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Integration concepts and recommendations

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TIS: TIENSE SUIKERRAFFINADERIJ N.V.

TLK: TLK ENERGY GMBH

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SPIL: Spilling Technologies GmbH

SKPS: Smurfit Westrock Paper Services B.V.

SKC: SMURFIT WESTROCK CZECH SRO

SP: STELLA POLARIS AS

ABBREVIATIONS AND ACRONYMS

COP: Coefficient of Performance

DHN: District Heating Network

GHI: Global Horizontal Irradiance

HX: Heat Exchanger

HP: Heat Pump

HTF: Heat Transfer Fluid

HTHP: High-Temperature Heat Pump

HVFP: High Vacuum Flat Plate (collector)

MVR: Mechanical Vapour Recompression

MT-Power: (Product name of TVP Solar collector)

SPIRIT: Implementation of sustainable heat upgrade technologies for industry

ST: Solar Thermal

TES: Thermal Energy Storage

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1. EXECUTIVE SUMMARY

This deliverable provides practical guidelines and integration concepts for decarbonizing industrial process heat, with a focus on high-temperature heat pumps (HTHPs) and solar thermal technologies. The report covers nine energy-intensive processes—spray drying, shrimp cooking, sugar and paper production, baking, distillation, brick drying, brewing, and slaughtering—examining both brownfield and greenfield integration options.

Key results show:

- Final energy savings across all sectors typically range from 40 % to 90 %, depending on process and integration level.
- Sector-specific savings include: Spray drying (40 % – 60 %), shrimp cooking (65 % – 85 %), sugar production (70 % – 86 %), paper production (52 % – 62 %), baking (30 % – 75 %), distillation (70 % – 95 %), brick drying (55% – 70%), brewing (25 % – 52 %), and slaughtering (70 % – 85 %).
- Solar thermal integration and storage further enhance efficiency, however requires right geographical location and production pattern.

Key takeaways:

- High energy and emission savings are achievable across diverse industrial processes.
- Effective planning (including energy mapping and advanced controls) maximizes benefits and avoids lock-in, even when retrofitting existing facilities.
- Retrofitting brownfield sites often requires preserving or modifying legacy heat recovery systems, but significant benefits are still achievable—as seen in slaughterhouse integration, where moving to horizontal scalding increases heat pump effectiveness.
- Upgrading legacy systems and adopting flexible, modular designs secure long-term decarbonization and competitiveness.

These strategies provide a clear roadmap for industries seeking efficient, reliable, and low-carbon heat supply, supporting progress toward European climate and energy goals.

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2. INTRODUCTION

Industrial heat demand makes up a significant share of global energy use and is a major driver of greenhouse gas emissions. In energy-intensive sectors—such as food & beverage, chemicals, and pulp & paper—high process temperatures have historically been met using fossil fuels, resulting in both high energy consumption and substantial CO_2 emissions. Decarbonizing these sectors is thus fundamental to achieving broader climate and energy targets.

High-temperature heat pumps (HTHPs) and solar thermal technologies have emerged as two of the most promising solutions for the deep decarbonization of industrial process heat. HTHPs enable the electrification of steam and hot water production by efficiently upgrading low-temperature waste heat; when supplied with renewable electricity, they become a cornerstone of sustainable heat supply. Solar thermal systems, capable of delivering high-grade heat directly to industrial processes or providing a high-temperature heat source for heat pumps, offer a complementary pathway to reducing reliance on fossil fuels, unlocking direct use of renewable heat and further enhancing system efficiency.

This deliverable presents guidelines for integration and standardized concepts for deploying HTHPs and solar thermal technologies in the most significant industrial sectors. Drawing on extensive experience from demonstrator sites and cross-sectoral expertise within the SPIRIT project consortium, the document addresses both brownfield (retrofit) and greenfield (new build) scenarios, with hybrid configurations that combine the strengths of heat pumps and solar thermal. Special focus is placed on the synergies between these technologies—such as using solar-heat as a source for HTHPs or employing thermal energy storage to bridge intermittent supply and continuous demand.

Across nine detailed integration concepts—covering processes such as spray drying, shrimp cooking, sugar and paper production, baking, distillation, brick drying, breweries, and slaughterhouses—the report serves as a practical guide to decarbonizing key industrial heat users. Each concept includes energy mapping, best-practice process integration, performance metrics, and insights on overcoming common barriers, such as site space limits and the adaptation of legacy heat recovery systems.

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By leveraging the dual strengths of HTHPs and solar thermal, and integrating advances in system controls, energy storage, and process optimization, this deliverable aims to provide sector leaders, engineers, and decision-makers with actionable strategies for improving efficiency, reducing emissions, and securing future-ready industrial heat supply

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3. METHODS

3.1 Heat pump modelling

The thermodynamic modelling of the heat pump system is based on the first and second laws of thermodynamics. In the analysis the following assumptions were considered: 1) The heat pump is considered as a grey box unit, 2) The heat transfer rate is calculated per unit heat capacity rate ($\dot{C}$) to account for ease of scalability and to cover a wide range of industrial processes, 3) No heat loss from the system is considered, 4) Additional auxiliary heating system (electric boiler) is considered for process temperatures > 200 °C. The following governing equations are used to estimate the heat pump Coefficient of Performance (COP), energy saving and emission reduction.

The heat output $\dot{Q}_{\text{sink}}$ of the heat pump is calculated using the Equation (1).

$$\dot{Q}_{\text{sink}} = \dot{C} \cdot (T_{H,o} - T_{H,i}) \tag{1}$$

Where, $T_{H,i}, T_{H,o}$ represents the heat sink inlet and outlet temperatures. For steam production the heat of vaporization is used as the heat output, $\dot{Q}_{\text{sink}}$. The required heat input $\dot{Q}_{\text{source}}$ to the heat pump is a function of heat output and heat pump COP and calculated using Equation (2).

$$\dot{Q}_{\text{source}} = \dot{Q}_{\text{sink}} \cdot \left(1 - \frac{1}{\text{COP}_{\text{HP}}}\right) \tag{2}$$

The COP of the heat pump system is estimated based on the Lorenz efficiency polynomial Equation (5) proposed by Andersen *et al.* [1]

$$\text{COP}_{\text{HP}} = \eta_{\text{Lorenz}} \cdot \text{COP}_{\text{Lorenz}} \tag{3}$$

$$\text{COP}_{\text{Lorenz}} = \frac{\bar{T}_H}{\bar{T}_H - \bar{T}_C} = \frac{\bar{T}_H}{\Delta \bar{T}_{\text{lift}}} = \frac{\Delta \text{H}}{\Delta \text{S}} \tag{4}$$

$$\eta_{\text{Lorenz}} = 0.486 + 10^{-4} \cdot (27.1 \cdot \Delta T_{\text{lift}} - 0.0737 \cdot \Delta T_{\text{lift}}^2 - 2.0 \cdot T_{\text{so, in}} - 13.0 \cdot \Delta T_{\text{so}} - 5.15 \cdot \Delta T_{\text{si}}) \tag{5}$$

The relative energy saving with the heat pump integration as a replacement of a Natural Gas (NG) boiler is estimated using the Equation (6). Here $\dot{E}_{\text{boiler}}$ describes the energy content supplied to the natural gas boiler while $\dot{W}_{\text{comp}}$ is the compressor power of the heat pump and $\dot{E}_{\text{eboiler}}$ is the electricity consumption of the electric boiler. The new heat pump system delivers $\dot{Q}_{\text{sink}}$ and electric boiler delivers $\dot{Q}_{\text{eboiler}}$ to the process and the old boiler supplied $\dot{Q}_{\text{Boiler}}$. The heat pump based and NG boiler-based systems are assumed to deliver the same amount of heat to the process. To estimate energy savings a boiler efficiency of 0.90 is assumed (Ommen *et al.*, 2015 [4]).

$$\text{Relative Energy saving} = \frac{\dot{E}_{\text{boiler}} - \dot{W}_{\text{comp}} - \dot{E}_{\text{eboiler}}}{\dot{E}_{\text{boiler}}} = \frac{\left(\frac{\dot{Q}_{\text{Boiler}}}{\eta_{\text{Boiler}}}\right) - \left(\frac{\dot{Q}_{\text{sink}}}{\text{COP}_{\text{HP}}}\right) - \dot{Q}_{\text{eboiler}}}{\left(\frac{\dot{Q}_{\text{Boiler}}}{\eta_{\text{Boiler}}}\right)} \tag{6}$$

The percentage of CO_2 emission reduction with the heat pump integration compared to NG boiler is estimated by the Equation (7). Also, the emission reduction percentage is calculated for different countries and the corresponding Carbon Intensity (CI) for both electricity and natural gas is presented in Table 1 .

$$\text{Relative emission reduction} = \frac{\left(\frac{\dot{Q}_{\text{Boiler}}}{\eta_{\text{Boiler}}} \cdot \text{CI}_{\text{NG}}\right) - \left(\left(\frac{\dot{Q}_{\text{sink}}}{\text{COP}_{\text{HP}}} + \dot{Q}_{\text{eboiler}}\right) \cdot \text{CI}_{\text{elec}}\right)}{\left(\frac{\dot{Q}_{\text{Boiler}}}{\eta_{\text{Boiler}}} \cdot \text{CI}_{\text{NG}}\right)} \tag{7}$$

Table 1: Carbon Intensity indicator for different countries

Country	Carbon Intensity Electricity ($kgCO_2$ eq./kWh)	Carbon Intensity Natural gas ($kgCO_2$ eq./kWh)	
Finland	0.040	(Europa.eu, 2025 [2])	0.219 (IPCC emission factor database, 2021 [3])
Denmark	0.094		
Germany	0.329		

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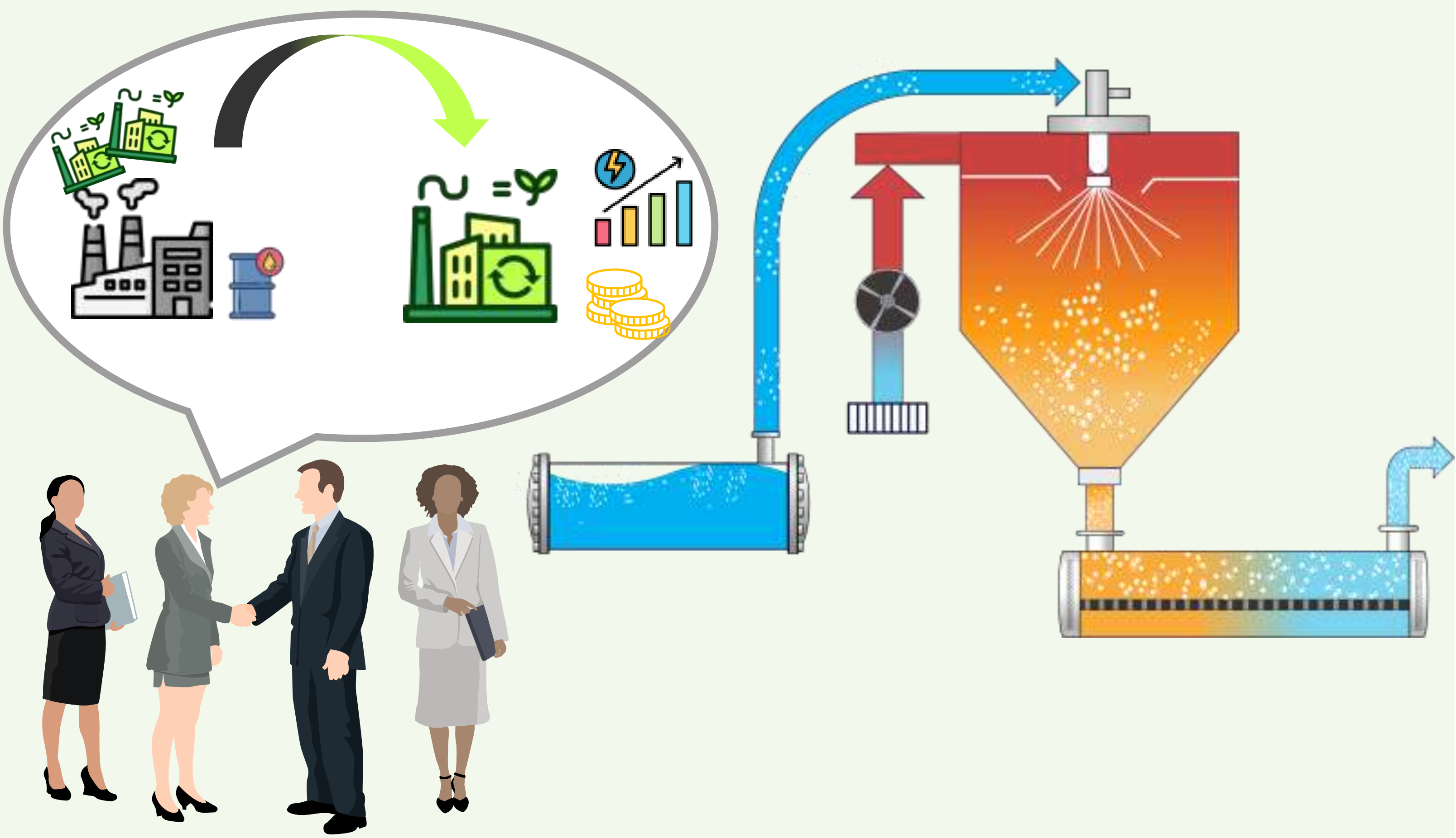
4. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF MILK POWDER SPRAY DRYING PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 65 %: Heat pump-integrated systems deliver the same heat using just 35 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 45 % - 90 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



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SPRAY DRYING

In the dairy industry, many heating and cooling processes are involved, accounting for a major portion of the energy demand of the sector. The global production of milk powder for the year 2024 is estimated around 4.4 million metric tons according to USDA [5]. The main process lines for conventional milk powder production are milk reception, standardization, homogenization, pasteurization, evaporation, and spray drying.

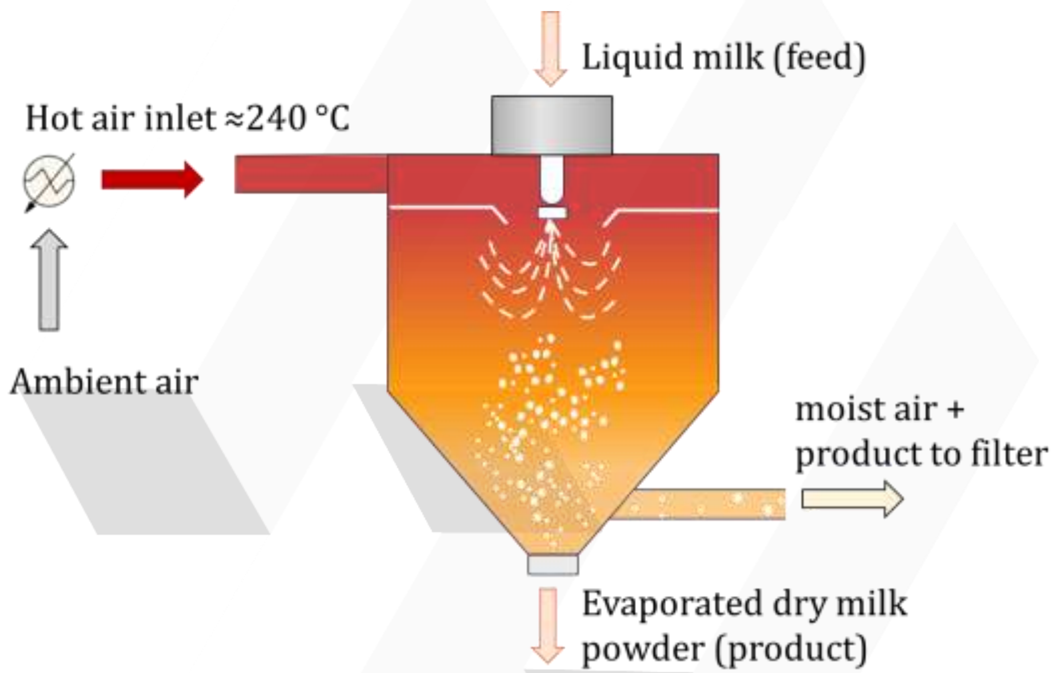

Figure 1: Schematic of milk powder spray dryer.

Spray drying is a highly energy-intensive process widely employed in the industry where the heat normally is delivered by fossil fuels. It is widely used to produce powdered forms of diverse products, such as sugar, milk, cheese, coffee, eggs, starch, etc. A typical spray dryer is depicted in Figure 1.

The temperature range of industrial spray drying process for dairy production ranges up to 240 °C. The majority of industrial dryers work with convection, reducing the moisture in a product through evaporation. The liquid milk is sprayed into the drying chamber, where it is dried by the hot air inlet. The dry milk powder leaves the spray drying chamber at the bottom, typically going to a fluidizing bed.

The moist exhaust air leaves the chamber, which could be used to preheat the liquid feed milk or directly integrated within the heat pump (HP) system. Industrial heat pump holds a significant potential in lowering the energy consumption. Therefore, it can be used as a substitute for the convectional based heating system.

