DECARBONIZING INDUSTRIAL PROCESS HEAT VIA – HIGH TEMPERATURE HEAT PUMP INTEGRATION IN EXISTING INDUSTRIAL FACILITIES

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ABSTRACT

Industrial High-temperature heat pumps (HTHPs) are one of the key technologies in improving energy efficiency and decarbonizing the industrial process heating sector which often relies on fossil fuels and is thus a major driver of greenhouse gas emissions. This study aims to shed light on the impacts of HTHP integration into different industrial processes at different temperature levels. For this, four industrial cases including Spray dryer, Shrimp cooking, Sugar production, Pulp & Paper have been selected for the analysis as case studies. The process heating requirements vary between different industrial sectors and are specific to industrial processes. Therefore, it is important to take the boundary conditions of the specific processes into account when evaluating the potential of HTHP integration. In the present analysis, the HTHP is considered a grey box unit but the boundary conditions such as temperature level of the reservoirs were considered to identify the HTHP integration potential and performance for each case. This study will provide general integration guidelines, estimates of general heat pump coefficient of performance (COP), energy savings and environmental benefits. The method on which the analysis is established does not require detailed energy mapping of complete industrial process streams, but rather an estimation of temperature level of heat source and heat sink in the process. The Lorenz efficiency is estimated using a polynomial regression of heat pump models from the literature, which allows for the calculation of the heat pump COP across a range of operating temperatures. In the spray drying process a COP of 2.5 can be achieved, with energy savings of 70 % and an 84 % reduction in emission. In shrimp cooking, the potential maximum COP reaches 6, alongside energy savings of up to 85 % and an 87 % decrease in emissions. In the sugar production process, a COP of 6.5, with energy savings and emission reductions reaching 86 % and 88 %, respectively. Similarly, the pulp and paper drying process can achieve a COP of up to 2.4, with energy savings of 65 % and a 79 % reduction in emissions. Thus, the analysis concludes the energy and environmental benefits of HTHP integration into the industrial process.

1 INTRODUCTION

The share of renewables in electricity generation has to rise by 60 % within 2030 to meet Net zero emission (NZE) by 2050 (IEA, 2022). To battle climate change, immediate actions are required in global energy transition. The European Industrial sector (EU28 countries) is responsible for 25 % of total European energy use, of which 66 % accounts for industrial process heating and responsible for 20 % of greenhouse gas (GHG) emissions (De Boer *et al*., 2020). Which highlights the need for increase in energy efficiency and energy transition for more sustainable process heat generation. Industrial High-temperature heat pumps (HTHPs) are one of the key technologies in improving energy efficiency and decarbonizing the industrial process heating sector which often relies on fossil fuels and is thus a major driver of greenhouse gas emissions. A heat pump utilizes electricity to upgrade the heat from lower temperature (including industrial waste heat, condensate from processes, exhaust gases) to higher temperature process heat (Zühlsdorf *et al*., 2023). The heat pump coefficient of performance (COP) is strongly influenced by the temperature lift which is the difference between the heat sink and heat source temperatures, depending on which the cycle configuration and refrigerant medium of the heat pump are selected. Ommen *et al.* (2015) investigated both technical and economic limitations of industrial heat pumps using natural refrigerants for temperature lift up to 70 K and heat sink temperature up to 120 °C. Arpagaus *et al.* (2018) reviewed the state-of-the-art HTHP and evaluated the heat pump COP over a range of heat sink temperature from 90 °C to 160 °C. Andersen *et al.* (2024) evaluated the heat pump performance over 16 working fluids in 10 HTHP configurations across wide range source temperatures from 0 °C to 100 °C and heat pump temperature lift up to 150 K.

Several studies on the investigation of HTHP integration for different industrial applications are available. The IEA HPT Annex 58 (Zühlsdorf *et al*., 2022) provides general integration guidelines and possible integration concepts for HTHP in different industrial applications. Walden *et al.* (2024) introduced an analytical equation based on the Lorenz efficiency to estimate the optimal heat pump integration temperature for the process heat electrification of spray dryer application. Schlosser *et al.* (2020) addressed the performance and economic feasibility of large-scale heat pump, integrated within different industrial processes based on pinch analysis.

