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Investigation on heat recovery strategies from low temperature food processing plants: Energy analysis and system comparison

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ABSTRACT

Industrial food processing plants often have significant thermal requirements at both low and high temperatures. These plants can produce a variety of products including frozen, chilled and grilled/steamed foodstuff, creating thermal demands at several temperature levels. Rapid freezing of the foodstuff at temperatures below -40 °C is required to preserve a high-quality product while steaming/grilling of foodstuff require heat above 100 °C. Heat recovery from the low-temperature refrigeration system provides an interesting opportunity to reduce the overall energy consumption of the plant. This paper presents different strategies to achieve heat recovery from a CO_2/NH_3 cascade refrigeration system. The low stage of the cascade features pump-circulated CO_2 circuits at -40 °C and -5 °C evaporation levels, while the high temperature stage consists of an ammonia circuit. For this investigation, a case is defined based on requirements for temperature level and heat quantity from the industry. Subsequently, different strategies for the integration and control of the energy systems are examined. Finally, the strategies are compared with selected key parameters and the results are presented.

Keywords: Industrial refrigeration, High temperature heat pumps, Heat recovery, Carbon Dioxide, Ammonia

1. INTRODUCTION

For the last decades, increased activities in the industrial sector have contributed to a significant growth in the global economy. The consequences of the higher activity in this sector are increasing demands of electricity and thermal energy, resulting in higher CO_2 emissions. Energy efficiency will play a crucial role in achieving the two-degree scenario consistent with the Paris Agreement, accounting for 44% of the required reduction in CO_2 emissions (International Energy Agency, 2018). The European industrial sector consumes about 3200 TWh of energy annually, and an estimation show that around 300 TWh is waste heat that can potentially be recovered, of which one third is below 200 °C (Papapetrou et al., 2018). Waste heat recovery can be utilised to reduce the primary energy use in industrial processes by using the thermal energy for processes with lower temperature requirement or by upgrading the recovered heat by means of high temperature heat pumps.

The topic of increasing system efficiency and environmentally friendly industrial processes through the integration of heat pump systems in continuous and non-continuous processes is gaining increasing interest (Wallerand et al. 2018; Stampfli et al. 2019; Schlosser et. al, 2019). There are two trends within the research and industry activities that can be observed. One is to keep both the operation boundaries of the specific process and used equipment constant and rather change the refrigerant used. This includes the development of new types of refrigerants as seen in the past from hydrofluorocarbons (HFCs) to new hydrofluoro-olefins (HFOs). The second approach is to adjust and modify the required equipment as for instance compressors used to make it capable of handling well-known natural refrigerants such as CO_2, NH_3, or hydrocarbons.

The new approach presented in this study is the modification through further integration of the investigated processes to be able to use high temperature heat pumps and thermal storage tanks. The aim of this study is to present possible steps of process integration to increase the utilization of heat pump systems. The integration results in increasing use of available waste heat and reduction of greenhouse gas (GHG) emissions applicable in various industrial applications with vary demand profiles. Current studies often investigate the system performance for a given system with different refrigerants within fixed boundary conditions (Mateu-Royo et al., 2021) or the adjustment of the boundary conditions to optimize the operation of the specific heat pump system (Bergamini et al., 2019). This study aims to investigate both of these strategies, as presented by Kvalsvik and Bantle (2018).

2. METHOD

The methodology is developed to achieve the aim of a step wise increasing system integration with focus on the impact on the system performance in terms of energy consumption (utilization of waste heat) and environmental influence (GHG emissions). In a first step, existing processes were evaluated for the identification of requirements, which were then be used to develop demand cases. Applicable "solution blocks" were defined based on market ready system solutions and the COP for the different temperature ranges determined. Different scenarios for the investigation were developed by further combination of these "solution blocks" to increasingly integrated energy systems. Finally, based on the defined demand cases performance parameters were determined for the developed scenarios and subsequently evaluated and compared against each other.

2.1. Identification of requirements

Many industrial food-processing plants involve a variety of different processes with specific requirements. Refrigeration demands include processes for freezing, chilling and air conditioning at varying temperature levels. Heating demand appears for building heat as well as a variety of cleaning and cooking processes. Currently, the cooling and heating processes are often supplied separately. For the cooling processes and air conditioning, refrigeration systems are employed with condensers/dry coolers for heat dissipation to the ambient. Depending on the temperature level and availability, several options such as district heating, electric boilers or fossil fuel boilers using oil or natural gas are used for the heating processes. The different requirements can tend to occur unsteadily and at varying intervals, making individual supply and/or the use of thermal storage tanks necessary to compensate for peaks and fluctuations in demand and supply.