HEAT PUMPS CAN BE INTEGRATED INTO THE SPRAY DRYING PROCESS

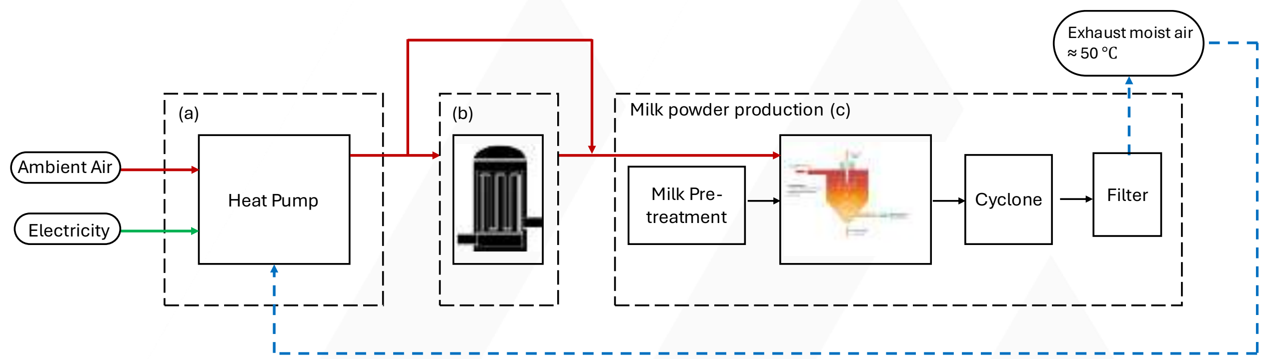

Figure 2: Schematic of Heat pump integration with spray dryer system

With the heat pump integrated within the spray drying process, the inlet air at ambient state can be heated up to the required temperature of the drying process by the heat pump (a) and supplied into the drying chamber (c) and passes through the Cyclone and exists the Filter as exhaust air.

The typical heat source for the heat pump system is the moist exhaust air from the filter of around 50 °C but the temperature varies depending on manufacturer and end product. The dew point of the air is around 45 °C. The majority of the energy will be available in the form of latent heat from the condensation of the moist air.

The heat pump system raises the temperature of the inlet ambient air up to 240 °C, which is then directed into the drying chamber to provide the required heat of evaporation to remove the moisture in the product flow. The additional utility (b) is an electric boiler system which is used as an auxiliary system and can be combined with the heat pump system for elevated temperature ranges.

INTEGRATION OUTCOME

Integrating a high-temperature heat pump into the spray dryer process results in increased energy efficiency, thereby lowering the energy needed to be supplied. Heating the air more with the heat pump decreases the heat pump COP, as it needs to increase the temperature more. But for the process with full electrification (only heat pump) the system efficiency increases as the complete heating demand is covered only by the heat pump instead of by other means such as electric boilers or electric heaters which accounts for additional energy consumption and thereby lower the system efficiency.

The presence of moisture in the exhaust air results in increased heat recovery from the resulting air stream, as the latent heat holds a large heat content. Figure 3, shows the effect of relative humidity in the exhaust air over the combined system performance HP+elec boiler for varying heat sink temperatures accounting for both full and partial electrification. Higher relative humidity in the exhaust air yields a higher dew point temperature resulting in pre-heating of the inlet air stream to higher temperatures increasing COP for the heat pump by reducing the ΔT_{lift} but also lowering the heat demand.

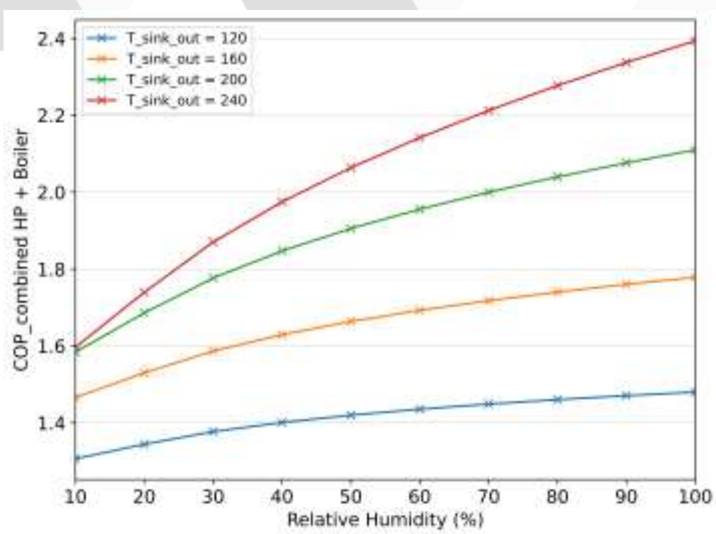

Figure 3: Combined system performance HP + Boiler for varying Relative humidity

Also, the Combined system performance of both heat pump and electric boiler, along with the energy saving for varying heat pump delivery temperature is shown in **Error! Reference source not found.**, the normalized energy consumption of the system is shown in Figure 5 and the CO_2 Emission reduction for different countries is shown in Table 2. In **Error! Reference source not found.**Figure 4 the heat pump delivery temperature is varied from 120 °C to 240 °C, to address both full coverage with the heat pump at 240 °C and partial coverage <240 °C where an electric boiler covers the rest. The red line indicates the combined system performance for both heat pump and electric boiler, which increases as the heat pump delivery temperature rises. With the integration the expected system performance can range between 1.5 – 2.5 for partial and full integration, for the exhaust stream with a dew point of 45 °C.

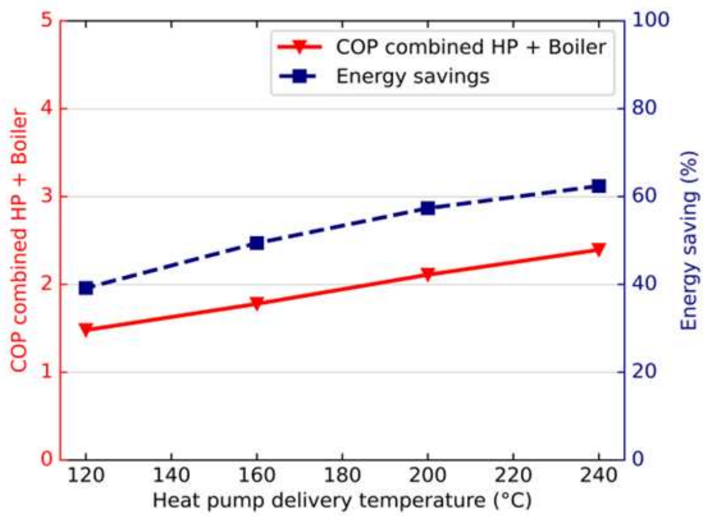

Figure 4 Combined system COP and Energy savings for varying heat pump delivery temperature

The energy savings is represented by the blue line, indicating the advantages of integrating a HP system as a replacement of a NG boiler for heating purposes. The combined system has energy savings within the range of 40 % - 60 %.

The Normalized heat consumption plot, Figure 5, indicates the heat load distribution of the individual component of the system and normalized to the total heat demand for varying heat pump delivery temperatures. For the case with full electrification with heat pump at 240 °C a minimum of 40 % of the total heat demand has to be covered by compression work (green area) and 50 % has to be covered by the heat source either by the exhaust air stream or other waste heat stream (blue area) in order to achieve the system performance as estimated in Figure 4.

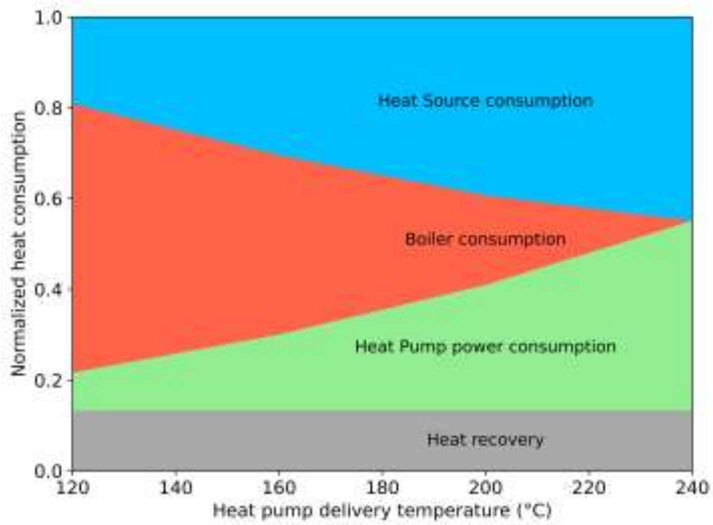

Figure 5: Normalized heat load distribution for the complete system

On the contrary, for partial electrification from a temperature of 120 °C to 220 °C an electric boiler is used in addition to the HP - represented by red area, increases for lower temperature and covers almost 60 % of total heat demand for 120 °C. Though it increases the individual HP COP, but it decreases the overall system performance as a larger portion of the heat demand is covered by a boiler with low efficiency. In addition, pre-heating a portion of the inlet air with the moist exhaust air can lower the heat demand as it enables direct heat recovery between the streams. Which is shown as the grey area covering almost 10 % of total heat demand.

Table 2: Emission reduction with full electrification for varying countries

Country	Emission reduction
Finland	93 %
Denmark	84 %
Germany	44 %

The emission reduction percentage is an indicator of the amount of CO_2 reduced with the heat pump integration compared to NG boiler. The indicator is a direct measure of Carbon Intensity of both electricity and NG grid. Table 2, represent the reduced emission for full electrification for countries Finland, Denmark, and Germany and are 93 %, 84 %, and 44 % respectively based on the emission intensity of the countries' specific electricity grids in 2023.

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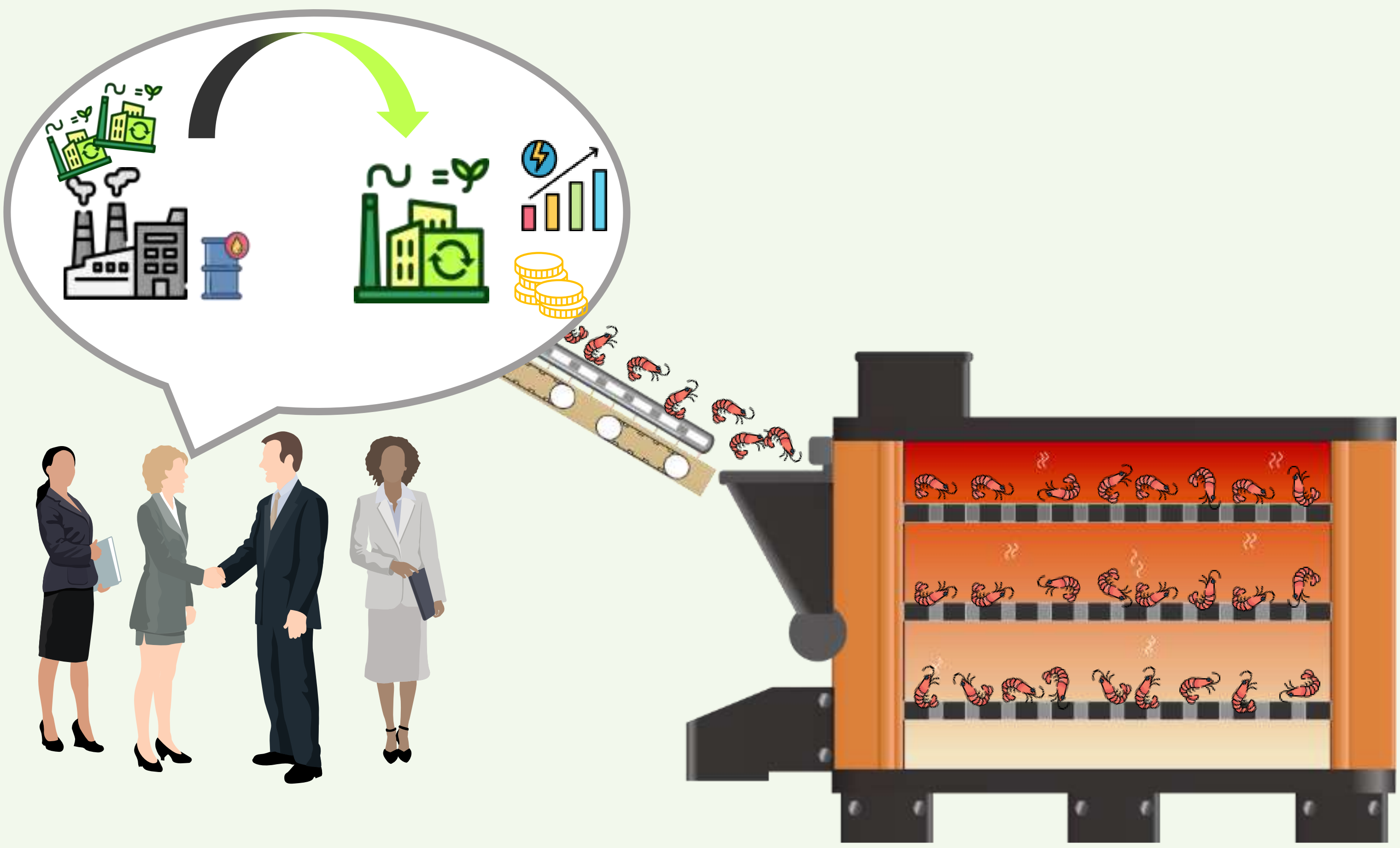
Brownfield: In brownfield applications, HTHPs and/or electric boilers can be retrofitted into existing spray drying systems to reheat inlet or exhaust air to the required temperature. This approach enables a gradual transition from NG boilers while reusing existing assets, limiting capital investment and operational disruption. Hybrid configurations, where HTHPs supply the base heat load and NG boilers cover peak demand, offer further flexibility and immediate emissions reductions.

Greenfield: In greenfield projects, the design can fully optimize waste heat recovery and electrification from the outset. This includes integrating HTHPs, and, where viable, direct solar thermal input. Integrating from the start allows for the highest energy efficiency and lowest footprint.

5. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF SHRIMP COOKING PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 65 %: Heat pump-integrated systems deliver the same heat using just 35 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 50 % - 90 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



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SHRIMP COOKING PROCESS

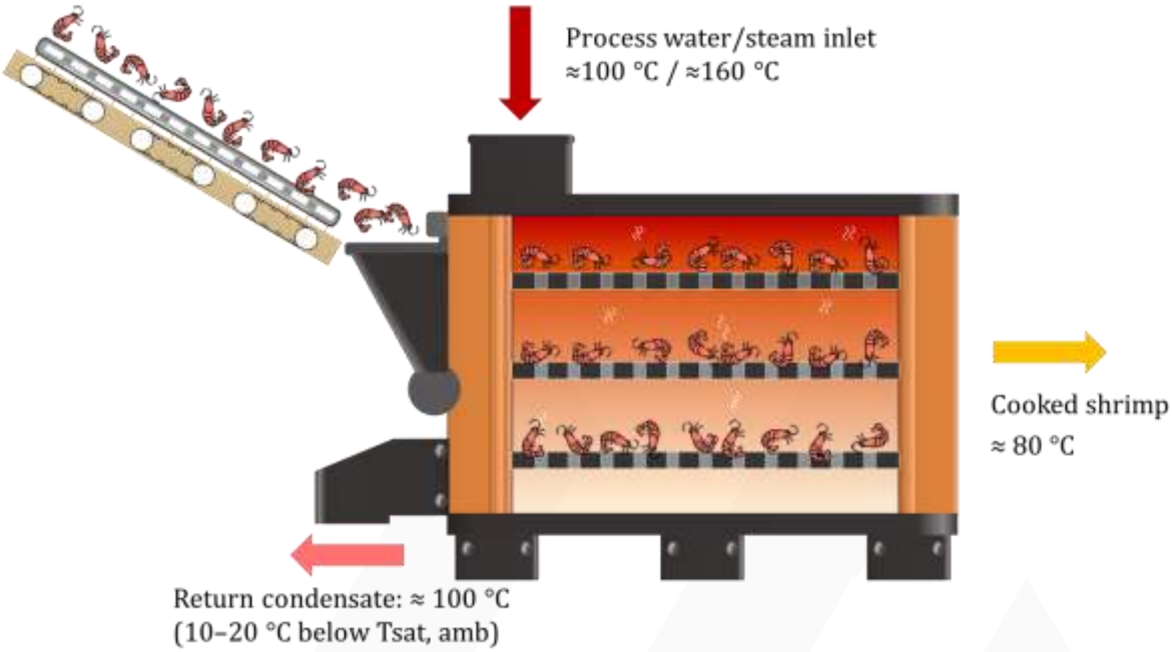

Figure 6: Schematic of a Shrimp cooking chamber

The annual global production of shrimps worldwide is around 5.6 million metric tons for the year 2023 according to Global Seafood alliance [6]. The process of producing cooked and peeled shrimp involves several operating stages including thawing, grading, cooking, freezing and packing. The shrimp is cooked inside the shrimp cooker and is the most energy intensive process typically requiring high temperature water at around 100 °C or steam up to 160 °C depending on the cooking process and blanching period of shrimp. The temperature and blanching period are crucial for achieving uniform cooking throughout the batch of shrimp and to maintain the texture and flavor of the shrimp.

After the cooking process, the shrimps are immediately cooled down to a temperature of 2 °C - 4 °C to stop cooking before transferred into the freezing chamber where it is cooled to below the freezing temperature, often as cold as around -30 °C to preserve the natural appearance, and to remove the odor and stickiness of the shrimp.

The return condensate from the steam or water used in the shrimp cooker is typically reused to preheat the fresh inlet shrimp, but it requires additional filtering as it is highly contaminated. Industrial heat pumps hold a significant potential in lowering the

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energy consumption as a substitute for the convectional based heating system for supplying necessary steam or hot water.