This study focuses on accessing the advantages of integrating HTHP across four industrial sectors: Spray dryer, Shrimp cooking, Sugar production, Pulp & Paper. In the analysis the HTHP is considered as a grey box unit, therefore the present study does not include the detailed thermodynamic modelling of the heat pump system but rather includes the estimates of heat output and input based on the temperature level of the process. Therefore, only the system boundary conditions, especially the temperature level of the heat sink and source reservoirs are considered for the analysis. The temperature level for the analyzed cases is estimated based on the data from the integration concepts studies of Annex 58 (Zühlsdorf *et al*., 2022) and SPIRIT demonstration case study (SPIRIT Heat Project, 2022).

To cover the wide range of operating temperature of specific industrial processes, the study evaluates the system performance over a range of temperature. The system performance COP is estimated using the Lorenz efficiency polynomial proposed by (Andersen *et al*., 2024) based on the temperature lift, sink and source temperature glide and source inlet temperature. The estimation of generalized heat pump COP highlights the potential increase in energy efficiency of the system compared to conventional based heating systems. Additionally, the environmental advantages on energy savings and CO_2 emission reduction achieved with the integration of heat pump as a replacement to natural Gas (NG) boiler is also addressed.

Section 2 describes the methodology, detailed description of each industrial case, and its heat pump integration concepts. The integration outcome for each industrial case is discussed in section 3. The discussion of the result is presented in Section 4. Section 5 presents the main conclusion of the analysis.

2 METHODOLOGY

This section presents a detailed description of each industrial case, the heat pump integration concept, and the approach used to estimate the performance indicator of the heat pump system. The description of each industrial case along with heat pump integration concept is discussed in subsection 2.2 - 2.5. In addition to the COP of the heat pump, Energy saving and Emission reduction potential with heat pump integration is also addressed.

2.1 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 transferred 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 temperature > 200 °C. The following governing equations are used to estimate the heat pump COP, energy saving and emission reduction.

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

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

Where, $T_{H,i}, T_{H,o}$ represents the heat sink inlet and outlet temperatures. The required heat input $\dot{Q}_{\text{source}}$ to the heat pump is estimated as a function of heat output and heat pump COP and calculated using the 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*., 2024)

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

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

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

The relative energy saving with the heat pump integration as a replacement of NG boiler is estimated using the Equation (6). To estimate energy savings the boiler efficiency of 0.90 is assumed (Ommen *et al*., 2015)

$$Relative\ Energy\ saving = \frac{\text{COP}_{\text{HP}} - \eta_{\text{Boiler}}}{\text{COP}_{\text{HP}}} \tag{6}$$

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.

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

Table 1: Carbon Intensity indicator for different countries

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

The temperature level of heat sink and heat source used in the analysis for each industrial case is listed in Table 2. As mentioned in Section 1. The temperature level for the analyzed cases is estimated based on the data from the integration concepts studies of Annex 58 (Zühlsdorf *et al*., 2022) and SPIRIT demonstration case study (SPIRIT Heat Project, 2022).

Table 2: Temperature level of heat sink and heat source for each industrial case

Industrial process	Typical Sink temperature	Typical Source temperature
Spray Drying	Ambient air → ≈ 240 °C	Moist air with dew point up to 45 °C
Shrimp Cooking	Steam up to 160 °C	Waste heat up to 20 °C
Sugar Production	Steam up to 140 °C	Vacuum steam up to 80 °C
Pulp & paper	Steam up to 180 °C	Moist air with dew point up to 60 °C

2.2 Spray Drying Process

In the dairy industry, many heating and cooling processes are involved, accounting for a major portion of the energy demand of the sector. The main process lines for conventional milk powder production are milk reception, standardization, homogenization, pasteurization, evaporation, and spray drying. Spray drying is a highly energy-intensive process widely employed in the industry normally powered by fossil fuels. It is widely used to produce powdered forms of diverse products, such as sugar, milk, cheese, coffee, eggs, starch, etc. 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.