2.2. Demand cases

It is important to identify demand cases to discuss the effects on the required energy system design. Based on the identified requirements of industrial food-processing plants, several cooling and heating processes at specific temperature levels with different demand cases were defined, as shown in Table 1. For the definition of the demand cases, exemplary load values for the occurring processes were determined and varied. The load values for cooling and building heat remained unchanged. The values for the cleaning and cooking processes are divided equally and the total value varies relatively for the examined cases from 50 %, 100 % to 200 % to the combined demand for chilling (-5°C) and freezing (-40°C) processes. Temporal fluctuations in demand are not considered for simplification.

Table 1. Overview of defined processes at specific temperature levels with different demand cases

Process	Temperature Level	Demand Type	Case (50 %) [kW]	Case (100 %) [kW]	Case (200 %) [kW]
Cooking	110 °C to 120 °C	Heating	2025	4050	8100
Cleaning	80 °C to 95 °C	Heating	2025	4050	8100
Building heat	40 °C to 60 °C	Heating		500	
Air conditioning	5 °C to 20 °C	Cooling		2500	
Chilling	-5 °C	Cooling		6500	
Freezing	-40 °C	Cooling		1600	

2.3. Market ready system solutions

CO_2 is recognized among the most energy-efficient solutions for refrigeration purposes in Nordic countries and widely used and available today. NH_3 has been a popular working fluid for both large heat pumps and industrial refrigeration systems due to excellent heat transfer properties and high volumetric refrigeration

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capacity (Stene, 2008), reducing the required compressor swept volume. However, for evaporation temperatures below -34 °C the vapor pressure of NH_3 is below the atmospheric pressure. Consequently, NH_3 cannot be used in the low stage of the cycle without risking entrainment of air into the refrigeration system.

In rapid freezing processes for food, the evaporation temperature of the refrigerant normally lies in the range from -30 °C to -50 °C. These plants have a large temperature difference between the evaporator and the condenser that rejects heat to the ambient. To achieve higher system efficiencies, this is in most practical cases solved by compressing the refrigerant vapor in multiple stages or by employing a cascade configuration. CO_2/NH_3 cascade refrigeration systems have been studied intensively in the past. Both theoretical and experimental studies demonstrate similar performance to HFC-based cycles, in addition to avoiding the use of high global warming potential (GWP) refrigerants. For low evaporating temperatures in the range from -35 °C to -50 °C, the CO_2/NH_3 cascade demonstrates comparable performance to a R404A two-stage cycle (Messineo, 2012). For freezing applications CO_2 is a good option for the bottom cycle in the cascade, and experiments using CO2 in the low temperature stage show a COP improvement of maximum 19.5% over a two-stage NH_3 system when the evaporating temperature are in the range of -40 °C to -50 °C (Dopazo and Fernández-Seara, 2011). Regarding the high temperature circuit of the cascade, NH_3 demonstrates higher COP with moderate superheat and subcooling compared to R404A using CO_2 as the low-temperature circuit in the cascade (Getu and Bansal, 2008).

In addition, NH_3 can be used for the temperature ranges for air conditioning and building heat. Furthermore, high-temperature heat pumps using natural refrigerants can be used to supply the cleaning and cooking processes at higher temperature levels. Ahrens et al. (2021) have demonstrated that it is possible by using hybrid absorption-compression heat pumps and a mixture of NH_3 and H_2O as working fluid.

2.4. Evaluated scenarios

To investigate and compare the system performance of the different configurations, several scenarios have been defined, shown in Figure 1. The scenarios represent the different system configurations from the most basic thermal energy system design (Fig. 1a) to the most advanced, integrated system design (Fig. 1d). All scenarios must satisfy the thermal demands at the specific temperature levels given in Table 1. The CO_2/NH_3 cascade refrigeration system to satisfy the freezing and cooling demands in the food-processing plant is included in all scenarios. The following describes the functions included for the reference scenario up to the full integrated system. For each scenario, new functions are integrated into the main thermal energy system.

The reference scenario, **Scenario 1**, is the most basic approach to satisfy the thermal demands in the food-processing plant, shown in Figure 1a. In this configuration, the different thermal demands are satisfied by separate systems or equipment. The freezing and cooling demands in the plant are satisfied by the CO_2/NH_3 cascade refrigeration system, rejecting the condensing heat to the ambient. A separate chiller takes care of the demand for air conditioning. The condensing heat from the chiller unit is also rejected to the ambient. The thermal demands on the hot side are satisfied exclusively by electric boilers or gas boilers, regardless of temperature level. Each temperature level is equipped with a hot water thermal storage tank.