CONCEPTUALIZATION OF HEAT PUMP INTEGRATION INTO THE SHRIMP COOKING PROCESS

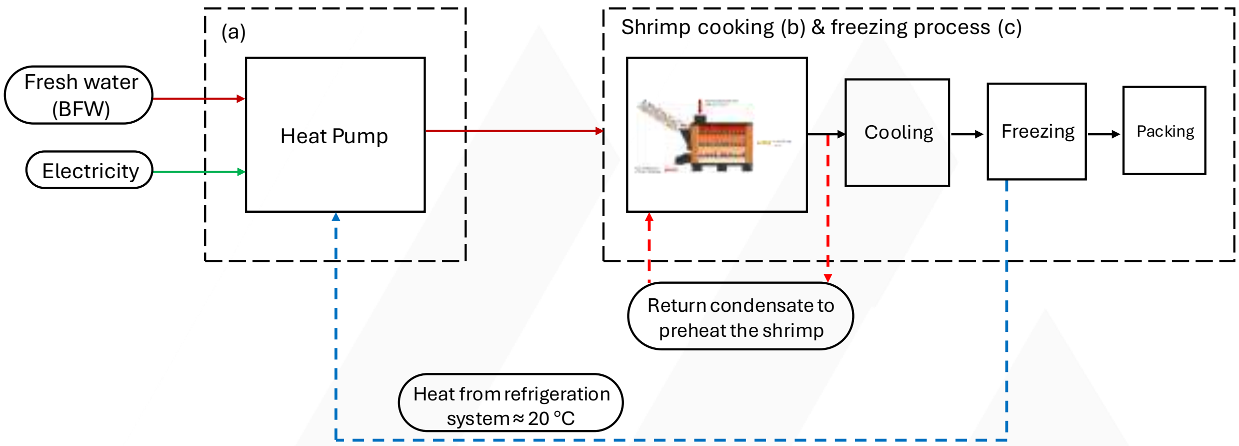

Figure 7: Schematic of Heat pump integration with the shrimp cooker system

With the heat pump system integrated within the shrimp cooking process, the fresh water at ambient temperature or the Boiler feed water is heated up to the required temperature of the cooking chamber by the heat pump (a) and transfers the heat uniformly to the shrimp in the cooking chamber, ensuring consistent boiling (b). After cooking, the shrimps are rapidly frozen to preserve quality. The heat released from the refrigeration system used in the Freezing process (c) of up to ≈ 20 °C can be used as heat source for the heat pump thereby lowering the portion of energy required for heating process. The heat sink of the heat pump system is water/steam up to ≈ 100 °C/≈ 160 °C respectively, depending on the blanching time and temperature range.

INTEGRATION OUTCOME

The shrimp cooks at a temperature of around 80 °C to 160 °C, according to the type of shrimp and the blanching period of shrimp inside the cooker. With the heat pump integration with the shrimp cooker, the COP of the heat pump system can be achieved between 5.5 to 2.5 for the process temperature increases from 80 °C to 160 °C, assuming a heat source temperature of 20 °C, as depicted by the red line in Figure 8. The higher heat pump COP indicates that the system is more efficient and energy savings of up to 85 % can be achieved by integrating a heat pump as a NG boiler replacement.

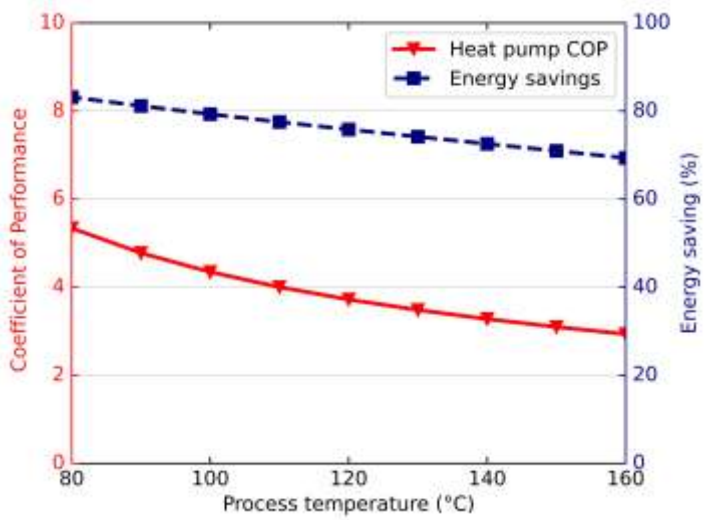

Figure 8: Heat pump COP, Energy saving for varying temperature

The Normalized heat consumption plot shown in Figure 9, indicating the heat load distribution of individual component of the system and normalized to the total heat demand for varying process temperature. The blue area represents the required minimum amount of heat source, and the green area represents the minimum required HP power for the given heat demand to achieve the estimated system performance in Figure 8. For the electrification of shrimp cooker with the heat pump the heat source has to cover a minimum of 60 % to 80 % of the total heat demand for the temperature ranging from 160 °C to 80 °C with a source inlet of 20 °C to achieve the estimated system performance.

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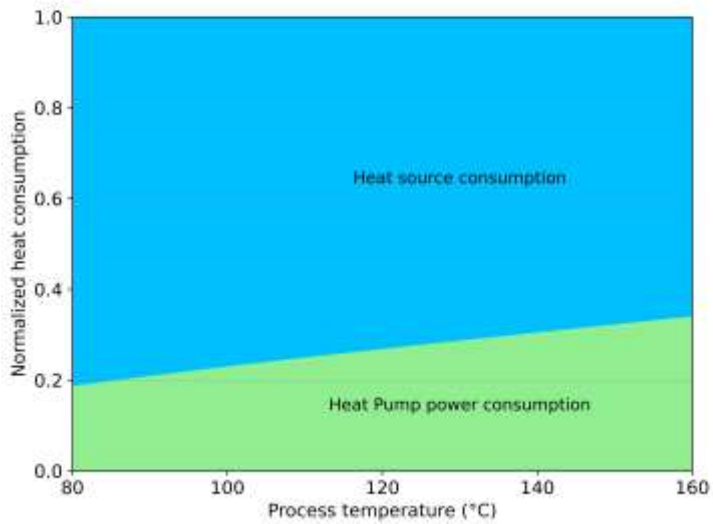

Figure 9: Normalized heat load distribution

An increase in heat source temperature will decrease the temperature lift of the heat pump and thus improve the COP. Table 3, presents the COP of the heat pump for varying source inlet temperature ranging from 60 °C to 20 °C for a process temperature 160 °C. With a higher source inlet temperature of 60 °C, an increase in COP of around 50 % can be achieved. However, the increase in source temperature increases the condenser temperature of the refrigeration system which lowers the performance of the system used for the freezing process.

Table 3: Heat pump COP for varying Source outlet temperature

Source inlet temperature (°C)	Heat pump COP
60	5.95
50	4.69
40	3.89
30	3.34
20	2.93

The emission reduction percentage is the amount of CO_2 reduced with the heat pump integration compared to NG boiler. The indicator is a direct measure of Carbon Intensity of both electricity and NG grid. Table 4, represents the reduced emission for full electrification for countries Finland, Denmark, and Germany and are in the range of 94 %, 86 %, and 53 % respectively.

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Table 4: Emission reduction with full electrification for Heat pump for varying countries

Country	Emission reduction
Finland	94 %
Denmark	86 %
Germany	53 %

Brownfield: In brownfield applications, HTHPs and/or electric boilers can be retrofitted into existing shrimp cooking systems to provide the required heat for cooking, typically by heating water or generating steam. HTHPs are especially valuable as they can utilize low-grade waste heat from the plant's refrigeration or freezing systems, reducing primary energy demand. Hybrid configurations, where HTHPs cover the base load and electric boilers handle peaks or redundancy, provide flexible pathways for gradual electrification and emissions reduction, while leveraging as much of the existing infrastructure as possible.

Greenfield: In greenfield projects, the design can fully integrate HTHPs with solar thermal and thermal storage systems to deliver all required heating—whether water (up to 90 °C) or low-pressure steam—efficiently and sustainably. A new project enables the optimization of the process equipment to lower temperatures, ensuring high HP COP. Heat recovery cascades, utilizing heat from refrigeration/freezing as a primary source for the HTHPs may be used for additional heat requirement.

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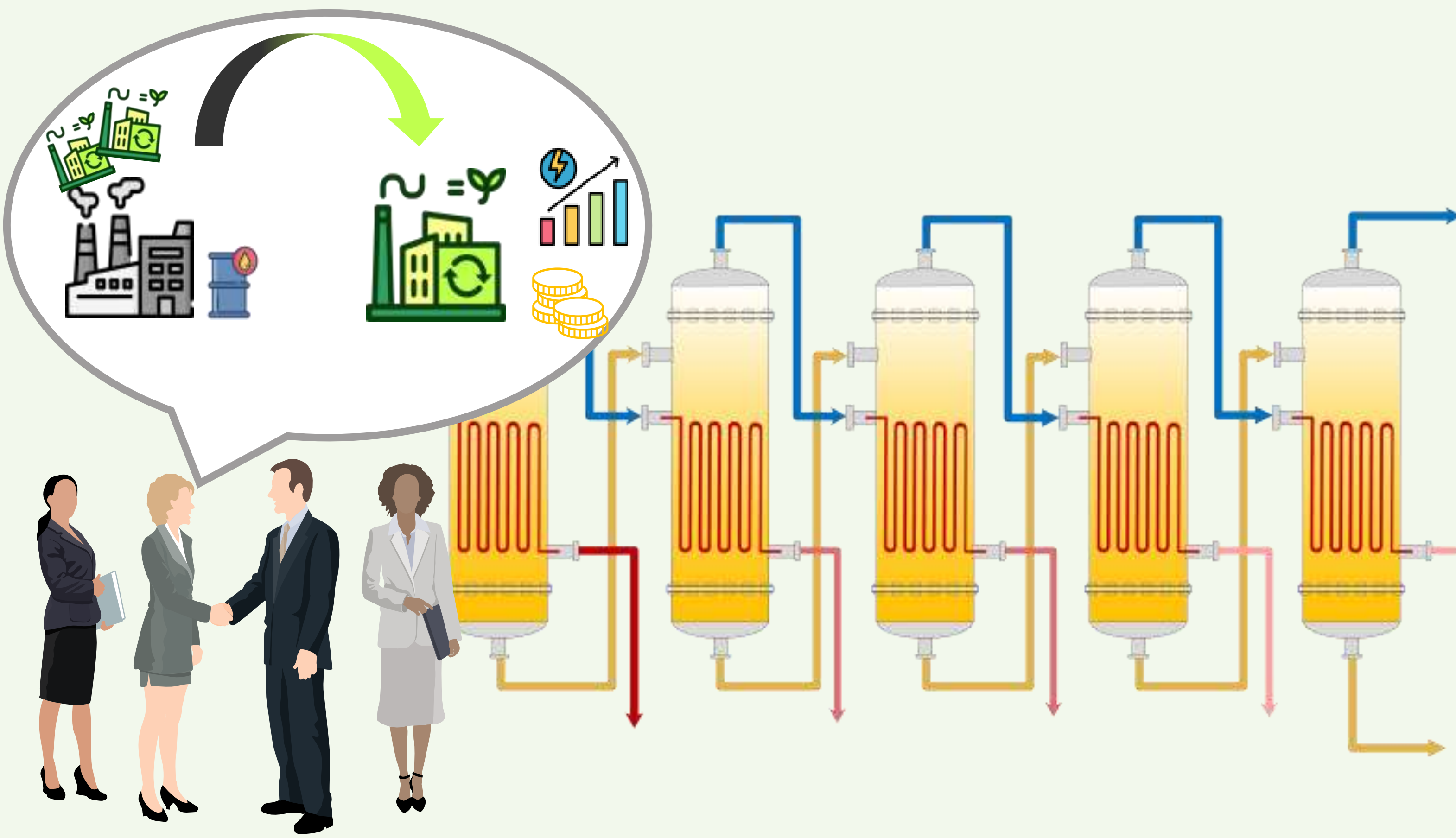
6. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF SUGAR PRODUCTION PLANT VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 70 %: Heat pump-integrated systems deliver the same heat using just 30 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 60 % - 90 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



SUGAR PRODUCTION PROCESS

Sugar is one of the major ingredients in everyday life. The European Union is the second largest sugar consumer in the world with an estimation of 16.8 million metric tons in the year 2023-2024 according to Statista [7].

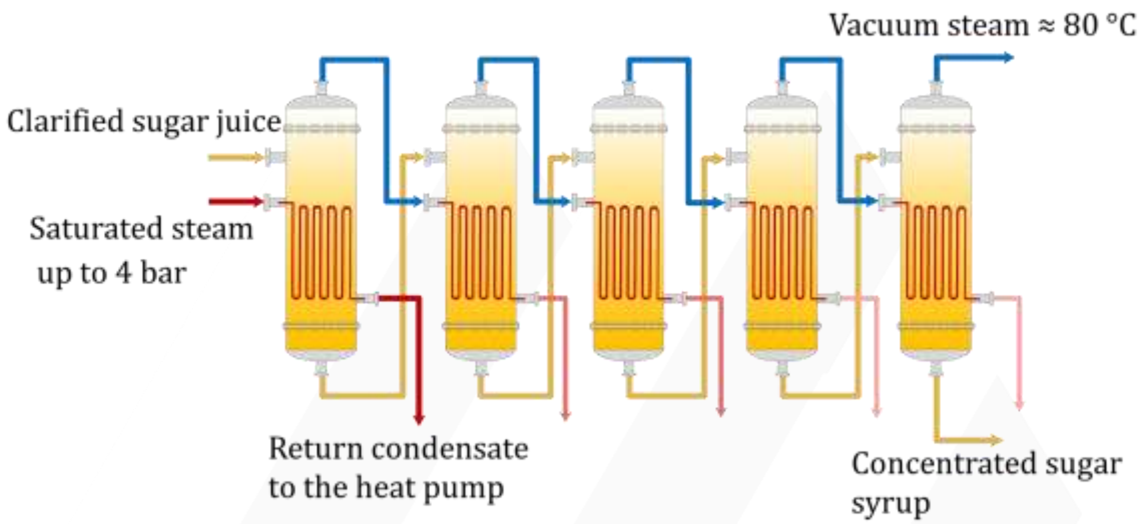


Figure 10: Schematic of a multiple effect evaporator unit

Sugar production is an energy intensive process, Particularly, the steam required to evaporate water from the sugar solution within the steam evaporator line uses significant energy within the whole process.

The process of sugar crystallization is as follows. Sugar production starts with harvesting of either Sugarcane or Sugar beets. After harvesting, the sugar cane is milled, the sugar juice is heated and clarified, whereas in Sugar beet, it is sliced into thin strips, soaked in hot water to extract sugar then purified, later the clear juice is sent through a multiple-effect evaporation line, with multiple evaporator units that operate at decreasing pressures, this increases the sugar concentration of the solution by evaporating the water. After passing the evaporation line, the highly concentrated sugar syrup is crystallized inside the vacuum chamber and sent to the storage.

During the evaporation process of the sugar solution, a high amount of energy at higher temperature is transferred to the subsequent evaporator and serves as a heat source for the next evaporator maintained at a lower pressure. With the integration of heat pumps, the final energy consumption for the steam production is reduced by utilizing the vacuum steam from the evaporator unit which cannot be directly used in the process.

CONCEPTUALIZATION OF HEAT PUMP INTEGRATION INTO THE SUGAR PRODUCTION PROCESS

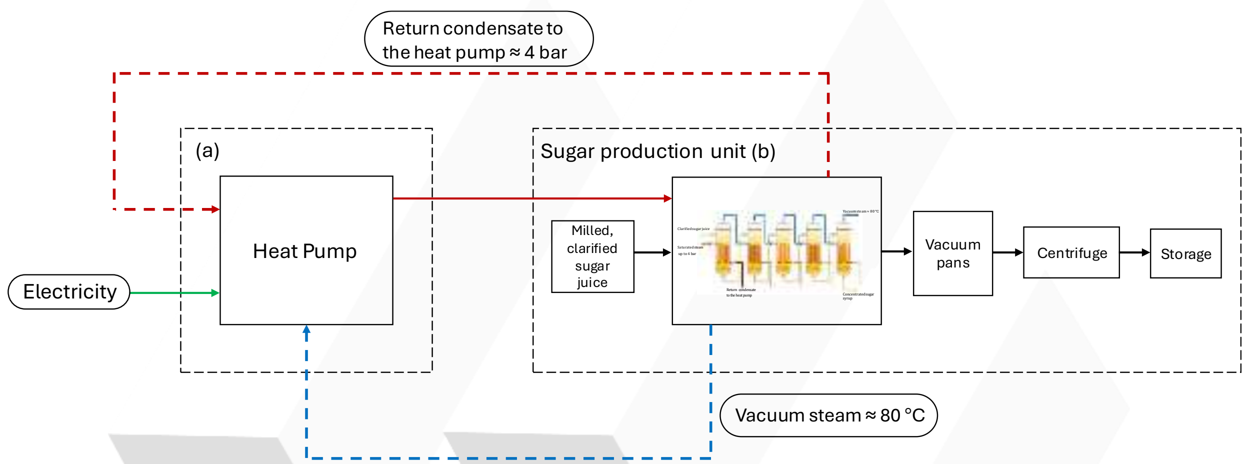


Figure 11: Schematic of Heat pump integration with the Sugar production plant

With the heat pump integrated within the sugar production process, the return condensate from the evaporator unit is reheated and fed back into the unit, which evaporates the water in the sugar syrup.

Heat source: The vacuum steam from the last evaporator unit can be integrated as a heat source for the heat pump system. Typical range of this vacuum steam is between 50 °C to 70 °C.

Heat Sink: The return condensate from the first evaporator unit, which typically has higher temperatures, can be reheated to the saturated temperature by the condenser of the heat pump system and supplied back to the evaporator unit. The typical temperature range of the condensate is around 115 °C to 140 °C, depending on the number of evaporation units.

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INTEGRATION OUTCOMES

As the return condensate temperature depends on the type of the system, therefore the heat pump COP and energy savings are calculated over a range of 115 °C to 140 °C, as depicted in Figure 12, the red line indicates the heat pump COP, and the blue line indicates the Energy saving potential with heat pump integration compared to NG boiler. The COP of the heat pump varies between 3.5 to 6.5 for process temperature from 140 °C to 100 °C with corresponding energy saving of 70 % to 86 % respectively.