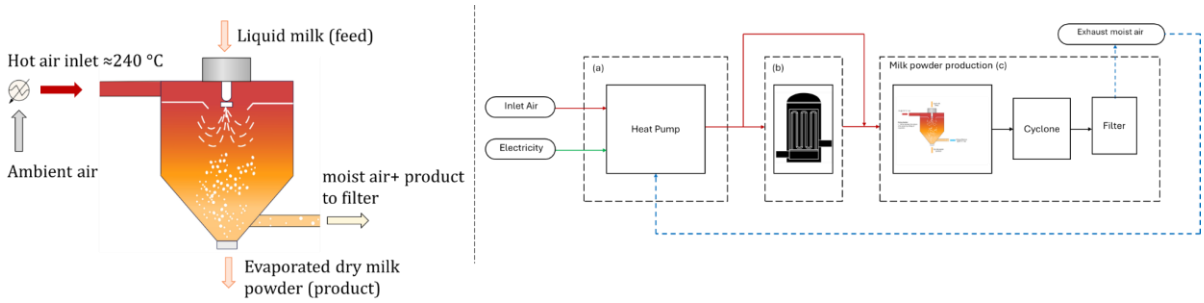


Figure 1: Schematic of milk powder spray drying chamber and Heat pump integrated concept

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

With the heat pump integrated within the spray drying process Figure 1., the inlet air at an 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 (b) and passes through the Cyclone and exists the Filter as exhaust air (c).

The typical heat source for the heat pump system is the exhaust moist air from the filter (c) of around 50 °C but varies depending on manufacturer and end product. The dew point of the air is around 45 °C. The majority of energy will be available from the latent heat of evaporation in the moisture. The heat pump system raises the temperature of the inlet ambient air up to 240 °C, 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 a boiler system which is used as an additional heater and can be combined with the heat pump system for elevated temperature ranges.

2.3 Shrimp Cooking Process

The process of producing cooked and peeled shrimp involves several operating stages including thawing, grading, cooking, freezing and packing. The cooking process inside the shrimp cooking chamber typically requires high temperature water at 100 °C or steam at up to 160 °C depending on the cooking process and blanching period of shrimp. The temperatures are crucial for achieving uniform cooking throughout the batch of shrimp and to maintain the texture and flavour of the shrimp. After the cooking process the shrimp is transferred into the freezing chamber where it is cooled to below 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 again, typically reused to preheat the fresh inlet shrimp, but it requires additional filtering as it is highly contaminated.

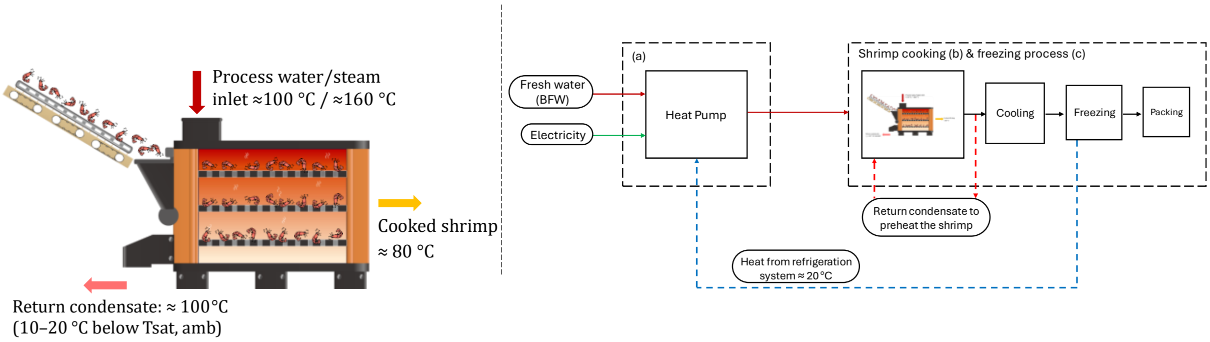


Figure 2: Schematic of Shrimp cooking chamber and Heat pump integrated concept

With the heat pump system integrated within the shrimp cooking process Figure 2, the fresh water at ambient temperature or the Boiler feed water (BFW) 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.