Scenario 2 represents the first stage towards an integrated system design, shown in Figure 1b. In this configuration, the air conditioning system is included into the cascade refrigeration system by including an additional evaporation level at the ammonia stage of the cascade and condensing heat is utilized for building heat purposes. The condensing heat is rejected to a 20/40 °C water tank connected through a NH_3 heat pump to the building heating system and is stored in an integrated water tank. The condensing temperature of the cascade refrigeration system must be increased to satisfy the temperature requirement of this demand. However, available waste heat is internally recovered and the use of boilers for this purpose is avoided. If there is no need for building heat, excess heat is rejected to the ambient instead.

The system configuration of **Scenario 3** is shown in Figure 1c. In addition to the features described in Scenario 1 and 2, a hybrid absorption-compression heat pump is added to satisfy the thermal demands at the temperature level ranging from 80 °C to 95 °C. The heat source for the heat pump is the integrated water tank of the building heat process at this temperature level. The relatively high source temperature for the heat pump enables production of hot water up to 95 °C with moderate pressure ratio. The highest temperature level for cooking processes is still covered by electric or gas boilers.

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The final step towards a fully integrated energy system for the investigated plant involves satisfying the highest temperature level by delivering heat up to 120 °C through a high temperature heat pump solution. The system configuration of **Scenario 4** is shown in Figure 1d. The heat source for the high temperature heat pump is the integrated water tank for the cleaning process. In the fully integrated configuration, all heat demands are supplied by heat pumps through internal heat recovery from the cooling processes.

