment and baseline:** Quantify current utility consumption, constraints, and bottlenecks. Establish a baseline case against which all integration concepts will be compared (energy, cost, and emissions).

3. **Integration study (pinch targeting and concept design):** Build the Composite Curves and Grand Composite Curve to identify the heat recovery potential, the pinch temperature region, and feasible temperature lifts. Screen solution concepts (direct HTR, intermediate loops, heat-pump integration) and perform ΔT_{min} optimization to balance recovery and investment.

4. **Project execution and operationalization:** Translate the preferred concept into detailed engineering (equipment sizing, control philosophy, fouling strategy, safety), procure and install, then verify performance through commissioning tests and KPI tracking.

Automating the workflow (data import, curve construction, diagram generation, and reporting) reduces iteration time and standardizes quality across studies. It also enables scenario analysis, energy prices, ΔT_{min} values, target temperatures, operating points, which is essential to build robust business cases rather than point-estimates.

Industries looking for execution-ready decision support, this approach can be strengthened through advanced optimization tools such as OSMOSE, the energy-integration platform developed at EPFL Lausanne. OSMOSE combines process integration, costing, and optimization in a single framework and is particularly suited to industrial systems with multiple recovery options and interacting design choices[12, 13]. Its underlying optimization methods also make it relevant for more complex cases involving variable production schedules, multiple operating regimes, and time-dependent utility interactions. EPFL research further connects these workflows through a MILP-based formulations for heat-pump and process integration[14].

For industrial stakeholders, the result is broader scenario coverage and clearer decision support. In practice, automated workflows help translate plant data into energy targets, heat-recovery concepts, heat-pump integration options, and decision-ready CAPEX/OPEX/CO_2 comparisons.

6. Discussion

This study shows that applying pinch methodology to drying systems provides a clear, data-driven basis for identifying and prioritizing heat recovery options. Starting from a minimal set of process data (temperatures, humidities, mass flows), the Composite Curves (CC) and Grand Composite Curve (GCC) translate plant measurements into thermodynamic targets, revealing both the direct heat recovery potential and the remaining demand that could be met by a heat-pump.

A first insight is that even a simple air drying system offers significant recoverable heat when exhaust condensation is properly accounted for. The CC highlights where a water-loop heat exchanger can efficiently pre-heat fresh air, while the GCC clarifies how much residual heat remains at which temperatures and whether a heat-pump integration is thermodynamically attractive. In this way, pinch analysis does not only quantify savings, it also indicates realistic temperature lifts and guides the placement and sizing of heat exchangers and heat-pumps.

Economically, the workflow makes CAPEX/OPEX trade-offs explicit: tighter approach temperatures increase recovery but require larger heat exchangers, while higher heat-pump supply temperatures save more fuel but decrease COP and increase compressor power. These trade-offs are clearly illustrated by the case study results. In Figure 13, positive paybacks, corresponding to roughly 10% total yearly cost reduction, are achieved for gas prices of 0.04 CHF/kWh and above through optimal heat-exchanger design, i.e. by selecting the optimum ΔT_{min}. This makes the heat exchanger a particularly attractive measure, as it is a nonadditional-cost solution requiring only relatively low investment; this is further confirmed in Figure 18, which compares TOTEX reduction against the corresponding increase in CAPEX.

Additionally, a heat-pump can be very attractive for further heat recovery with a comparatively small electricity input. As shown in Figure 16, a large share of the process energy demand can be covered by heating the air up to the maximum heat-pump temperature of 120°C. A positive return is obtained for electricity-to-gas price ratios of 1.7 and below, with the economic benefit increasing strongly as this ratio decreases. More generally, Figure 18 summarizes the gains in TOTEX relative to the additional required CAPEX, annualized over 30 years, for an optimized case.

From a sustainability perspective, replacing part of the combustion-based heat with recovered and upgraded waste heat reduces fuel use, lowers direct (Scope1) emissions, and improves energy intensity indicators that are commonly reported in ESG frameworks. The physically grounded nature of pinch analysis offers a traceable justification for these measures in the context of audits and decarbonization roadmaps. In this case, Figure 19 shows that substantial CO_2 reductions can be achieved with these solutions for electricity emission factors below 0.75kg/kWh, with around 5000t/y of CO_2 avoided when green electricity is used (0.2kg/kWh emission factor).