2.4 Sugar Production Process

Sugar production is an energy intensive process, as it requires different process heat at different temperature levels within the production process to crystallize sugar from the sugar solution. Particularly, the steam required to evaporate the sugar solution within the steam evaporator line uses significant energy within the whole process. The process of sugar crystallization is as follows. After the sugar cane is milled, sugar juice is heated and clarified, the clear juice is sent through a multiple-effect evaporation line, with multiple evaporator units that operate at decreasing pressures, to increase the concentration of sugar solution by evaporating the water present in the sugar solution. After passing the evaporation line, the highly concentrated sugar syrup is crystallized inside the vacuum chamber and sent to the storage.

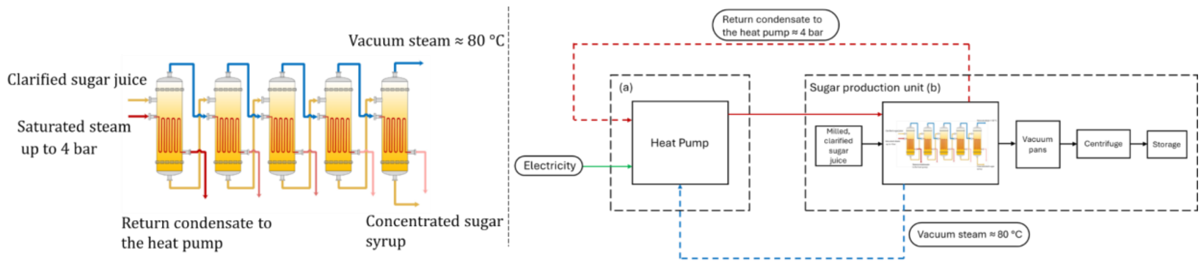


Figure 3: Schematic of Multiple effect evaporator and Heat pump integrated concept

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. With the integration of heat pump the high temperature return condensate from the first evaporator line can be reheated to a saturated steam and utilized within the system again. And the heat exhaust from the last evaporator typically at lower temperature and pressure can be used as potential heat source for the heat pump system.

With the heat pump integrated within the sugar production process Figure 3., the return condensate from the evaporator unit is heated and supplied into the process (a). Followed by passing the concentrated sugar syrup into the vacuum chamber to crystallize. The heat exhaust from the last evaporator unit can be integrated as a heat source for the heat pump system. Typical range between 50 °C to 70 °C. Which is typically a vacuum steam at lower pressure and temperature. The return condensate from the evaporator unit 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.

2.5 Paper and Pulp Production Process

Paper manufacturing is an energy intensive process, accounting for 70 % of energy required only for pulp drying process. The manufacturing process starts with the recipe of paper, Logs are debarked and chipped, followed by digester where the wood chips are cooked with water, chemical. 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 pulp is passed over multiple steam heated cylinders, where it is dried continuously by evaporating the moisture content from the pulp. The steam pressures for the drying section ranges between 0 bar – 8 bar, which depends on the drying sections and the number of cylinders. With the integration of heat pump, the return condensate from the drying cylinder can be heated up into the saturated steam and the exhaust moisture air can be used as heat source for the heat pump system.