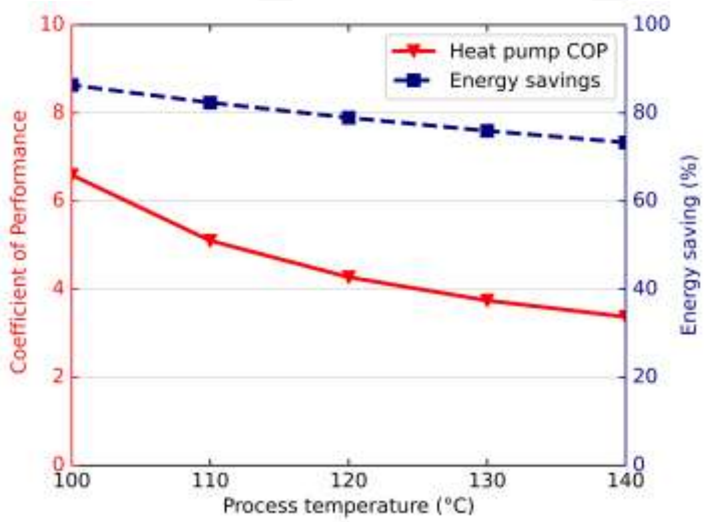

Figure 12: Combined system performance, Energy saving for varying temperature

The Normalized heat consumption plot shown in Figure 13, indicating the heat load distribution of individual components of the system and normalized to the total heat demand for varying process temperatures. The blue area represents the required minimum amount of heat source, and the green area represents the minimum required HP power for the given heat demand to achieve the estimated system performance in Figure 12. For electrifying the sugar production process with heat pump, a COP of 3.5 can be expected at a process temperature of 140 °C, for which the heat source must supply approximately 65 % of total heat demand.

A significant amount of energy is required to heat the return condensate, therefore if the energy available from the vacuum steam is not sufficient then the system will utilize more electrical load and thus decrease the HP system COP. An external boiler can be an option to provide sufficient heat source or to heat the condensate, but it has a significant penalty in the system COP and energy savings.

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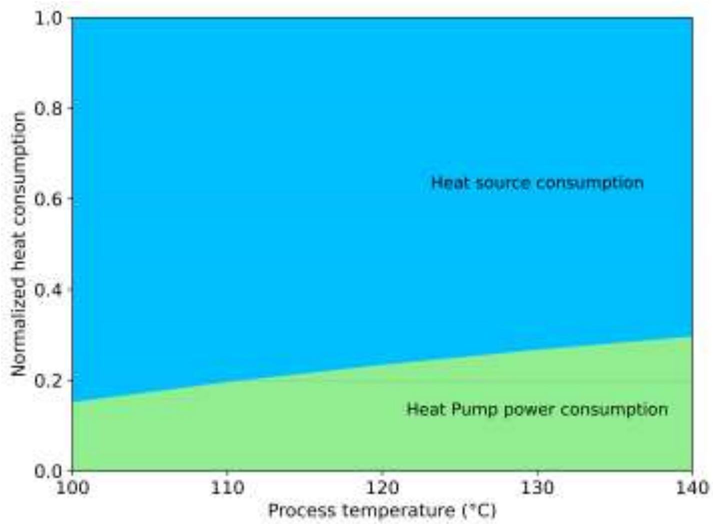

Figure 13: Normalized heat load distribution

The emission reduction percentage is an indicator of the amount of CO2 reduced with the heat pump integration compared to a NG boiler. The indicator is a direct measure of Carbon Intensity of both electricity and NG grid. Table 5, represent the reduced emission for full electrification for countries Finland, Denmark, and Germany and in the range of 95 %, 88 %, and 60 % respectively.

Table 5: Emission reduction with full electrification for Heat pump for varying countries

Country	Emission reduction
Finland	95 %
Denmark	88 %
Germany	60 %

Greenfield: In greenfield (new build) sugar production facilities, the process layout can be designed from the outset to maximize energy efficiency, waste heat recovery, and the use of electrified heating solutions. This enables a holistic rethinking of the heat cascade and allows for optimal integration of HTHPs, mechanical vapor recompression (MVR), and renewable heat sources such as solar thermal. MVR is particularly interesting, increasing the potential system COP even further.

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Brownfield: MVR also present the highest potential efficiency for brownfield application, if direct contact between production steam and steam compressors are allowed. Otherwise, HTHPs present the best alternative. While space limitations or legacy heat recovery systems may present challenges, carefully planned retrofits allow heat pumps to supplement or fully replace traditional steam generation without major disruptions to ongoing production.

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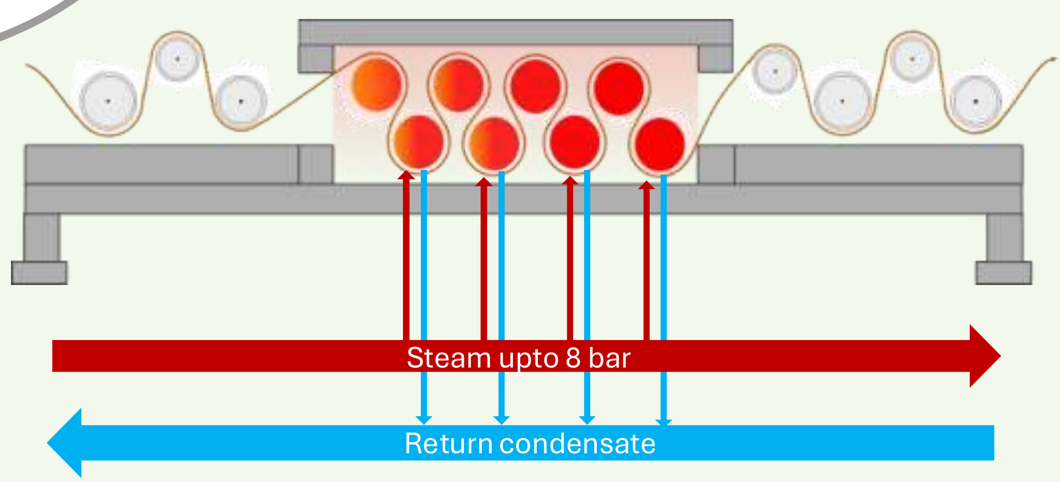
7. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF PAPER PRODUCTION PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 52 %: Heat pump-integrated systems deliver the same heat using just 48 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 30 % - 90 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



PAPER PRODUCTION PROCESS

The European paper and board production for the year 2024 is estimated at around 77.8 million tonnes according to the Cepi [8]. Paper manufacturing is an energy intensive process, in which the paper drying process alone accounts up to 70 % of the total energy. The manufacturing process starts with the recipe of paper: Logs are debarked and chipped (only relevant for integrated mills),

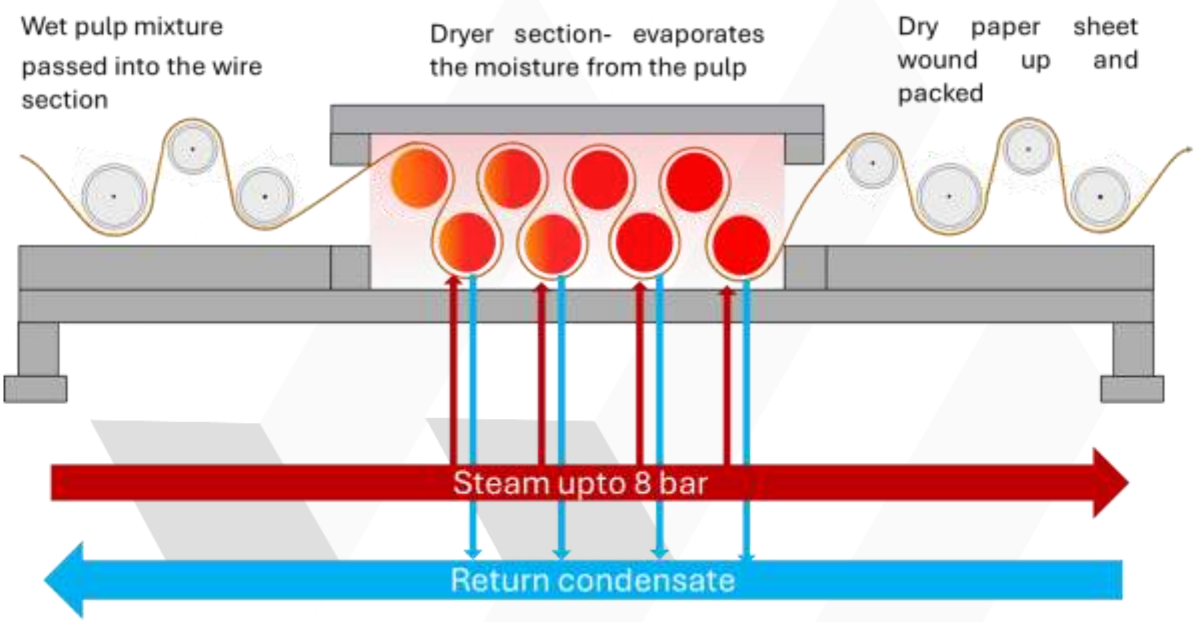


Figure 14 Schematic of a paper drying process

followed by Digester where the wood chips are cooked with water and chemicals. This mixture is then washed to remove chemicals and lignin, transforming it into pulp. The wet pulp is transformed into paper by passing into the drying channels were moisture content in the paper webs decreases. Later it is wound up and cut down to the required size and ready to be shipped.

During the drying process, the wet paper is passed over multiple steam heated cylinders, where it is dried continuously by evaporating the moisture content from the paper. The steam pressures for the drying section range between 1 bar – 8 bar, depending on the drying sections and the number of cylinders. With the integration of heat pumps the final energy consumption required for the heating and steam production can be reduced by utilizing the heat from the moist exhaust air from the drying cylinder and heating the return condensate from the drying cylinder up to the saturated steam.

CONCEPTUALIZATION OF HEAT PUMP INTEGRATION INTO THE PAPER PRODUCTION PROCESS

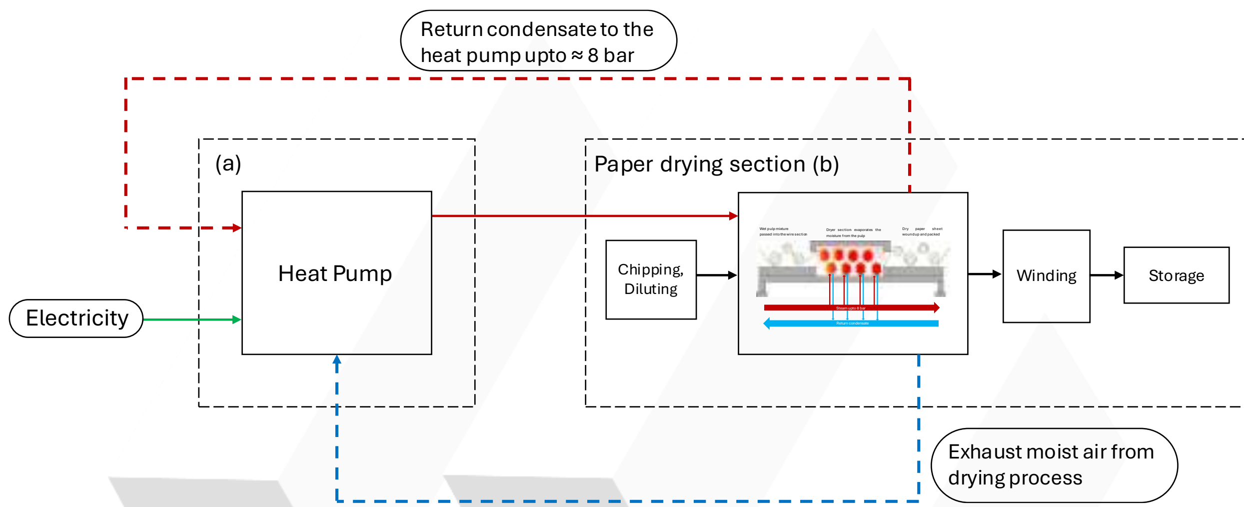


Figure 15: Schematic of Heat pump integration with the paper production process

With the heat pump integrated within the paper production process, the moist exhaust air vented from the drying section, can be used as a heat source. The energy is used together with the compressor power to evaporate the return condensate from the steam-heated cylinders and compress it to higher pressures and temperature which can be returned to the cylinders. Integrated mills have an abundance of biomass available for steam production which can be utilized as an energy source instead of electrification.

Heat source Moist air with typical dew point temperature of around 50 °C - 70 °C.

Heat sink: The return condensate from the steam-heated cylinders is pumped and heated to the corresponding saturation temperature up to 180 °C depending on the temperature requirement of the drying cylinders.

INTEGRATION OUTCOME

The heat pump integrated into the pulp drying process, boosts the system efficiency and improves the energy savings as depicted by the Heat pump COP (red line) and energy saving (blue line) in Figure 16. Where the process temperature of the heat pump varied from 100 °C to 180 °C. The COP of approximately 2.4 to 1.9, and the energy savings of about 62 % - 52 % for the process temperature 100 °C to 180 °C respectively can be achieved. Though the COP of the HP is lower, the system can still expect to achieve around 50 % energy savings even at higher temperatures, which highlights the potential for efficient and cost-effective operation compared to a NG boiler.

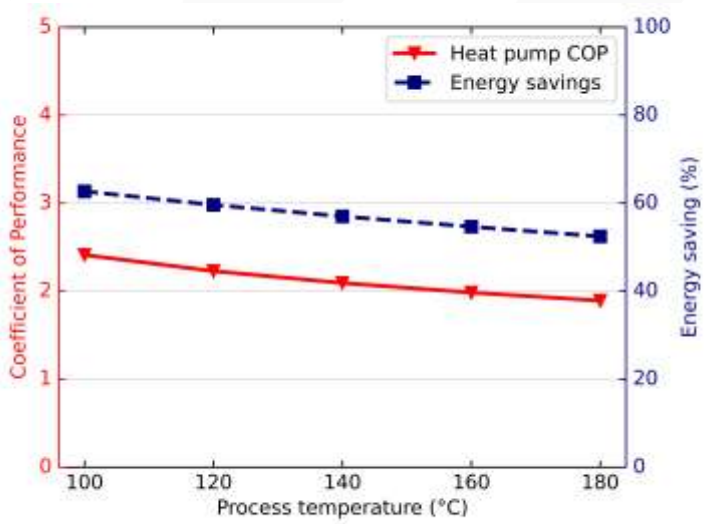


Figure 16: System performance and Energy saving for varying temperatures

The Normalized heat consumption plot shown in Figure 17, indicating the heat load distribution of individual component of the system and normalized to the total heat demand for varying process temperature from 100 °C - 180 °C. The blue area represents the required minimum share of total heat supplied by heat source, and the green area represents the minimum share of HP power for the given heat demand to achieve the estimated system performance in Figure 16. For the electrification of paper production process with the heat pump, the heat supplied by the source has to cover approximately 40 %- 60 % of total heat demand to avoid increase in HP power and to maintain the projected COP.

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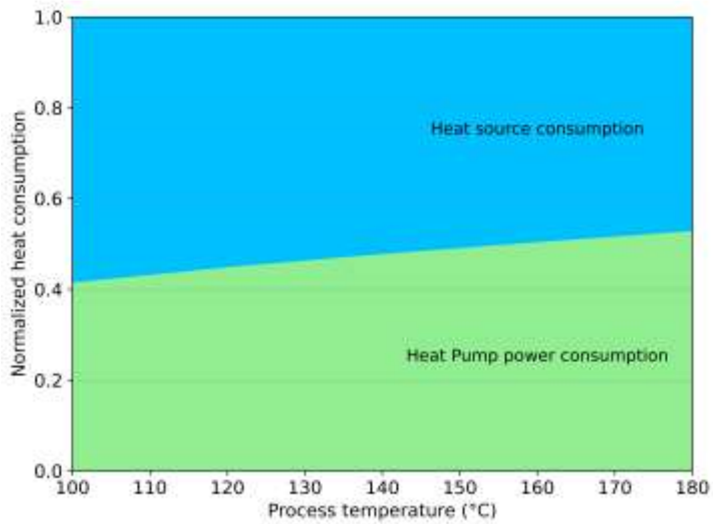

Figure 17: Normalized heat load distribution

The emission reduction percentage is an indicator of amount of CO_2 reduced with the heat pump integration compared to NG boiler. The indicator is a direct measure of Carbon Intensity of both electricity and NG grid. Table 6, represents the reduced emission for full electrification for countries Finland, Denmark, and Germany and in the range of 91 %, 79 %, and 28 % respectively.

Table 6: Emission reduction percentage for full electrification for varying countries

Country	Emission reduction
Finland	91 %
Denmark	79 %
Germany	28 %

Greenfield: Developments are ongoing to reach higher dewpoints within the drying zone to improve the system COP. This requires further closing the drying hood and learning to operate in high-humidity conditions. Airless or superheated steam drying would result in optimum energy efficiency as the temperature difference between supply steam and exhaust air in the drying zone would be reduced.