Some limitations remain: the analysis is based on steady-state, representative conditions and does not fully capture seasonal or operational variability; practical constraints (corrosion, fouling, hygiene, layout) may limit the theoretical potential; and future energy prices and grid emission factors are uncertain. These aspects should be addressed when moving from conceptual targeting to final design.

Overall, the case confirms the value of pinch-based tools for drying systems: they are transparent, require limited input data, and can be automated, enabling rapid screening of direct heat recovery and heat-pump options. Future applications include extending the workflow to multiple dryers and sites, incorporating more detailed operating profiles, and combining heat recovery with other low-carbon heat sources or thermal storage to support robust, portfolio-wide decarbonization strategies.

7. Pinch Methodology Combined with Bühler's Expertise

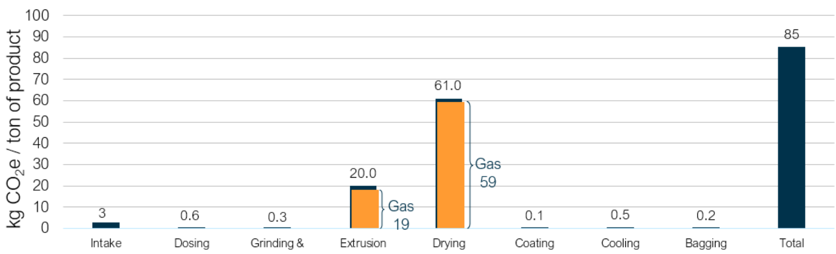

Figure 20. Environmental process footprint of a typical extrusion drying line (assumed low carbon electricity with 0.04 $kgCO_{2e}$/kWh).

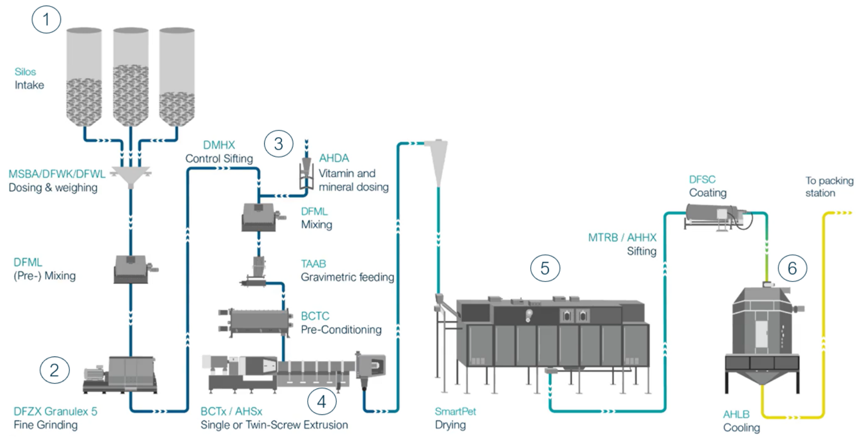

Figure 21. Holistic process view of extrusion and drying

Classical pinch analysis is a powerful tool to identify the theoretical maximum of heat recovery for a given set of hot and cold streams, but it usually assumes that the underlying process is fixed: mass flows, moisture contents, and temperature levels are taken as given. In practice, this is rarely optimal. By first optimizing the process itself, in particular its thermal demand and temperature levels, we can significantly increase the recoverable heat and improve the business case for heat pumps and other advanced energy technologies. The holistic footprint optimization work for extrusion and drying lines illustrates this idea (see process diagram in Figure 21). In this case study, assuming low-carbon electricity, more than 90% of the manufacturing-related greenhouse-gas emissions are associated with the thermal processes in extrusion and drying (see Figure 20). This means that the main leverage for decarbonization and cost reduction lies in reducing and electrifying these thermal steps, while at the same time improving the possibilities for internal heat recovery.

7.1 Reducing Thermal Load Before Pinch

The first step is to minimize the thermal load of the process itself. In the extrusion–drying line, this is achieved through a combination of raw material selection, recipe formulation, particle-size reduction, and extrusion optimization that is explicitly targeted at reducing the moisture load entering the dryer.