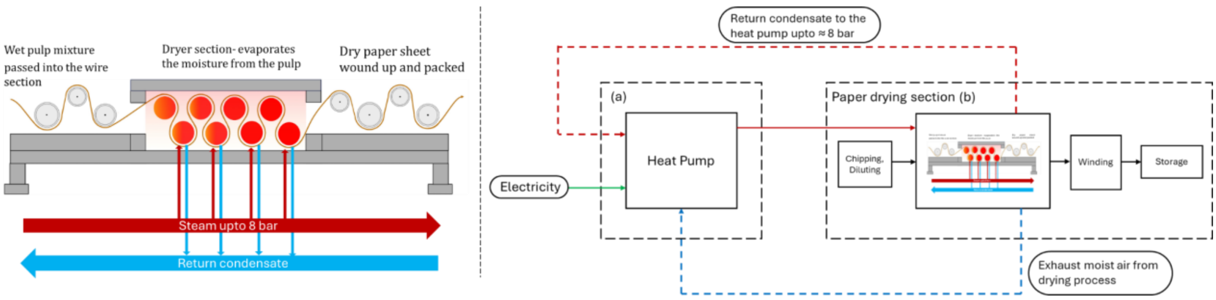


Figure 4: Schematic of Pulp drying process and Heat pump integrated concept

With the heat pump integrated within the paper production process Figure 4., the return condensate from the drying section is heated to saturated steam and supplied into the system (a). Once the pulp is dried it turns into paper, which is sized and packed. The exhaust moist air escapes from the drying section, with higher relative humidity and a dew point of 60 °C, is used as heat source for the heat pump. As it holds enormous heat in the form of latent heat. The return condensate from the Drying sections with temperature ranges between ≈ 100 °C to 180 °C is heated back to the saturation temperature and supplied back into the sections.

3 RESULT

3.1 Spray Drying Process

Integrating a high-temperature heat pump into the spray dryer process results in increased energy efficiency by lowering the primary energy need. The red line in Figure 5(a). indicates the combined system performance for both heat pump and electric boiler, which increases as the heat pump delivery temperature rises. The increase in COP indicates that the system becomes more efficient at higher temperatures, due to increased heat recovery between the source and sink process streams, also reduced operational power for complete HP integration. With the integration the expected system performance can be ranges between 1,5 – 2,5 for partial and complete integration respectively. The energy savings is represented by the blue line, also increases with the temperature, which indicate the advantages of integrating HP system as a replacement of NG boiler for heating purpose. With the integration the combined system has the energy saving within the range of 40 % - 70 %.

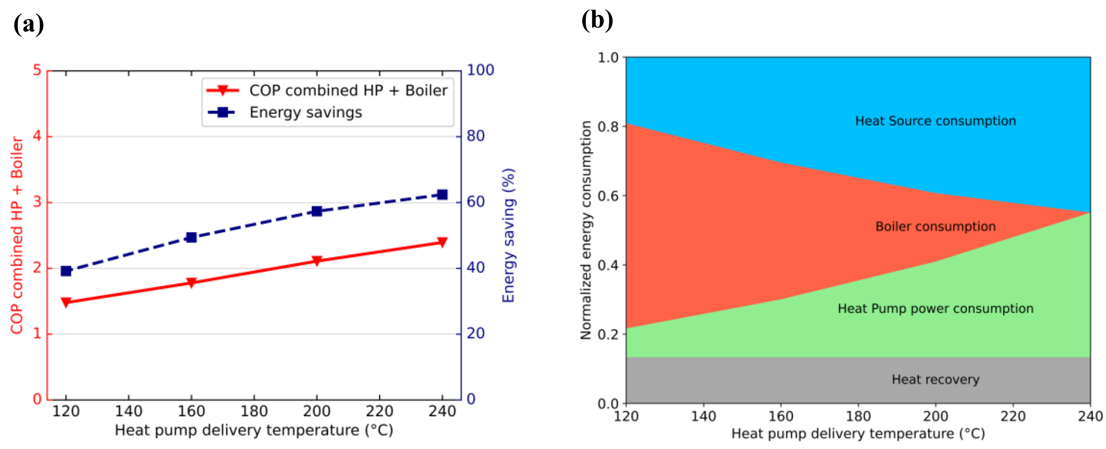


Figure 5: Heat pump delivery temperature vs Combined system performance (HP+Boiler) & Energy saving (a) and Normalized energy consumption with heat recovery (b)

The Figure 5(b). shows the Normalized energy consumption of the system to the total heat output for varying heat pump delivery temperature. It indicates that to electrify the complete process, the heat pump requires more electrical energy (green area) and source energy (blue area) to achieve higher performance. On the contrary, for partial electrification from temperature 120 °C to 220 °C an electric boiler is used in addition to HP - represented by red area, increases for lower temperature and covers almost 60 % of total energy consumption for 120 °C. Though it increases the individual HP COP, but it decreases the overall system efficiency as a larger portion of the heating is covered by boiler.

Table 2. represents the relative emission reduction percentage with the heat pump integration compared to NG boiler for countries Finland, Denmark, and Germany and in the range of 93 %, 84 %, and 44 % respectively.