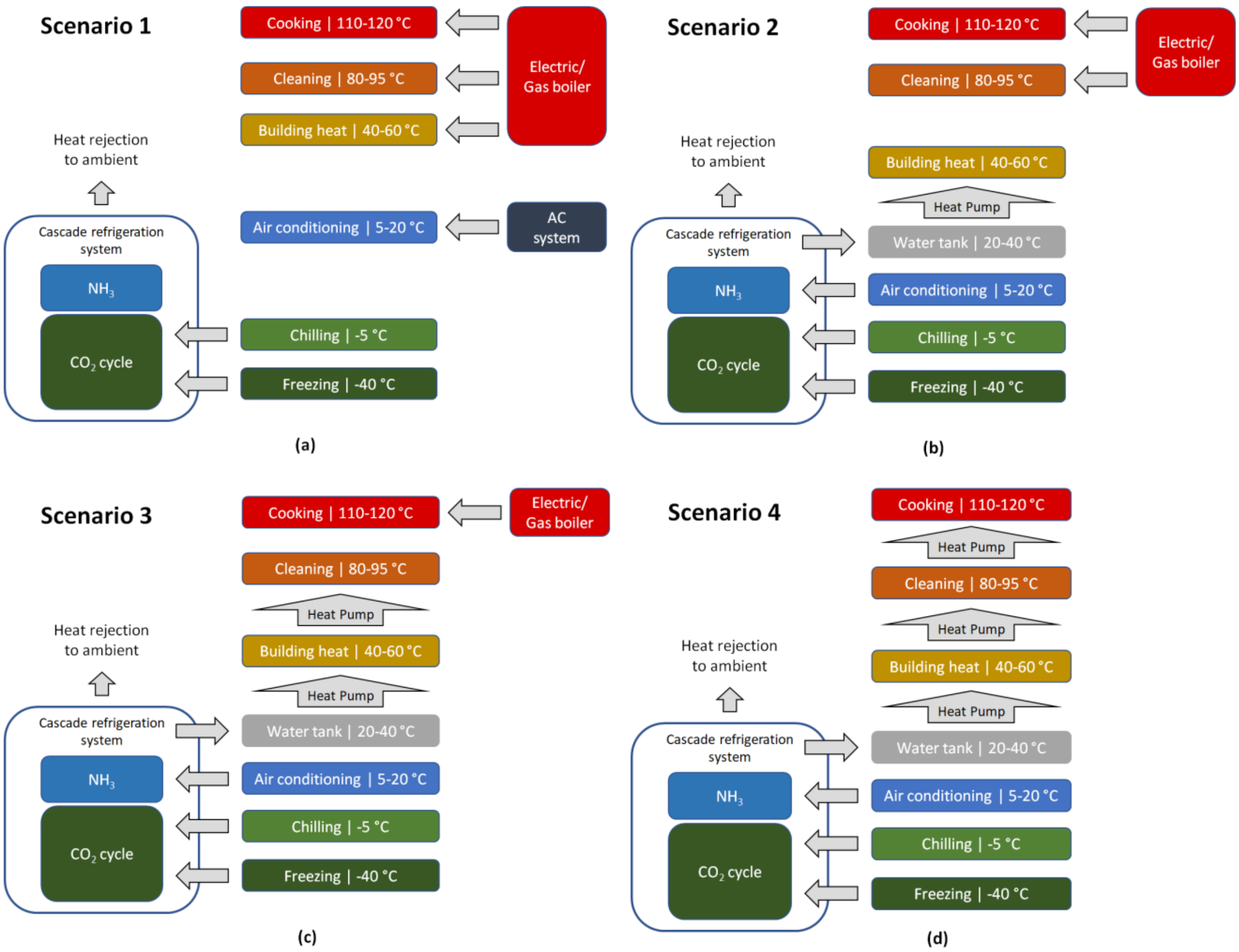

Figure 1. Simplified representation of the evaluated scenarios with increasing system integration from (a) to (d)

2.5. Scenario simulation

Solution blocks were developed for the defined processes and scenarios based on the identified requirements and market ready system solutions. Cooling and heating COPs for each "solution block" at the specific temperature levels were determined by using the CoolPack software (Version 1.48, TOOL C.10). Here, single-stage circuits with a fixed isentropic efficiency of 0.7 for the compressor were applied. For further simplification, occurring pressure and temperature losses were neglected and all temperature levels were defined as constant. The source temperature was set to the lowest temperature of the heat source and a minimum difference of 7 K to the maximum heat sink temperature was applied for the condensation temperature except for the freezing system in the cascade refrigeration system. For the chilling and air conditioning systems, there are two options regarding the sink temperature depending on the selected operation. For heat rejection through the chillers to the ambient, a temperature of 20 °C was specified. When used internally for waste heat recovery through the heat pumps, heat was released at 40 °C to a thermal storage tank.

For the calculation of the power consumption, the defined loads and determined COPs were used. For the discharged heat on the sink side, 90 % of the power supplied via the compressor was added to the consumed heat on the source side. Thus, the cooling load of the chilling stage for the cascade refrigeration system is increased by the heat output of the freezing stage. Likewise with the integrated heat pumps for the heating

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processes, where the heating load of the low stage is increased by the input demand of the higher stages. When using electric or gas boilers, a thermal efficiency of 100 % is assumed, thus the power consumption corresponds to the heat demand.

Figure 2 provides an overview of the parameters used in the calculation of the scenarios with exemplary values for Scenario 4 and demand case (200 %). In the calculation of the scenarios, the cooling loads are divided in such a way that the internally usable waste heat provided by the cooling processes satisfies the demand for the recovered waste heat through the heat pumps (values in red).

Cooling processes with heat rejection to 20 °C ambient

Freezing (CO_2) -40 °C		Chilling (NH_3) -12 to -5 °C		Air conditioning (NH_3) | 5 to 20 °C	
Source temperature	-40.0 °C	Source temperature	-12.0 °C	Source temperature	5.0 °C
Sink temperature	-5.0 °C	Sink temperature	27.0 °C	Sink temperature	27.0 °C
Cooling COP	3.5 -	Cooling COP	3.9 -	Cooling COP	7.6 -
Cooling load	**1600 kW**	**Cooling load**	**4401 kW**	**Cooling load**	**0 kW**
Power consumption	457 kW	Power consumption	1129 kW	Power consumption	0 kW
Heat output	2011 kW	Heat output	5417 kW	Heat output	0 kW

Cooling processes with heat rejection for heat recovery to the 20 to 40 °C thermal storage tank

Freezing (CO_2) -40 °C		Chilling (NH_3) | -12 to -5 °C		Air conditioning (NH_3) | 5 to 20 °C	
Source temperature	-40.0 °C	Source temperature	-12.0 °C	Source temperature	5.0 °C
Sink temperature	-5.0 °C	Sink temperature	47.0 °C	Sink temperature	47.0 °C
Cooling COP	3.5 -	Cooling COP	2.4 -	Cooling COP	3.7 -
Cooling load	**0 kW**	**Cooling load**	**4110 kW**	**Cooling load**	**2500 kW**
Power consumption	0 kW	Power consumption	1713 kW	Power consumption	676 kW
Heat output	0 kW	Useable waste heat	5651 kW	Useable waste heat	3108 kW