- **Recipe formulation and water activity:** By formulating recipes to achieve lower water activity and lower absolute water content at the extruder outlet, less moisture has to be evaporated in the dryer. Case-study results show that reducing the product water content before the dryer by only 1–2 percentage points can already lower dryer energy demand by roughly 3–6%. This is a strong lever because most of the dryer energy goes into phase change, not sensible heating.
- **Extruder configuration and die-plate design:** Screw configuration, barrel temperature profile, and die-plate geometry are engineered to increase flash-off of water at the extruder exit while respecting product quality constraints (density, structure, texture). By moving part of the water removal from a relatively inefficient convective dryer to the extrusion step, the downstream drying load is reduced by 3–6% without compromising product specifications.
- **Optimal particle-size reduction:** Upstream grinding and granulation are optimized to create particle-size distributions that are easier to extrude and dry. This reduces required residence times and helps avoid over-drying in parts of the bed while other regions are still wet.

These measures directly change the mass and energy balances that would enter a pinch study: mass flow rates of water to be evaporated are reduced, and in many cases the required peak temperatures in the dryer can be lowered because the process is no longer operated with large safety margins to compensate for variability.

7.2 Improving Efficiency and Temperature Levels

In addition to reducing the thermal load, we can improve the efficiency of the remaining heating duty and bring temperature levels closer to what is technically required:

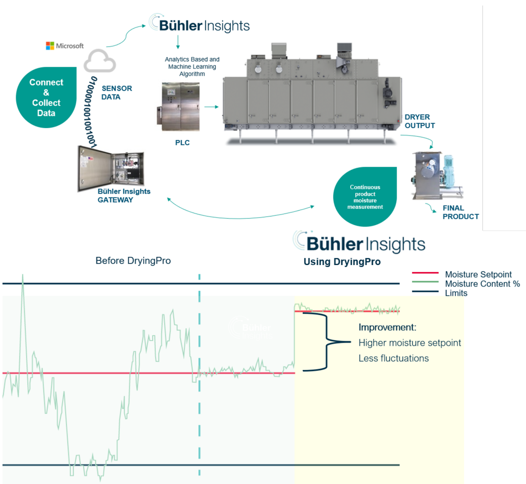

Figure 22. Dryer humidity control with DryingPro for smarter, stable and more energy-efficient drying.

- **Dryer operation and control:** Measures such as optimizing product distribution on the dryer bed, balancing air flows between zones, and controlling exhaust humidity ensure that the dryer operates at the minimum necessary temperature and with minimal bypass or leakage. Digital tools like DryingPro (real-time moisture and humidity control, see Figure 22) further stabilize end moisture, allowing us to eliminate systematic over-drying and run with tighter tolerances, saving roughtly 3
- **Cooling and downstream heat reuse:** Heat from coolers and exhaust air from dryers can be reused to preheat process air, pneumatic conveying air, or water for the extruder. In the case study, this is organized as part of a holistic energy-flow concept where heat recovery from cooling and drying contributes to upstream preheating.
- **Energy-source conversion and electrification:** With reduced temperature levels and more stable operation, it becomes feasible to convert fossil-fired utilities (e.g. direct gas firing or steam) to electrified options such as electric heaters or heat pumps.

From a pinch perspective, these measures flatten and shift the composite curves: the hot composite curve (representing waste heat) becomes richer at lower temperature levels due to better recovery and control, while the cold composite curve (representing demand) moves downward because less high-temperature heat is needed. This creates an enlarged overlap between available waste heat and heat demand at temperatures where heat pumps can operate with high coefficients of performance.

7.3 Maximizing Recovery and Heat-Pump Value

Once the process has been optimized, we can apply pinch analysis on this new, improved baseline. The result is a fundamentally different heat-integration problem compared to the pinch study performed on the original, unoptimized process:

- The **total heating and cooling loads** are lower, reducing the size and cost of external utilities.
- **Temperature levels** of both hot and cold streams are closer together, enabling more internal heat exchange and increasing the share of demand that can be met by heat recovery.
- The remaining gap between hot and cold composite curves, especially across moderate temperature lifts, is ideally suited for mechanical heat pumps. Because process temperatures

have been reduced, the required temperature lift for the heat pump is smaller, which improves COP and reduces operating cost.

- The overall system is more stable (thanks to improved control of moisture, density, and product distribution), which is critical for robust operation of tightly integrated heat-recovery and heat-pump systems.

In other words, by “pre-conditioning” the process through holistic optimization, we do not simply apply pinch analysis to a given process; we use pinch as the second step in a combined methodology. Step 1 minimizes and lowers the demand by acting on raw materials, formulation, extrusion, and drying parameters. Step 2 then maximizes internal heat recovery and cost-effective electrification (via heat exchangers and heat pumps) on this optimized basis.