Table 2: Relative emission reduction for full electrification of Heat pump for varying countries

Country	Relative emission reduction
Finland	93 %
Denmark	84 %
Germany	44 %

3.2 Shrimp Cooking Process

With the heat pump integration within the shrimp cooker, the COP of the heat pump system can be achieved between 6 to 2 for temperature 80 °C to 160 °C respectively, as depicted by the red line in Figure 6(a). The expected higher heat pump COP indicates that the system is more efficient as the energy from the exhaust is utilized and on the other hand, an energy saving of up to 85 % can be achieved by the integration. The Normalized energy consumption of the heat pump to the total heat output is shown in Figure 6(b), indicates the required heat source energy (blue area) to achieve the estimated performance for the electrification of shrimp cooker. It depicts that the system requires higher heat source energy about 60 % to 80 % of the total energy consumption of heat pump. As the heat sink requires a significant portion of latent heat to convert the return condensate in to saturated condition.

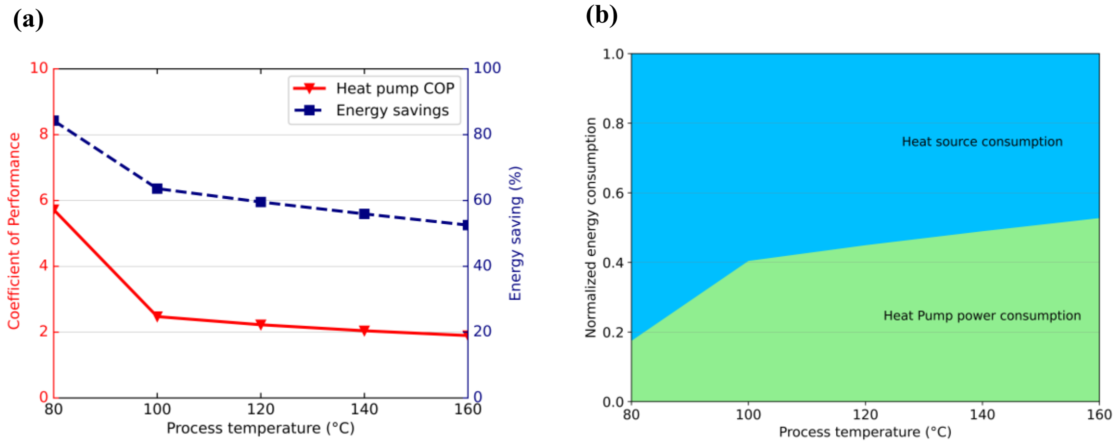


Figure 6: Process temperature vs Heat pump COP & Energy saving (a) and Normalized energy consumption (b)

For the increase in source temperature the temperature lift of the heat pump decreases and thus improves the COP. Therefore, Table 3. Represent the COP of the heat pump for varying source inlet temperature ranging from 60 °C to 20 °C for process temperature 120 °C. With higher source inlet temperature of 60 °C, increase in COP of around 30 % is achieved but simultaneously it requires higher heat source energy from the refrigeration system.

Table 3: Heat pump COP for varying source temperature for process temperature 120°C

Source temperature (°C)	Heat pump COP
60	3.22
40	2.61
20	2.22

The relative emission reduction percentage with the heat pump integration for process temperature 160 °C represented in Table 4. for countries Finland, Denmark, and Germany and in the range of 91 %, 79 %, and 28 % respectively.

Table 4: Relative emission reduction for full electrification of Heat pump for varying countries

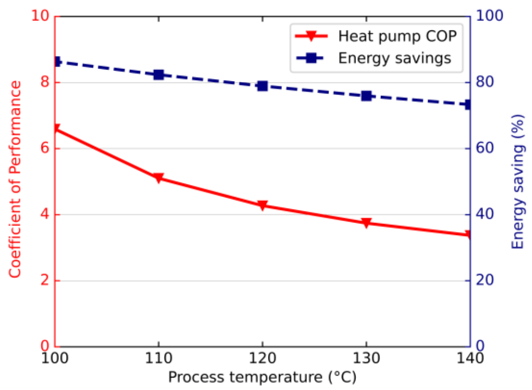
Country	Relative emission reduction
Finland	91 %
Denmark	79 %
Germany	28 %