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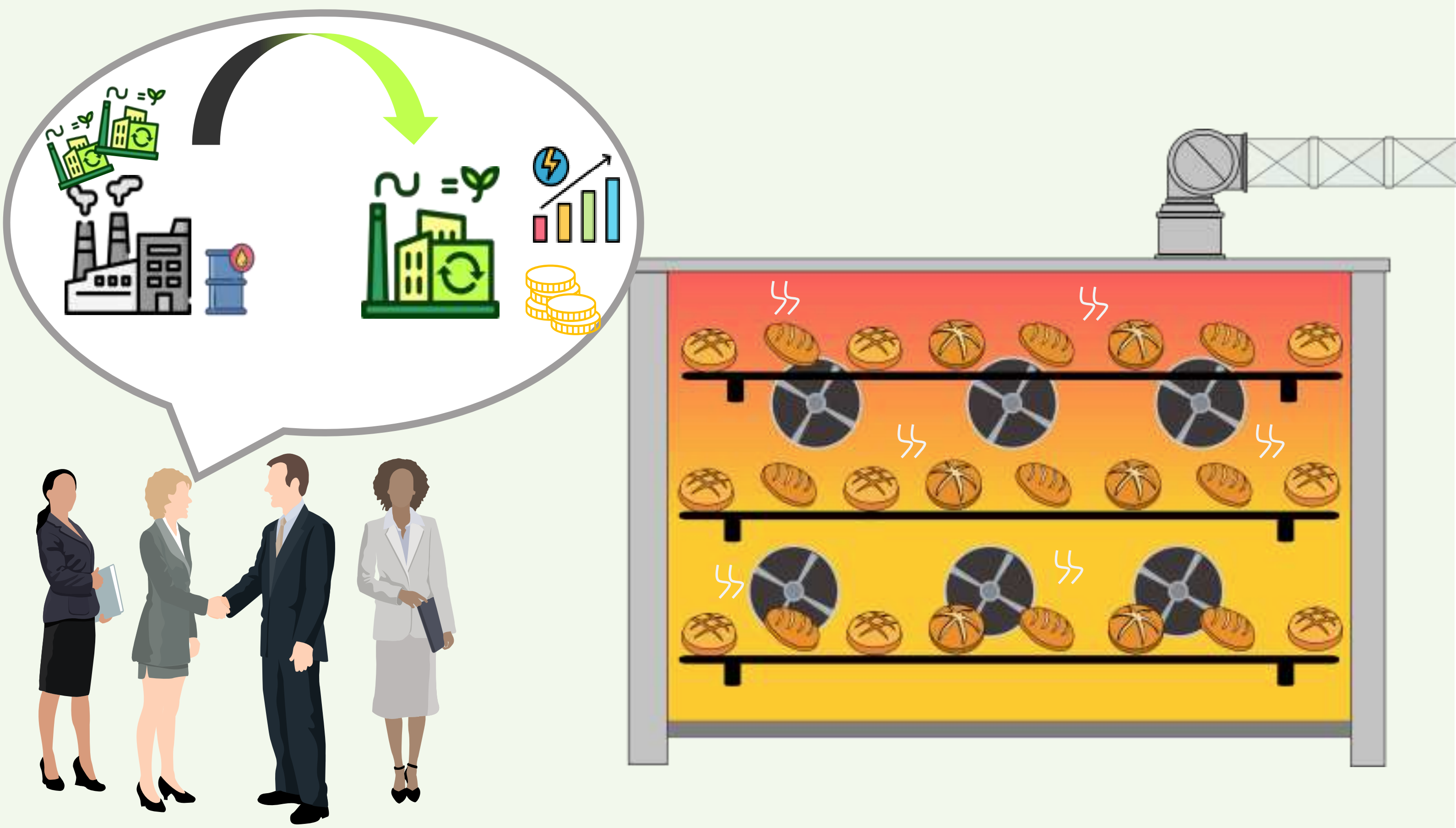
Brownfield: In brownfield paper production facilities, significant portions of the moist exhaust air from drying sections are often already utilized for heat recovery. This recovered heat is commonly used to preheat incoming process water, support space heating needs within the facility, or supply other secondary processes. As a result, the potential for integrating high-temperature heat pumps may be constrained not only by physical space or legacy equipment, but also by the necessity to preserve or adapt these existing heat recovery streams.

8. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF BAKING OVEN PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 30 %: Heat pump-integrated systems deliver the same heat using just 70 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 20 % - 90 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



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BAKING PROCES

The consumption of baked products has been increasing significantly over the years. It was estimated that about 31 million tons of bakery products have been consumed in the EU for the year 2021 [9]. Various types of bread, biscuit, and cookies are baked at a high temperature typically in the range of 140 °C to 200 °C.

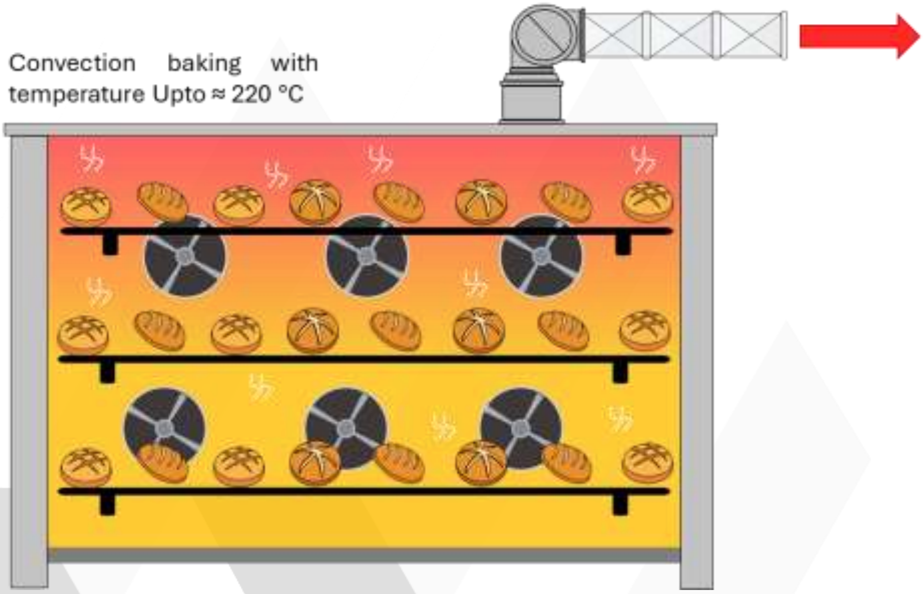

Figure 18: Schematic of Baking process

The process of baking bread starts with the Mixing and Dough processing, where the ingredients are measured and mixed to form a homogeneous dough. Followed by the Kneading process where they stretched to ensure optimal dough consistency. Later, the dough is fermented to enhance the texture and flavor. Later it is shaped to the requirement and baked inside the oven. The baking temperature, humidity, and time are controlled inside the oven to ensure the crisp and crust formation. Once baked it is cooled immediately to decrease the bread internal temperature to avoid continuous cooking and formation of condensation. Once cooled the bread is sliced and packed, later shipped.

During the baking process, a substantial amount of heat is released. For a convection oven the exhaust temperature range is typically higher compared to a tunnel oven. The availability of high temperature exhaust air can be exploited with the integration of a heat pump, thereby it could potentially lower the final energy consumption of the baking process.

INTEGRATION OF HEAT PUMP INTO THE BAKING PROCESS

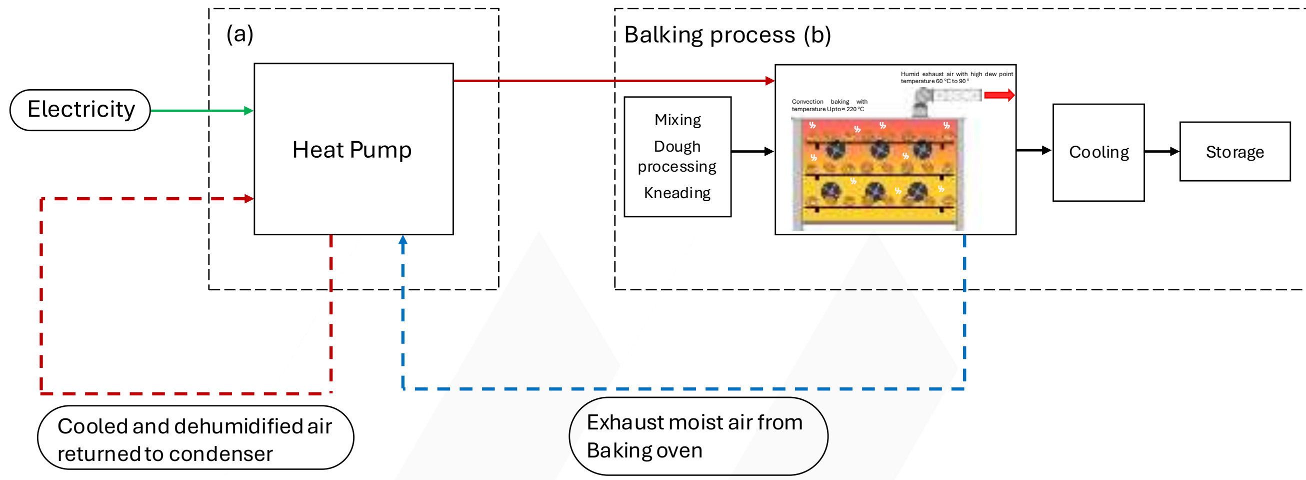

Figure 19: Schematic of Heat pump integration within the baking process

With the heat pump integrated system (a) the heat from the exhaust air can be utilized as heat source, cooled and dehumidified and later reheated again to higher temperature and supplied back to the oven (b). For continuous baking processes the oven is often divided into multiple zones which are individually controlled. A heat pump may be installed for each zone, if the capacity is large enough.

Heat Source: The hot humid exhaust air with a temperature range similar to the oven operating temperature of around 140 °C to 200 °C, can be cooled and dehumidified below the dew point up to 65 °C to 90 °C, and the energy extracted from the dehumidification process can be used as a heat source for the heat pump system.

Heat Sink: The dehumidified air is reheated up to a higher temperature corresponding to the product baked in the oven up to 200 °C with the heat pump and supplied back into the oven, where the water present within the dough evaporates as the internal temperature rises, and produces a fully baked brown crust layer with texture.

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INTEGRATION OUTCOME

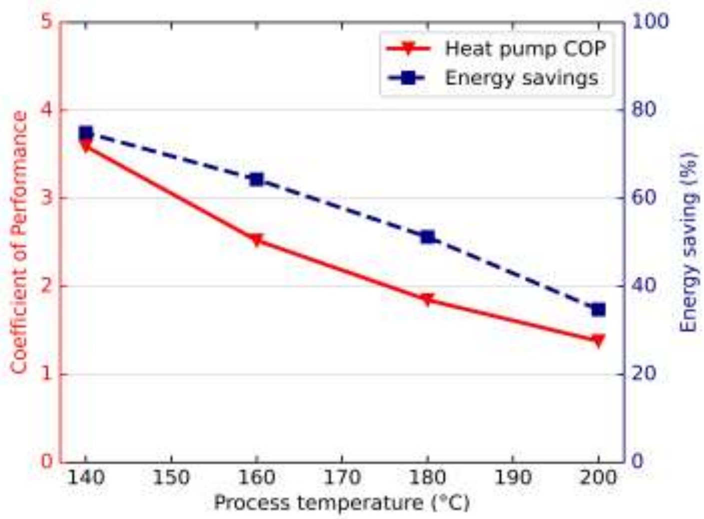


Figure 20: Heat pump system COP, Energy saving for varying process temperatures

The heat pump integrated into the baking process increases the efficiency of the overall system as depicted by the (red line) in Figure 20. Where the process temperature of the heat pump is varied from 140 °C to 200 °C, according to the type of product being baked inside the oven. The COP increases from approximately 1.5 to approximately 3.5, similarly the energy savings (blue line) increased from 30 % to about 75 % when decreasing the process temperature from 200 °C to 140 °C. Nevertheless, the system can expect to achieve around 30 % energy savings even at higher temperatures, which highlights the potential for efficient and cost-effective operation compared to an NG boiler.

Figure 21, shows the Normalized heat consumption of the heat pump, indicating the heat load distribution of the system and normalized to the total heat demand. The blue area represents the required minimum share of total heat supplied by heat source, and the green area represents the minimum share of HP power for the given heat demand to achieve the estimated system performance in Figure 20. For the electrification of baking process the heat supplied by the source has to cover approximately 30 % - 80 % of total heat demand to avoid increase in HP power and to maintain the projected COP.

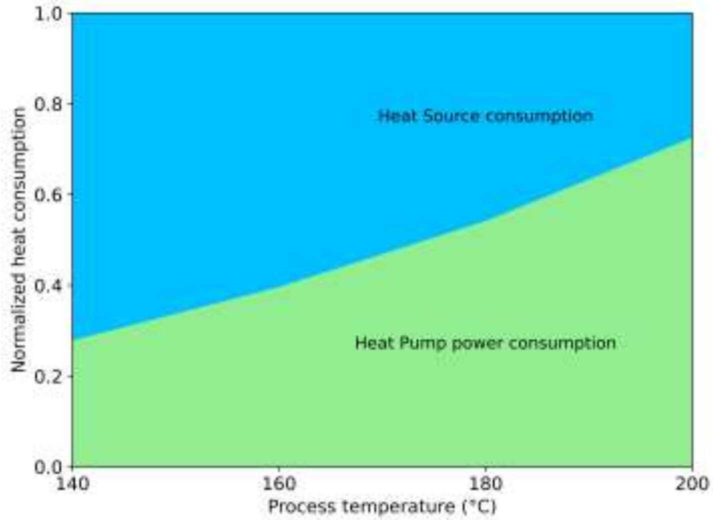


Figure 21: Normalized heat load distribution

The emission reduction percentage is an indicator of the amount of CO_2 emission reduced with the heat pump integration compared to NG boiler. The indicator is a direct measure of Carbon Intensity of both electricity and NG grid. Table 7, represent the reduced emission for full electrification for countries Finland, Denmark, and Germany in the range of 88 %, 80 % and 20 %, respectively.

Table 7: Emission reduction with full electrification for Heat pump for varying countries

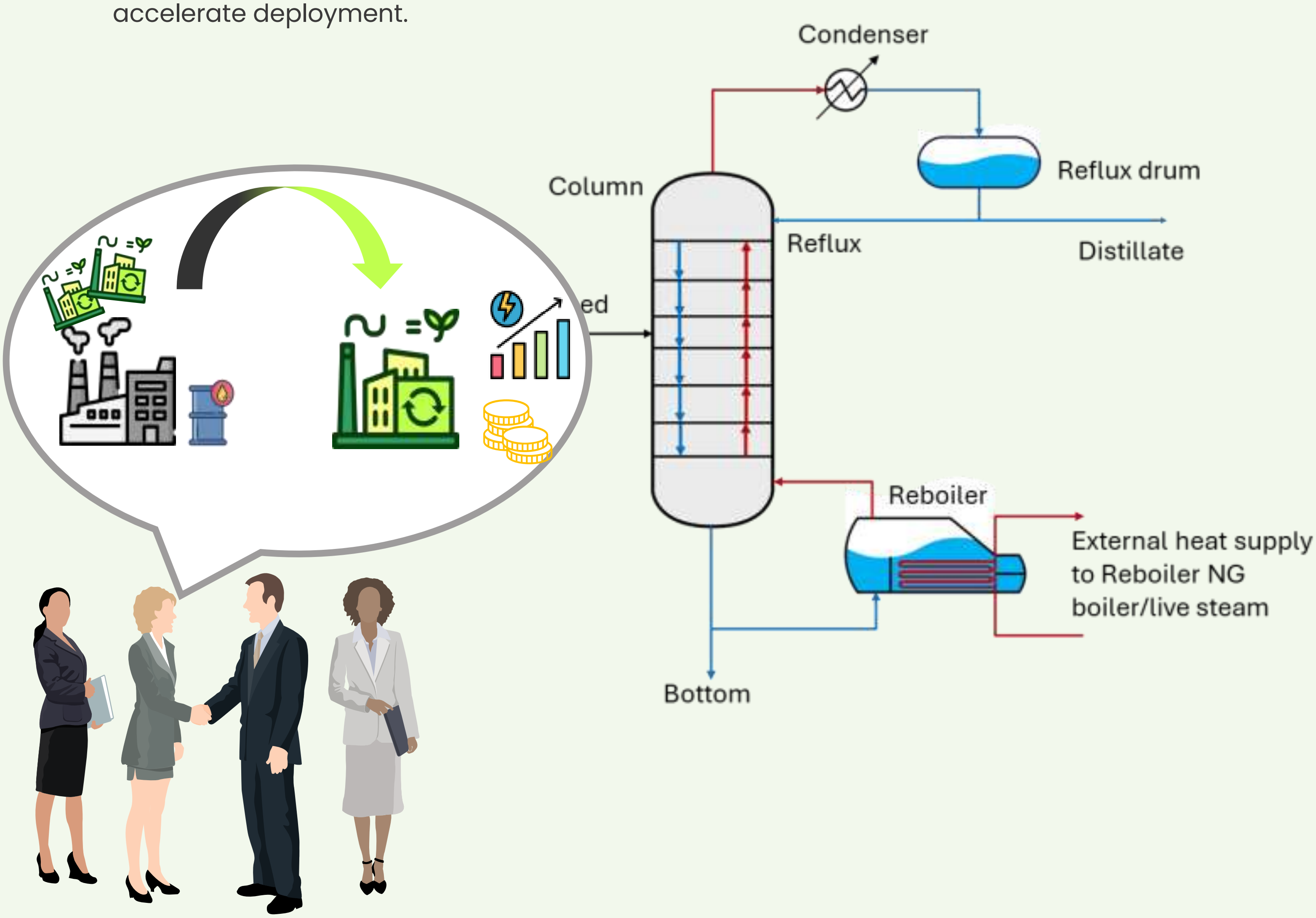
Country	Emission reduction
Finland	88 %
Denmark	70 %
Germany	20 %

Brownfield: In brownfield application various oven types will result in different optimal strategies to reduce emission. Convection ovens will have the highest potential to incorporate heat pumps as the air can be integrated directly into the hood. Other types of ovens will require a larger rebuild of the baking chamber. For products baked at low humidity, there may not be enough energy in the source to cover all heat demand by the high-temperature heat pump. It may be necessary to incorporate cooling of the product as a heat source to reach full electrification. Converting from fired ovens to electric ovens will also change the humidity in the baking chamber requiring a change of the product baking curve.

Greenfield: In greenfield baking facilities, there is an opportunity to design the energy system from the beginning for maximum efficiency and sustainability. Increasing the air velocity and humidity in convection ovens will allow for lower operating temperatures and higher dew point in the oven, increasing HTHP COP. For smaller ovens, It should be considered to make fewer, larger baking zones to access a greater amount of commercially available heat pumps.

9. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF DISTILLATION PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 88 %: MVR-integrated systems deliver the same heat using just 20 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 80 % - 95 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



DISTILLATION PROCESS

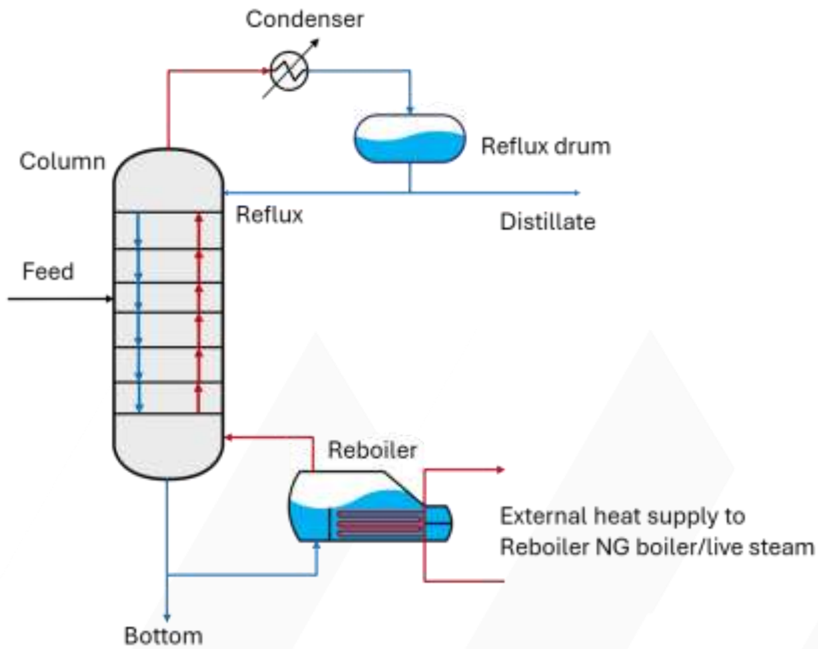


Figure 22: Schematic of Distillation column

Distillation is a widely used thermal separation process and consumes about 40 % of the total energy in the chemical industry. The distillation process in chemical industry is used to separate/purify liquid mixtures from the volatile substance by boiling off the lower temperature volatile substance and separate the liquid by evaporation process, therefore a significant amount of heat in the form of steam/solvent vapor at higher temperature is required for the distillation process.

The heat required and the temperature range of distillation process depend on the type of inlet feed mixtures. The light hydrocarbon distillation process typically requires an operating temperature of around 75 °C to 200 °C.

In the chemical industry using a conventional distillation process, the input feed passes down through the Column and the heat supplied by the Reboiler partially vaporizes the input feed and the separation process takes place. The remaining feed liquid is stripped down through the Column and collected at the Column base. These further flows back into the Reboiler to vaporize the lighter component and the enriched feed liquid is collected from the column base as Bottoms.

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The enriched vapor feed is extracted from the column head and is completely condensed before passing into the Reflux drum. The liquid in the Reflux drum is partly supplied back into the top of the Column for further purification by the enriched vapor feed and extracted from the Reflux drum as distillate.

INTEGRATION OF MECHANICAL VAPOR RECOMPRESSION WITHIN THE DISTILLATION COLUMN

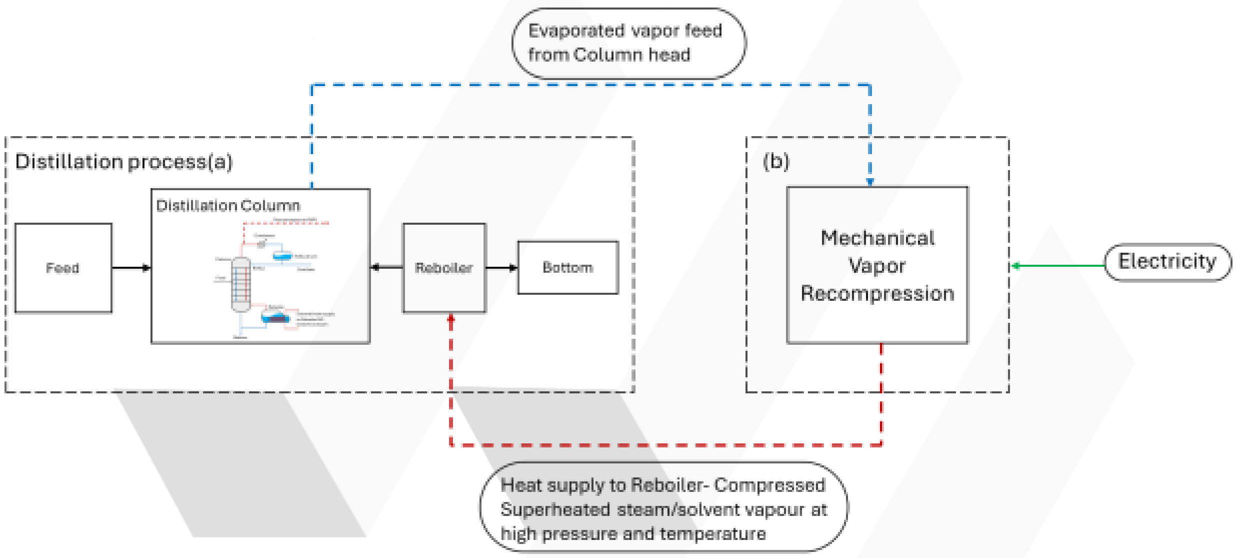

Figure 23: Schematic of MVR integration in Distillation process

In the convectional distillation column, only a partial vapor feed from the column head is reused as most of the energy in the vapor feed is cooled and condensed in the condenser with an external cooling medium. A continuous supply of live steam/heat source is required for the Reboiler. Therefore, it possesses a huge potential for electrification by the integration of an MVR system.

With the integration of MVR within the distillation column the evaporated vapor feed from the liquid mixture exists from the top of the Column head at its evaporation temperature. The majority of vapors, can be compressed directly by a MVR system and the compressed superheated vapor at higher temperature and pressure is supplied directly to the Reboiler. Thereby, supplying the necessary heat for vaporization in the distillation column. Alternatively, the heat from the condenser column may be used as a heat source for a high-temperature heat pump which will supply heat to the reboiler. Thus, the integration reduces a significant portion of the final energy supplied to the Reboiler.

INTEGRATION OUTCOME

With the MVR system integrated into the Distillation process, an increase in overall system efficiency is achieved. Figure 24, depicts the system performance for the solvent mixtures widely used in chemical industry including Ethanol-water mixture, Methanol-water mixture, Butanol-water mixture, Acetone-water mixture and Dimethylformamide (DMF)–water mixture with corresponding process temperature.

The integration of MVR system within the distillation column of Ethanol-water mixture, the system can achieve a COP of approximately 8 and energy savings up to 88 % compared to using a NG boiler to heat the reboiler, by utilizing the energy from the column head solvent vapor at around 78.8 °C, compressing it to 90 °C and supply it to the reboiler. Similarly for other solvent mixtures Methanol-water, Acetone-water, DMF-water the system COP in the range of 5.5-7 can be achieved. For Butanol or Ethanol distillation from water the potential system COP is even higher yielding 8.1 and 9.2, respectively.

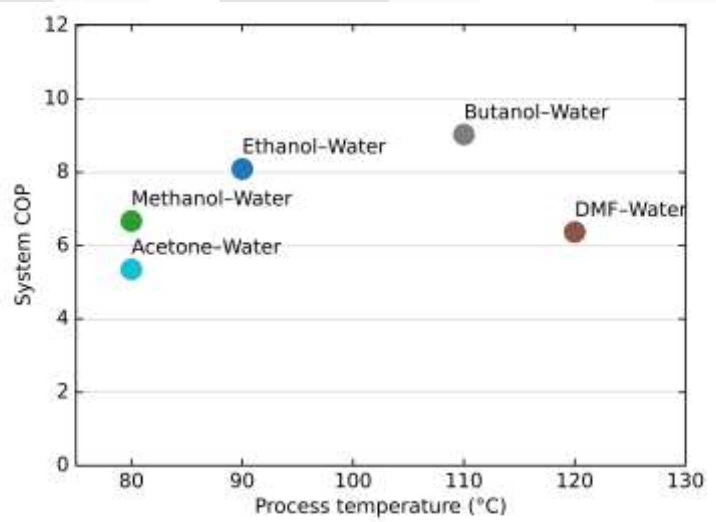

Figure 24: System COP for varying temperature

The emission reduction percentage is an indicator of amount of CO_2 emission reduced with the heat pump integration compared to NG boiler. The indicator is a direct measure of Carbon Intensity of both electricity and NG grid. Table 8, represent the reduced emission with MVR for an Ethanol-water distillation for the countries Finland, Denmark, and Germany yielding 97 %, 94 %, and 82 %, respectively.

Table 8: Emission reduction with full electrification for Heat pump for varying countries

Country	Emission reduction
Finland	97 %
Denmark	94 %
Germany	82 %

Brownfield: While MVR is a proven and efficient technology for many distillation processes, it is not universally applicable. MVR performs best when the temperature lift between the column overhead vapor and the reboiler is small and operating conditions are steady. If the required temperature lift is large, the efficiency of MVR will be lower. If the vapors are corrosive, prone to fouling, or otherwise challenging for compressors, the technical feasibility and cost-effectiveness of MVR may be limited. In these situations, high-temperature heat pumps should be considered for heating the reboiler. Initial electrification steps may be implementing hybrid configurations where MVR and traditional boilers work together to handle peak demand.

Greenfield: In greenfield distillation processes, equipment can be fully optimized to minimize the temperature difference between the column and the reboiler, which is crucial for achieving high system efficiency. By designing the plant with the flexibility to adjust both the column pressure and the flow from the reboiler, it is possible to reduce the required temperature lift and maximize heat recovery potential. This approach enables the effective integration of HTHPs or MVR, resulting in lower energy consumption and enhanced process performance from the outset.

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10. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF BRICK DRYING PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 55 %: Heat pump-integrated systems deliver the same heat using just 45 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 45 % - 90 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.

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BRICK PRODUCTION PROCESS

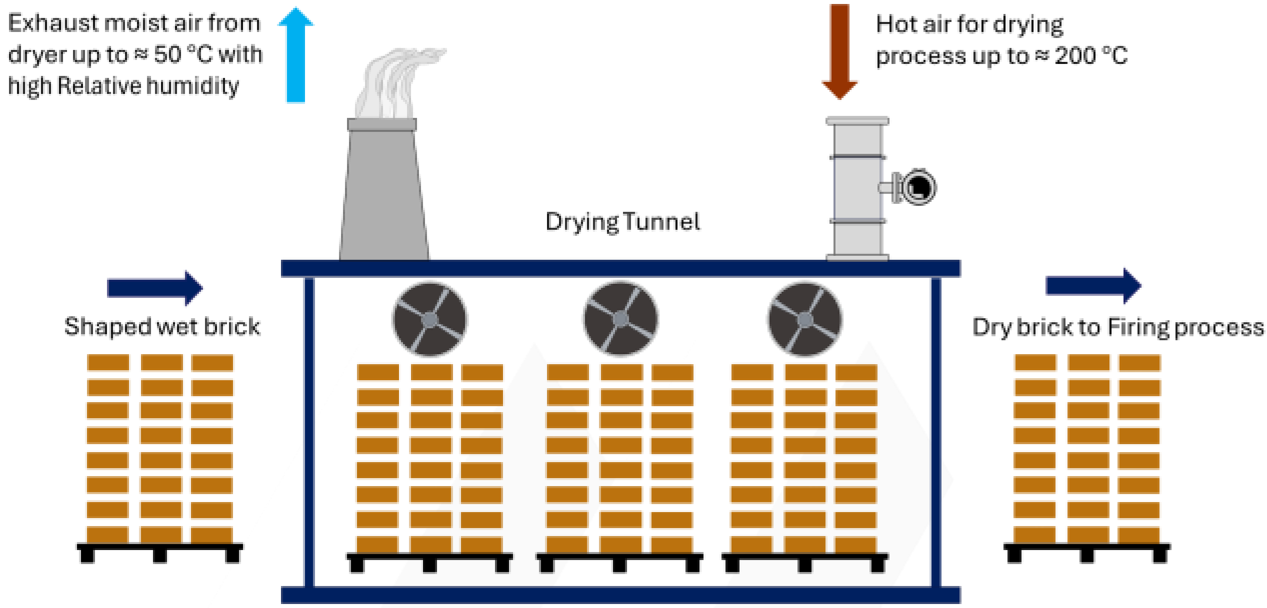

Figure 25: Schematic of a convective Brick dryer

Clay bricks are one of the widely used building materials in constructions. Every year around 1.3 trillion bricks are manufactured globally and shows significant growth in production [10]. The firing process required to produce 250 billion bricks emits approximately 42.64 Mt of CO_2 into the atmosphere. Thus, the brick production process is energy intensive and has significant environmental impact.

The Brick production process begins with the crushing and grinding of raw materials to ensure a homogeneous mixture of the raw materials. The mixture is then shaped into bricks through the extrusion process by passing the clay into the extrusion dies. After shaping, the brick undergoes the drying process where the moisture in the brick is reduced by the enthalpy of evaporation to reduce the risk of crack during Firing. The period of drying depends on the type of clay and the length of the dryer. Fossil-fired convective air dryers are widely used in the brick drying process to supply temperatures up to ≈ 180 °C. Once the brick is dried it is transported into a tunnel kiln where it is heated up by the natural gas burners up to approximately 1000 °C. The exposure to a higher temperature enhances the bricks durability, strength and resistance to fire. After the firing process, the brick is cooled, stored and packed for shipping.

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The drying and firing of bricks is the most energy intensive process in brick production. On the contrary, the drying process has the highest potential for electrification via heat pump due to the availability of exhaust waste heat and the drying temperature range. With the utilization of the exhaust air from the dryer with high relative humidity a substantial energy and emission reduction can be achieved.

INTEGRATION OF HEAT PUMP SYSTEM WITHIN THE BRICK PRODUCTION PROCESS

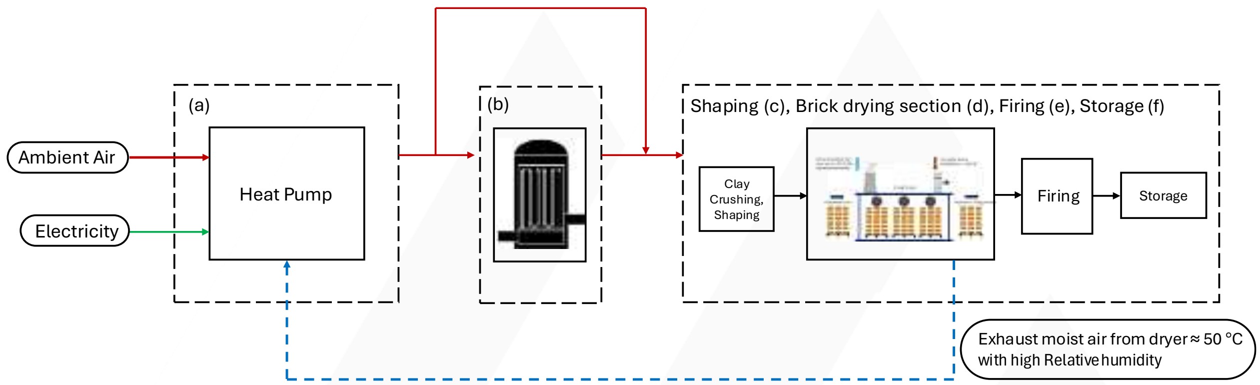

Figure 26: Schematic of HP integration in Brick production process

Using the convection-based heating system for drying processes, a substantial amount of energy is untapped and released into the atmosphere. With the heat pump integrated within the brick drying process as a substitute for the conventional based heating systems, the ambient air is heated up to the required temperature for the dryer up to 180 °C and the required energy can be supplied by the heat pump (a) to the dryer (d).

The heat from the exhaust moist air with a temperature range of approximately 50 °C with humidity in the range of 60 % to 80 % from the Dryer can be used as a heat source for the heat pump. The energy from the heat source is tapped by cooling and dehumidifying the exhaust moist air, therewith improving overall energy efficiency. Another possibility for improving efficiency is by reheating the exhaust air from the kiln to a higher temperature rather than heating from the ambient conditions.

INTEGRATION OUTCOME

Integrating a high-temperature heat pump into the Brick drying process results in an increased energy efficiency and lowers the final energy need. Heating the air more with the heat pump decreases the heat pump COP, as it needs to increase the temperature more. But for the process with a fixed supply temperature, the system efficiency increases as the complete heating demand is covered increasingly by the heat pump instead of by other means such as electric boilers or electric which accounts for additional energy consumption and thereby lower the system efficiency.

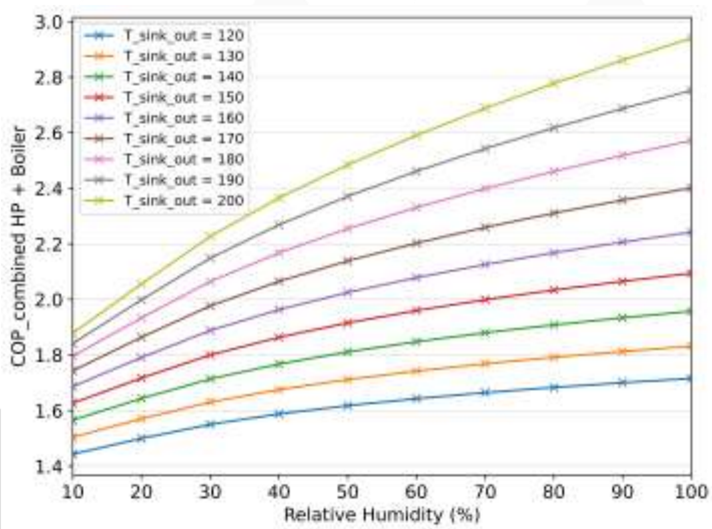

Figure 27: Combined system performance HP+Boiler for varying Relative humidity

The presence of moisture in the exhaust air results in increased heat recovery from the resulting air stream, as it holds enormous heat content in the form of latent heat. Figure 27, shows the effect of relative humidity in the exhaust air over the combined system performance HP+elec boiler for varying heat sink temperatures accounting for both full and partial electrification. Higher relative humidity in the exhaust air has higher dew point temperature results in pre-heating of inlet air stream to higher temperatures helps in increased COP gain for the heat pump by reducing the ΔT_{lift} but also lowers the heat demand.