This combined approach, process-first optimization followed by enhanced pinch-based heat integration, allows us to reach significantly higher levels of energy and CO_2 savings than pinch alone. It directly leverages Bühler’s deep process know-how (from raw materials to extrusion and drying) and translates it into a differentiated solution: not only designing the heat-recovery system, but reshaping the process so that maximum recovery becomes technically and economically achievable, a key element of competitiveness in thermal-process industries.

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Abbreviations

HTR: Heat Recovery
HP: Heat Pump
COP: Coefficient of Performance
HEX: Heat Exchanger
CC: Composite Curve
GCC: Grand Composite Curve

Appendix

Appendix A

Figure 13 was obtained from the following list of equations.

$$r = 1 - \frac{TOTEX_{new}}{OPEX_{ref}} \tag{5}$$

$$TOTEX_{new} = OPEX_{ref} - OPEX_{hex,saved} + a \cdot HEX_{inv} \tag{6}$$

$$OPEX_{ref} = GAS \times OP \times PRICE_{gas} \tag{7}$$

$$OPEX_{hex,saved} = HTR_{hex} \times OP \times PRICE_{gas} \tag{8}$$

$$a = \frac{i \cdot (i+1)^n}{(i+1)^n - 1} \tag{9}$$

With:

- r [-]: total cost reduction
- $OPEX_{ref}$ [CHF/year]: reference operational cost (without heat recovery)
- $TOTEX_{new}$ [CHF/year]: total cost including operational cost and annualized HEX investment
- $OPEX_{hex,saved}$ [CHF/year]: reduction in operational cost associated with the HEX investment
- HEX_{inv} [CHF]: estimated investment of the water-loop system
- $PRICE_{gas}$ [CHF/kWh]: price of gas
- HTR_{hex} [kW]: heat recovered with the water-loop
- OP [hours/year]: operating time of the dryer
- a [/year]: annualization factor, which depends on:
  - i [-]: interest rate
  - n [year]: lifetime of the process

Appendix B

Figure 16 was obtained by using the equations presented in Appendix A, along with the following additional equations to account for the heat-pump savings.

$$TOTEX_{new} = OPEX_{ref} - OPEX_{hex,saved} - OPEX_{hp,saved} + a \cdot (HEX_{inv} + HP_{inv}) \tag{10}$$

$$OPEX_{hp,saved} = HTR_{hp} \times OP \times PRICE_{gas} - P_{el} \times OP \times PRICE_{elec} \tag{11}$$

$$PRICE_{elec} = ratio \times PRICE_{gas} \tag{12}$$

With:

- $OPEX_{hp,saved}$ [CHF/year]: reduction in operational cost associated with the HP installation (substracting required electricity input)
- HP_{inv} [CHF]: estimated investment of the heat-pump system
- $PRICE_{elec}$ [CHF/kWh]: price of electricity

- HTR_{hp} [kW]: heat recovered with the heat-pump (condensation)
- *ratio* [-]: the electricity to gas price ratio

Appendix C

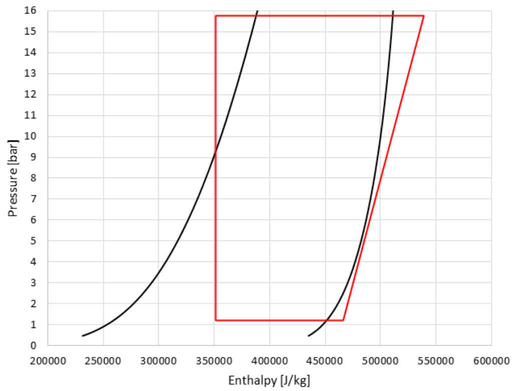

Figure 23. Pressure-Enthalpy (PH) diagram of the heat-pump cycle presented in Figure 17.

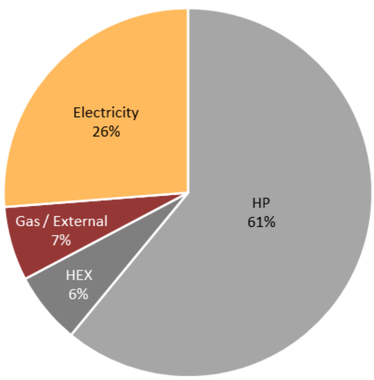

Figure 24. Energy share of the dryer-HTR system, including required electricty from the heat-pump (total=9020 kW).