3.3 Sugar Production Process

Depending on the number of evaporation units the temperature of the return condensate from the evaporator varies in the range of 115 °C to 140 °C as mentioned in Section.2. With the heat pump integration within the evaporation process for sugar production a highly efficient energy production can be achieved. Figure 7(a) depicts the heat pump system COP and energy savings for varying process temperature range. The red line indicates the heat pump COP and blue line indicates the Energy saving potential with heat pump integration compared to NG boiler. The COP of heat pump varies between ≈ 3.5 to 6.5 for process temperature 140 °C to 100 °C with corresponding energy saving of 70 % to 86 % respectively.

In addition, the Normalized energy consumption of the heat pump to the total heat output is shown in Figure 7(b). The energy consumption of heat source (blue area) and electrical power (green area) is plotted for varying process temperature. For the process temperature of 140 °C, a heat pump COP of 3.5 can be achieved, for which the heat source has to cover ≈ 65 % of total heat pump energy consumed. Lower the process temperature increase the COP, but requires high heat source energy consumption as the process requires significant amount of latent heat to heat the return condensate. Thus, corresponds to increase in HP system COP of up to 6.5 for process temperature 100 °C.

(a)



(b)

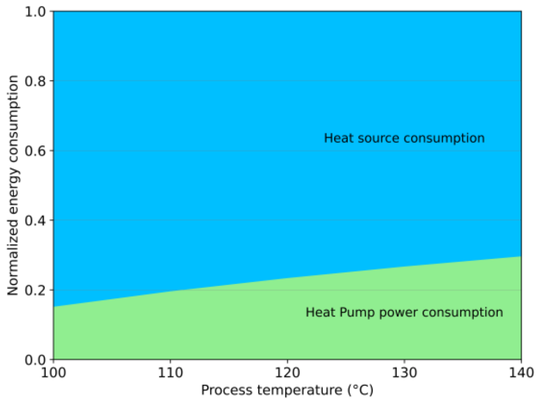


Figure 7: Process temperature vs Heat pump COP & Energy saving (a) and Normalized energy consumption (b)

The percentage of CO_2 reduced with the heat pump integration for countries Finland, Denmark, and Germany is represented in Table 5. Moreover, Finland the highest reduction percentage of 95 % compared to Denmark of 88 % and Germany of around 60 % due to the high carbon intensity of the electricity grid.

Table 5: Relative emission reduction for full electrification of Heat pump for varying countries

Country	Relative emission reduction
Finland	95 %
Denmark	88 %
Germany	60 %

3.4 Paper and Pulp Production Process

With the heat pump integrated into the pulp drying process, the return condensate is heated up to the required temperature by utilizing the energy from the exhaust moist air, thereby increasing the efficiency as depicted by the Heat pump COP (red line) in Figure 8(a). Where the process temperature of the heat pump varied from 100 °C to 180 °C, according to the type of product being dried. The COP decreases from about ≈ 2.4 to ≈ 1.9 due to higher temperature lift, which reduces the second law efficiency, similarly the energy savings (blue line) drop from 65 % to about 50 % for the process temperature 100 °C to 180 °C respectively. However, 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 8(b). shows the Normalized energy consumption of the heat pump to the total heat output. To achieve the required heat pump COP for varying process temperature shown in Figure 8(a), the heat source energy (blue area) of up to 40 % to 60 % is required over the total heat pump energy consumption. The remaining is covered by the electrical energy consumption (green area) of the heat pump.