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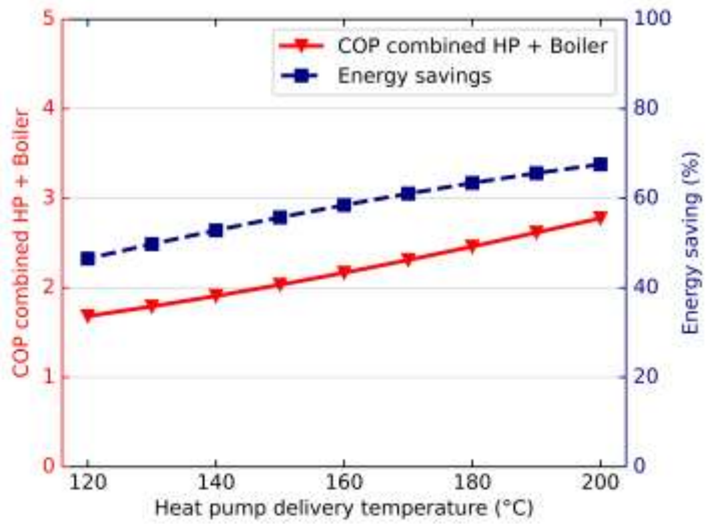

Figure 28: Combined system performance, Energy saving for varying temperature

Figure 28, shows the Combined system performance of both heat pump and electric boiler, together with the energy saving for varying heat pump delivery temperature from 120 °C to 200 °C, to address both full electrification at 200 °C and partial electrification <200 °C. The red line indicates the combined system performance for both heat pump and electric boiler, which increases as the heat pump delivery temperature rises. With the integration the expected system performance can be between 1.7 to 2.9 for partial and full integration, considering the exhaust stream with 100 % relative humidity.

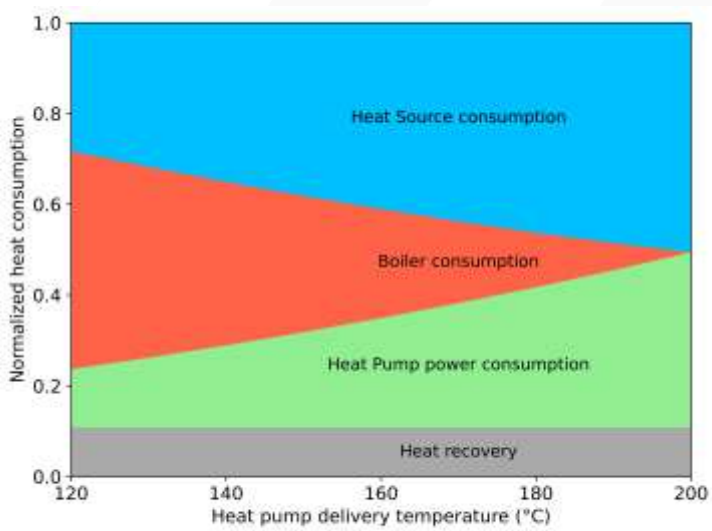

Figure 29: Normalized heat load distribution

The energy savings is represented by the blue line, also increases with the temperature, which indicates the advantages of integrating HP system as a replacement of NG boiler for heating purpose. The complete system has energy savings within the range of 50 % - 70 %.

The Normalized heat consumption plot Figure 29, indicates the heat load distribution of individual component of the system and normalized to the total heat demand for varying heat pump delivery temperature. For the case with full electrification with heat pump at 200 °C a minimum of 40 % of the total heat demand has to be covered by compression work (green area) and 50 % has to be covered by the heat source either by the exhaust air stream or other waste heat stream (blue area) in order to achieve the system performance as estimated in Figure 28.

In addition, pre-heating portion of inlet air with the moist exhaust air can lower the heat demand that enables the direct heat recovery between the streams. Which is shown as grey area covering almost 10 % of total heat demand. On the contrary, for partial electrification from temperature 120 °C to 190 °C an electric boiler is used in addition to HP - represented by red area, increases for lower temperature and covers almost 55 % of total heat demand for 120 °C. Though it increases the individual HP COP, but it decreases the overall system performance as a larger portion of the heat demand is covered by boiler.

The emission reduction percentage is an indicator of amount of CO_2 emission can be reduced with the heat pump integration compared to NG boiler. The indicator is a direct measure of Carbon Intensity of both electricity and NG grid. Table 9, represent the reduced emission for full electrification for countries Finland, Denmark, and Germany and in the range of 93 %, 84 %, and 45 % respectively.

Table 9: Emission reduction with full electrification for Heat pump for varying countries

Country	Emission reduction
Finland	93 %
Denmark	84 %
Germany	45 %

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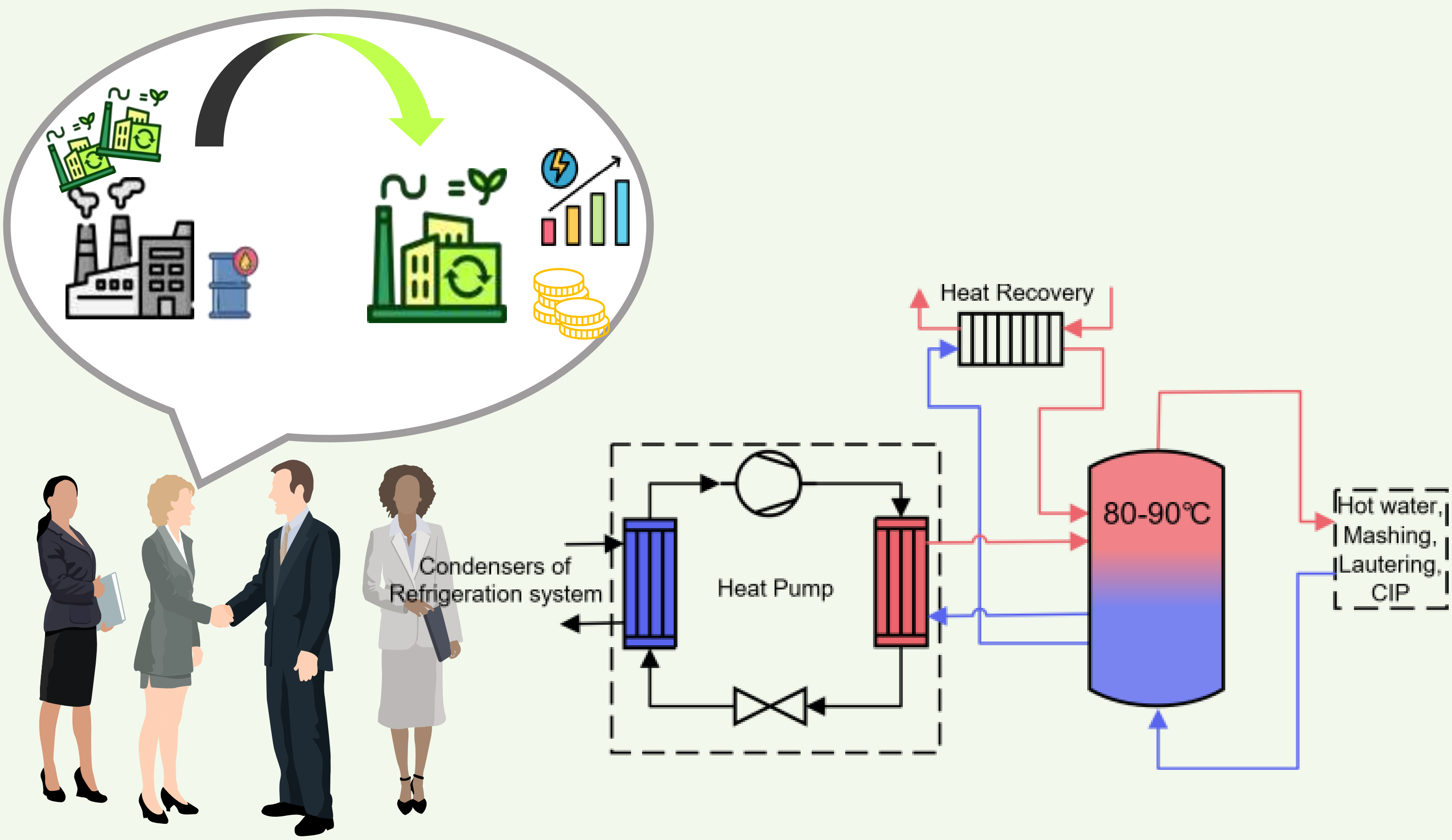
Greenfield: In greenfield projects, the entire brick drying process can be optimally designed for maximum energy efficiency, product quality, and decarbonization by leveraging superheated steam drying. The dryer can be engineered as a fully sealed, high-tightness chamber, minimizing air infiltration and maximizing the recovery and reuse of latent heat from the evaporated moisture. The entire system—fans, airlocks, insulation, control—can be chosen to support stable humid or even fully steam atmospheres ensuring exceptionally fast and energy efficient drying at controlled rate to avoid brick cracking.

Brownfield: In brownfield applications brick drying processes, many of the same principles for achieving high energy efficiency and product quality apply as in greenfield projects, but retrofits must work within the limitations of existing equipment and plant layout. Upgrading to superheated steam drying or improving chamber sealing can still deliver substantial efficiency gains, but modifications such as increasing tightness, enhancing insulation, or adapting controls for stable steam atmospheres may be more complex to implement. A heat pump is still an efficient solution, but COP will be highly dependent on the ability to upgrade the existing drying oven.

11. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF BREWERY PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 71 %: Heat pump-integrated systems deliver the same heat using just 29 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 68 % - 83 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



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BREWERY PROCESS

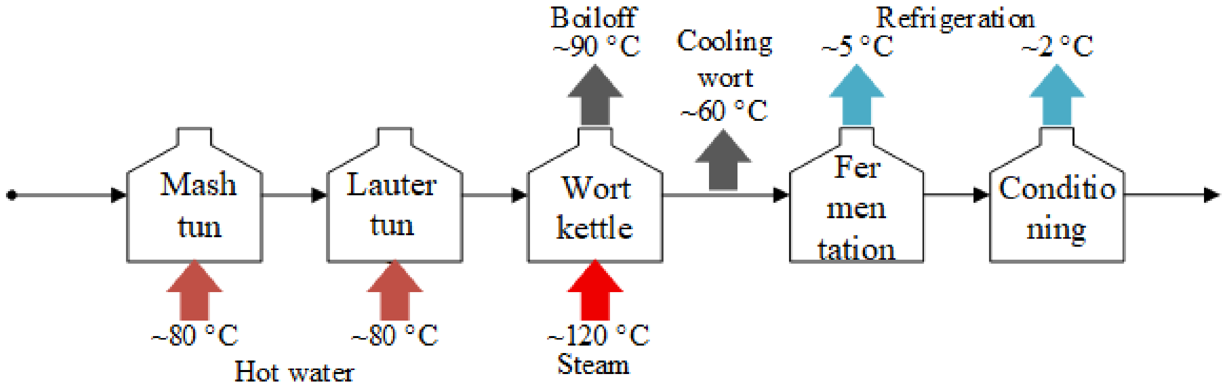

Figure 30: Heat demands and heat available during the brewing process

The global beer consumption for the year 2023 was approximately 188 billion liters [11]. In addition to beverages milk, tea and coffee, beer is the fifth-largest consumed beverage category within the global food industry. The production of beer involves several stages including Malting - where the barley is soaked and allowed to germinate and sprout to extract the nutrients from the grain, followed by Milling – where the malt is crushed finely and sent into the Mashing process (Mash tun) where the milled malt is mixed with water to convert the starch, enzymes into a solute rich liquid called Wort. After the Mashing process the sweet wort is separated (Lauter tun) and boiled together with the hops which provide flavor to the beer inside a kettle where the conversion of hops constituents, removal of unwanted components, the aroma and the bitter taste is achieved. After boiling, the wort is cooled and the hops, grains are removed from the wort and is sent for the Fermentation process, where the sugar in wort is metabolized and converted to alcohol and carbon dioxide by the addition of yeast and finally the mature beer is produced and packed.

Beer production is an energy intensive process as the product requires continuous heating and cooling needs at different temperature levels. Particularly, the Mash tun (Mashing process), lauter tun (separation process) requires up to 70 °C, Wort boiling from 100 °C up to 145 °C, Fermentation up to 15 °C.

The availability of waste heat at higher temperatures from the cooling process can be recovered and utilized within the processes directly or upgrading it. Thereby the required heating needs for the process streams can be reduced. The steam from the Wort boiling can be used to preheat the wort entering the kettle (or) the excess heat from the cooling process after the Wort boiling can be used as heat source and upgraded to higher temperature and can be supplied to other process streams using a heat pump. But the availability of waste heat is limited during the start-up, therefore external heating such as an electric boiler or a hot water tank are required initially.

INTEGRATION CONCEPTS OF HEAT PUMP SYSTEM WITHIN THE BREWERY PROCESS

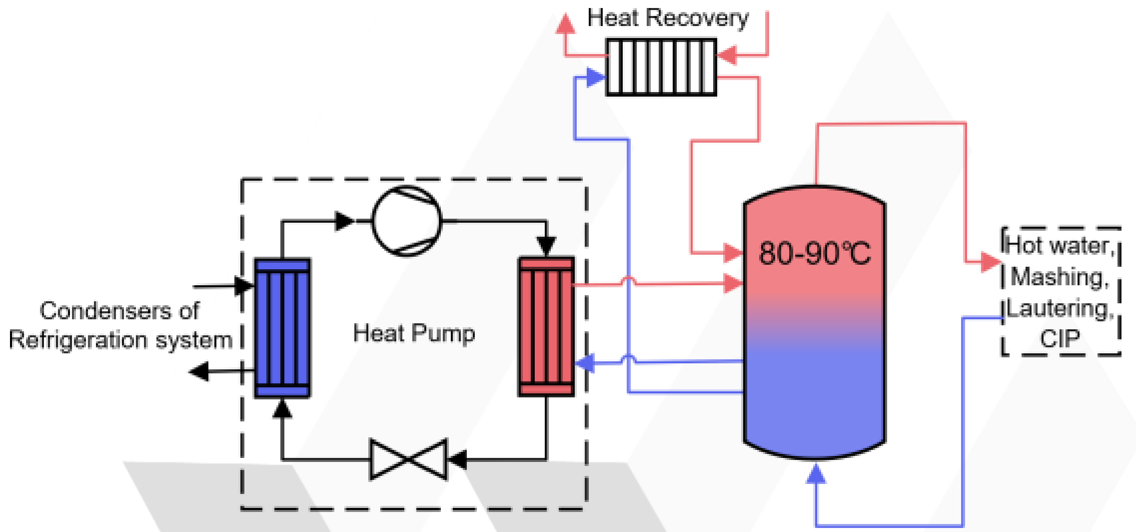

Figure 31: Proposed heat pump integration in the brewing process combining with the heat recovery system

Heat pump integration into the brewing process can lead to significant reductions in energy use, especially when combined with the implementation of heat recovery measures. Common heat recovery measures include capturing the boil-off heat from the wort boiling process, which can be reused to heat other processes within the brewery and also helps to reduce odors. Another widely adopted solution is recovering heat from cooling the wort after boiling, prior to fermentation. This recovered heat is typically used to produce hot water, which is stored in a tank at around 80°C and can be utilized for processes such as mashing, lautering, or cleaning-in-place (CIP).

Heat pumps can be integrated to support the production of this hot water, using the brewery's refrigeration system as a heat source to improve overall efficiency. Combining the heat pump with a hot water tank adds operational flexibility, which can be exploited for optimal heat pump performance.

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INTEGRATION OUTCOME

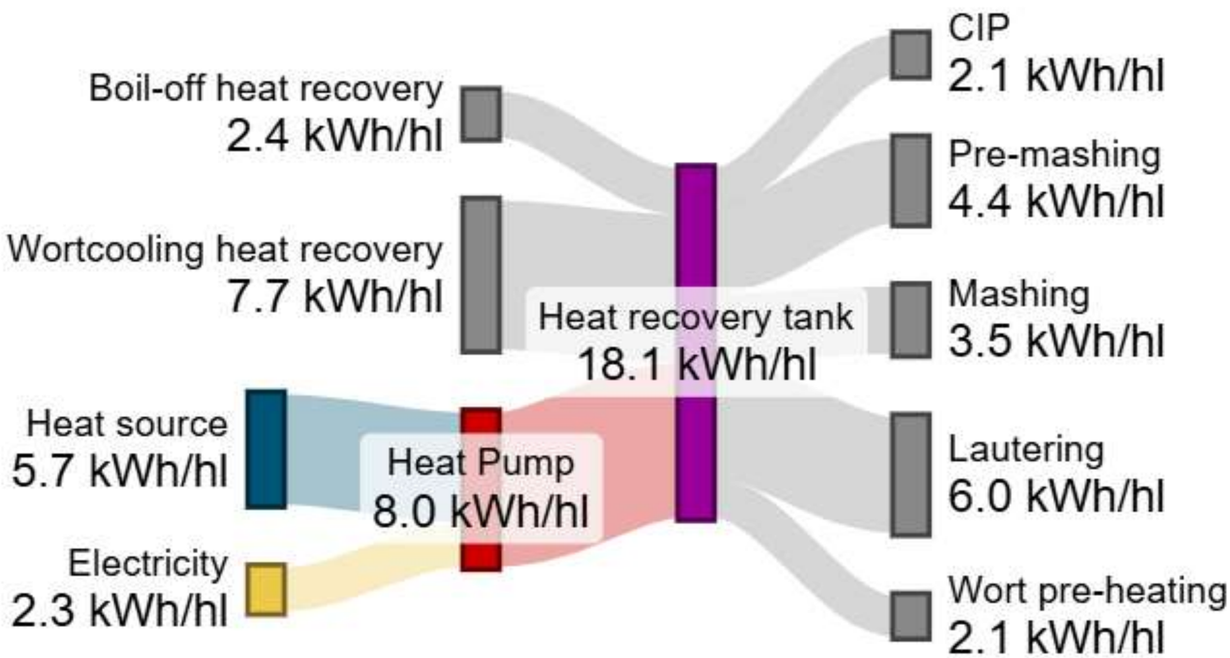

Figure 32:Sankey diagram of the proposed integration illustrating energy flows, including electricity use, per hectoliter of product.