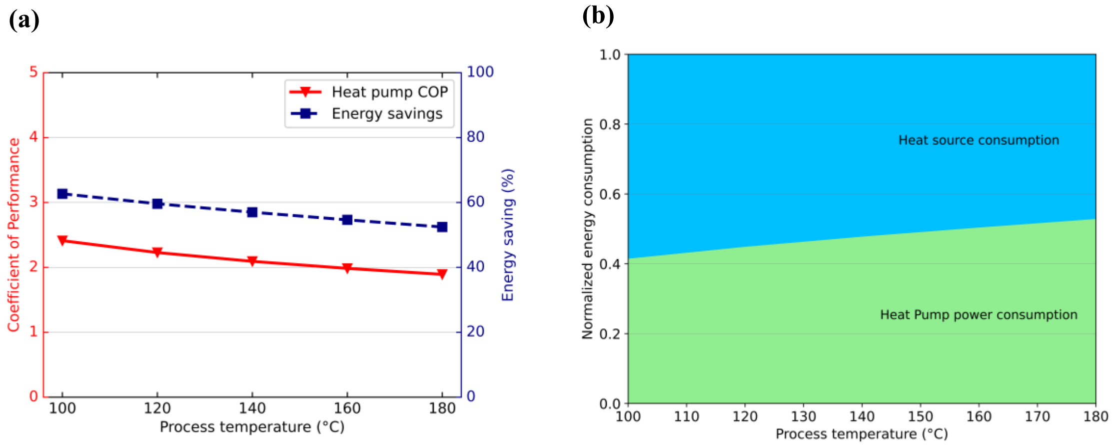


Figure 8: Process temperature vs Heat pump COP & Energy saving (a) and Normalized energy consumption (b)

With the integration of heat pump as a substitute for the NG boiler, a significant amount of CO_2 emission can be reduced. Table 6. represent the emission reduction percentage for full electrification of heat pump for varying countries. With highest emission reduction for Finland of around 91 %, and Denmark around 79 %, followed by Germany of around 28 %. The increase in emission reduction for Finland is due to the low carbon intensity in electricity generation which is about 87 % lower compared to Germany.

Table 6: Relative emission reduction percentage for full electrification of Heat pump for varying countries

Country	Relative emission reduction
Finland	91 %
Denmark	79 %
Germany	28 %

4 DISCUSSION

The method used in the analysis presents a simple and generic way to estimate the heat pump COP integrated within an industrial process. It does not provide information regarding the optimal level of heat pump integration within the industrial process. Also, in the analysis, only the temperature level of heat demand and waste heat are taken into consideration for each case. A detailed energy mapping of the complete process streams is required to determine the optimal integration level. For simplicity and ease of scalability, the analysis assumes a constant heat capacity flow rate for both sensible and latent heat processes, which oversimplifies the solution, since the industrial process involves multiple streams with different heat capacities.

5 CONCLUSIONS

This study focused on a numerical evaluation of heat pump COP, energy savings, and emission reduction for a HTHP integrated within the four distinct industrial cases. The following conclusions were drawn from the suggested heat pump integration concepts:

- Spray Drying Process: With the HTHP integrated within the spray drying process COP of ≈ 2.5, with energy savings of 70 % and an 84 % reduction in emissions can be achieved.

- Shrimp Cooking Process: In shrimp cooking process the potential maximum COP reaches ≈ 6, alongside energy savings of up to 85% and an 87% decrease in emissions.

- Sugar Production Process: The integration reaches a COP of ≈ 6.5, with energy savings and emission reductions reaching 86 % and 88 %, respectively.

- Pulp & Paper Drying Process: HTHP integration can achieve a COP of up to ≈ 2.4, with energy savings of 65 % and a 79 % reduction in emissions.

Thus, the study shows the electrification potential of heat pump integration and the corresponding efficiency improvements and environmental benefits over the Convectional based heating systems.

NOMENCLATURE

COP	Coefficient of performance (-)
$COP_{Loerenz}$	Lorenz COP (-)
$\dot{C}$	Heat capacity rate (kW/K)
HTHP	High-temperature heat pump
HP	Heat pump
NG	Natural gas
$\dot{Q}_{sink}$	Heat flow of heat sink (kW)
$\dot{Q}_{source}$	Heat flow of heat source (kW)
$T_{so, in}$	source inlet temperature (K)
$\dot{W}_{HP}$	Heat pump power consumption (kW)
$\dot{W}_{Boiler}$	Boiler power consumption (kW)

Greek symbols

ΔT_{lift}	Temperature lift (K)
η_{Lorenz}	Lorenz efficiency (-)
η_{Boiler}	Boiler efficiency (-)
ΔT_{si}	Sink temperature glide (K)
ΔT_{so}	Source temperature glide (K)

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