The integration of a heat pump in combination with heat recovery can significantly increase overall energy efficiency of the brewing process. With a heat recovery tank at 80 ºC to 90 ºC, and a condenser from the refrigeration plant operating at 20 ºC, the COP can be estimated to 3.4.

The energy flows to the heat recovery tank can be illustrated for a representative brewery as in Figure 32. The batch nature of the brewing process requires the storage capacity of the heat recovery tank to be considerable. The operation of the heat pump can benefit from the additional flexibility of this storage capacity by leveraging on the fluctuations of the electricity price or the availability of solar energy.

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Table 10: Emission reduction with full electrification of heat pump for varying countries

Country	Heat recovery only	Heat recovery and Heat Pump
Finland	47 %	83 %
Denmark	47 %	80 %
Germany	47 %	68 %

The emission reduction is a measure of amount of CO_2 emission can be reduced with the heat pump integration compared to NG boiler. The estimated emission reduction with the utilization of heat recovery and heat pump for the brewery process is presented in Table 10. With the utilization of heat from the Wort Boil-off and Wort cooling process lowers the emission up to 47 %, as the heat recovered reduce the heat demand thus reduce the final energy consumption. On the contrary, integrating heat pump together with heat recovery, a significant amount of emission can be reduced of up to 83 % for Finland, 80 % for Denmark and 68 % for Germany respectively.

Greenfield: In greenfield brewery projects, the optimal solution combines the coldest possible hot water circuit, a CO_2-based system for the warm water loop with integrated heat recovery, MVR for the wort kettle.

Brownfield: In brownfield breweries, high-temperature heat pumps (HTHPs) can be retrofitted with the existing steam or hot water networks to gradually electrify process heating and increase energy efficiency. Integrating HTHPs in combination with optimized heat recovery offers substantial reductions in energy use and CO_2 emissions—especially when leveraging heat recovered from wort cooling.

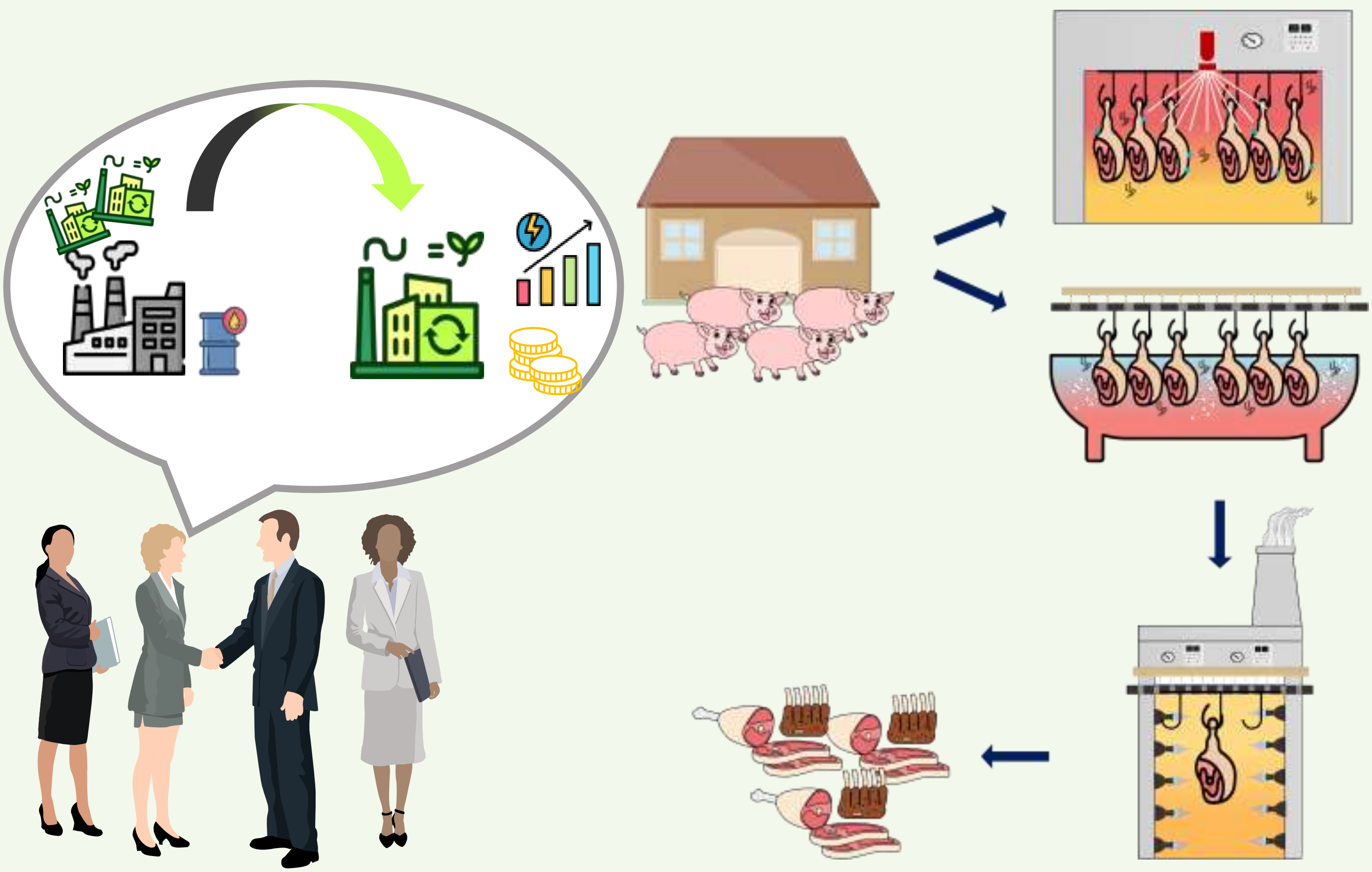
For boiloff heat recovery, Pfaduko systems are particularly effective paired with centralized HTHPs, as they directly supply low-temperature needs, while MVR becomes efficient only when combined with a lower-temperature heat pump and additional investment.

When planning brownfield electrification, it is important to look beyond immediate boiler replacement or single technologies: although quick solutions like Pfaduko or a direct HTHP retrofit may be attractive now, they risk technological lock-in and could limit future efficiency gains—such as shifting to lower-pressure steam, adopting integrated multi-heat pump systems, or further expanding heat recovery.

Funded by the European Union

12. DECARBONIZING INDUSTRIAL HEAT - ELECTRIFICATION OF SLAUGHTERING PROCESS VIA HIGH-TEMPERATURE HEAT PUMPS

- Cut energy consumption by up to 75 %: Heat pump-integrated systems deliver the same heat using just 35 % of the energy required by gas boilers.
- Drastically reduce CO_2 emissions: Achieve 50 % - 95 % CO_2 emission reductions through electrification
- Streamlined, Cost-Efficient Integration: Integration concepts lower upfront CAPEX and accelerate deployment.



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SLAUGHTERING PROCESS

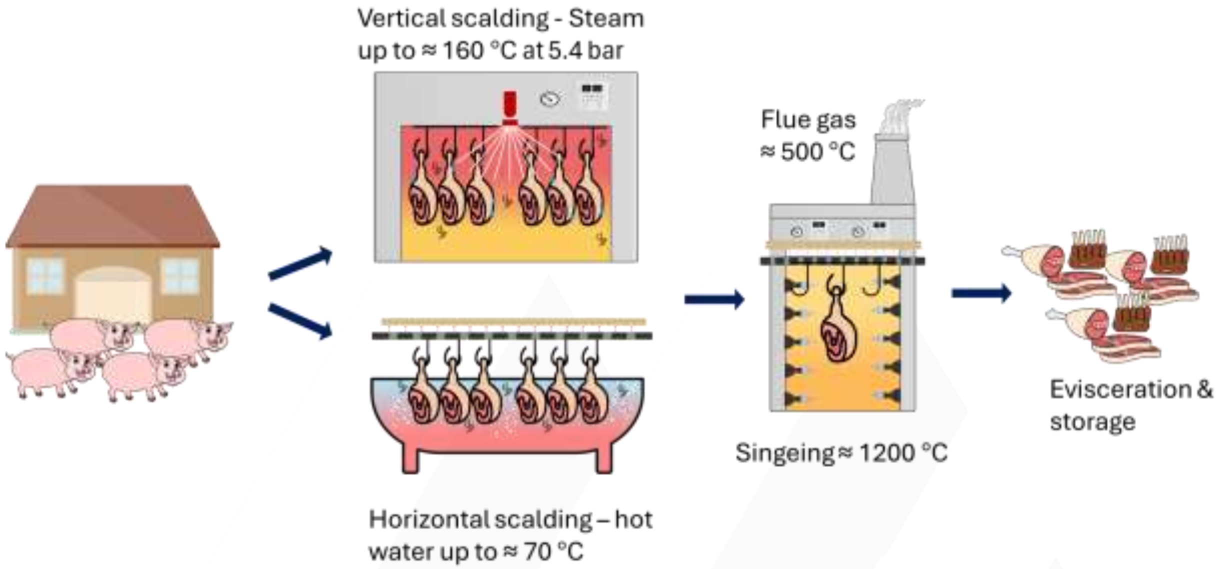

Figure 33: Schematic of Slaughterhouse

The global meat consumption for the year 2024 is estimated to be 373 million tons. In 2023, ≈ 140 million tons of poultry meat were consumed worldwide, and pork was the second most consumed meat worldwide [12]. The meat production process requires significant amount of energy, particularly the pig slaughterhouse requires high temperature levels of up to 1200 °C.

The production of meat in a pig slaughterhouse begins with the pretreatment of pig where the pigs are anesthetized, electrocuted and the blood is removed. Later the carcass undergoes the Scalding process where Pigs are placed in scalding tank in a horizontal (water-based scalding) or a vertical position (vertical condensation scalding). In the vertical condensation scalding the carcasses are exposed to the injected steam of up to 160 °C and in horizontal scalding the carcass are directly immersed in hot water up to 70 °C. Followed by Singeing process where the dehaired carcass is passed through a short tunnel and exposes to high-temperature flames to burn off any stubborn hair at a temperature of approximately 1200 °C. Followed by the Polishing and Evisceration where it is cut down and washed completely before passing to the inspection and storage process.

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The pig slaughtering process requires continuous heating and cooling needs at varying temperature levels. The blood treatment process requires hot water up to 65 °C, the Scalding process requires steam/hot water up to 160 °C/60 °C, The Singeing is the most energy intensive process requires hot air up to 1200 °C hot water for several processes including cleaning, washing etc. is needed Also, the process requires high cooling demand for storage, Freezers etc. maintained below 0 °C. The excess heat from the process lines can be recovered/upgraded to higher temperature. The possible heat sources are the exhaust heat from the Singeing process at a temperature of approximately 500 °C, return condensate from Scalding process, and the heat from the refrigeration plant (Condenser) of approximately 50 °C to 30 °C.

INTEGRATION CONCEPT OF HEAT PUMP SYSTEM WITHIN THE PIG SLAUGHTERING PROCESS

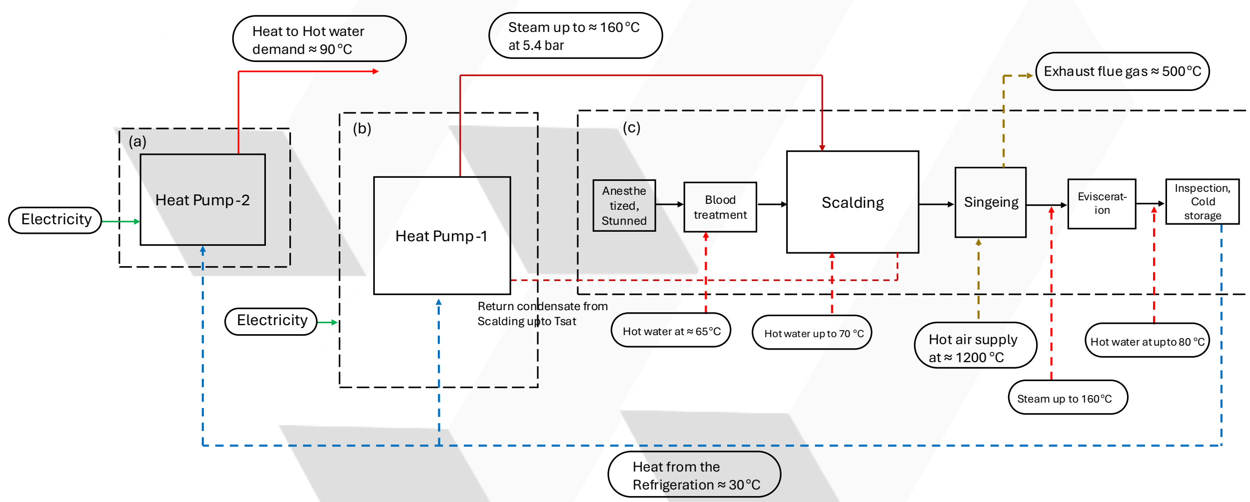

Figure 34: Schematic of HP integration in Slaughterhouse

The energy demand of the slaughtering process can be significantly reduced with the integration of a Heat pump and a Mechanical Vapor Recompression system. In the current integration concept two heat pump integration solutions were considered according to the type of the heat demand, hot water and Steam production. **Utility-1:** Heat Pump-1 - the steam required for the Scalding and Fat melting process can be supplied by the integration of Utility-1 which utilizes the heat from the refrigeration plant of ≈ 30 °C as heat source for the heat pump and supplies the required amount of heat to evaporate the return condensate from the scalding process, which is further compressed to high pressure steam of up to 6 bar with a steam compressor.

Utility-2: Heat pump-2: hot water up to a temperature of approximately 80 °C is required within the process including cleaning, sterilization and other process. This can be supplied with the integration of a separate heat pump which utilize the heat from the refrigeration plant, upgrade it and the energy is transferred to heat the inlet water from approximately 20 °C to 90 °C. The flue gas from the Singeing process can be as high as 500 °C and can be used to heat the inlet water feed for hot water production or can be used to preheat the return condensate from the Scalding process, but the flue gas carries comparatively less energy and is highly contaminated with the hair dust and other particles which affect the heat exchanger performance over time. Additionally, the recovery of heat from fossil-based sources will not lead to full decarbonization. Therefore, heat recovery of flue gas is excluded from this study.

INTEGRATION OUTCOME

With the proposed heat pump integration solution, the final energy required for both hot water and steam production can be significantly reduced—by up to 70 % – 85 %—compared to the energy needed to deliver the same heat with a NG boiler. This dramatic reduction is achieved by utilizing waste heat from the plant's own refrigeration systems as the source for HTHPs, enabling efficient heat recovery and upgrade.

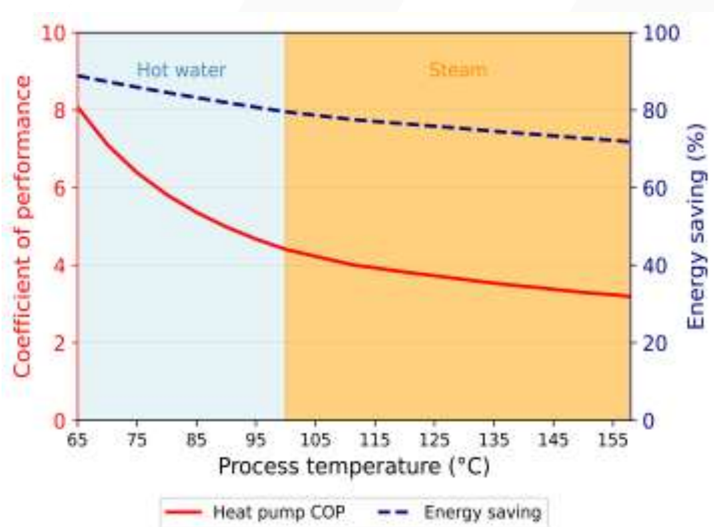

Figure 35: System performance, Energy saving for varying process temperature

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Figure 35, illustrates the relationship between heat pump Coefficient of Performance (COP) and the energy savings achieved with integration. The expected COP of the heat pump used in hot water production ranges around 4 to 8 and for the steam generating heat pump COP of 3.5 to 4.5 can be achieved. By utilizing the excess heat from the refrigeration plant.

The resulting improvements in energy efficiency are directly reflected in site emissions. The percentage reduction in CO_2 emissions is a robust indicator of the decarbonization effect and is determined by the carbon intensity of the electricity used to power the heat pumps versus the NG grid.

Table 11, shows the impact for three reference countries: full electrification of heating through HTHPs would deliver emission reductions of approximately 94% in Finland, 86% in Denmark, and 54% in Germany (2023 grid carbon factors). The highest savings are realized in regions with low-carbon electricity supplies, highlighting the synergy between electrification and renewable energy integration.

Table 11: Emission reduction for full electrification of Heat pump for varying countries

Country	Emission reduction
Finland	94 %
Denmark	86 %
Germany	54 %

Brownfield: When retrofitting brownfield slaughterhouses, shifting from vertical to horizontal scalding brings important advantages for heat pump integration. Horizontal scalding, which immerses carcasses in hot water rather than exposing them to live steam, is less energy intensive and operates at lower temperature conditions that further increase the potential of using heat pumps. This configuration not only allows for greater heat recovery potential but also enables heat pumps to achieve higher COPs. A key point is basing the process on heat recovery from the exhaust flue gas is a temporary solution, as this heat is not available when moving away from fossil fuel heating.

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Greenfield: In greenfield slaughterhouses, it is possible to eliminate the need for steam and design an integrated system that uses a hot water loop for process heating and cold glycol loops for cooling/freezing. All circuits can be efficiently supplied by a high-temperature heat pump system, which supplies simultaneous heating and cooling with minimal energy use.

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