Heating processes with heat extraction from the 20 to 40 °C thermal storage tank

Building heat (NH_3) | 40 to 60 °C		Cleaning (NH_3-H_2O) | 80 to 95 °C		Cooking (NH_3-H_2O) | 110 to 120 °C	
Source temperature	20.0 °C	Source temperature	40.0 °C	Source temperature	80.0 °C
Sink temperature	67.0 °C	Sink temperature	102.0 °C	Sink temperature	127.0 °C
Heating COP	4.3 -	Heating COP	3.4 -	Heating COP	4.0 -
Heating load	**11072 kW**	**Heating load**	**14378 kW**	**Heating load**	**8100 kW**
Power consumption	2575 kW	Power consumption	4229 kW	Power consumption	2025 kW
Recovered waste heat	8754 kW	Recovered heat	10572 kW	Recovered heat	6278 kW

Figure 2. Overview of parameters used for the simulations with values for Scenario 4 and demand case (200%)

The determined values for the investigated scenarios and different demand cases are then evaluated for the energy analysis and the comparison of the system performance. To provide an environmental perspective of the benefits of the integrated energy systems, the CO_2 equivalent values for supplying the demands are determined to enable a comparison in terms of released GHG emissions. For this, three cases are examined: 1. Site in Norway (NO) only using electricity with 50 g $CO_{2,eq.}$ kWh^{-1} based on range given by (Clauß et al., 2019); 2. Site in NO using electricity and natural gas boilers with 205 g $CO_{2,eq.}$ kWh^{-1} (Scoccia et al., 2018) and 3. Site in the European Union (EU) using natural gas boilers and electricity with 295.8 g $CO_{2,eq.}$ kWh^{-1} (European Environment Agency, 2018). For comparison, the GHG emissions for a one-hour period are exemplary calculated.

3. RESULTS

The energy analysis and system performance evaluation for the different energy systems are performed and evaluated based on the determined performance parameters such as power consumption and achieved COP values for the investigated scenarios with different demand cases. To compare the systems in terms of environmental sustainability, the determined GHG emissions are evaluated. Figure 3 presents a summary of the results obtained for the investigated scenarios and different demand cases.

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The most important parameters of the four scenarios are presented collectively for each of the demand cases. As described before, the cooling loads remain identical for all demand cases and the total demand changes due to the varied heat loads. Occurring change from Scenario 1 to 4 are identical in trend for all demand cases although the magnitude of the change differs between the scenarios and demand cases. For the cooling processes, the growing system integration leads to an increasing waste heat recovery load. At the same time, the power consumption also increases due to the increased temperature sink of the NH_3 system to enable heat recovery, resulting in decreasing cooling COPs for identical cooling loads. With increasing system integration, the heating load provided by the heat pumps increases for constant heating demand. On the other hand, the power consumption decreases continuously, resulting in a significant increase in the obtained heating COPs. Overall, the total power consumption decreases, and the system COP improves with increasing system integration. This illustrates that the changes in the heating processes have a greater influence on the overall performance parameters than the changes in the cooling COP. For all cases investigated, GHG emissions decrease with increasing system integration and waste heat recovery because less primary energy (electricity and gas) is required by the plant. The lowest GHG values are achieved by the fully electric plant in NO while the highest GHG values are obtained by using electricity and gas boilers in the EU.

Demand case (50%) | Cooling load of 12611 kW_{th} and total demand of 15150 kW_{th}											
	Recovered waste heat [kW_{th}]	Cooling Power [kW_{el}]	Cooling COP [-]	Heating load [kW_{th}]	Heating Power [kW_{el}]	Heating COP [-]	Total Power [kW_{el}]	Total COP [-]	$NO_{,el}$ [kg $CO_{2\,eq.}$ h^{-1}]	$NO_{,el}$ + Gas [kg $CO_{2\,eq.}$ h^{-1}]	$EU_{,el}$ + Gas [kg $CO_{2\,eq.}$ h^{-1}]
Scenario 1	0	2969	4.25	4550	4550	1.00	**7519**	**2.28**	376	1081	1811
Scenario 2	398	3013	4.19	4550	4166	1.09	**7179**	**2.39**	359	1005	1745
Scenario 3	1573	3144	4.01	6039	3083	1.96	**6227**	**3.00**	311	789	1562
Scenario 4	2486	3246	3.89	8762	2294	3.82	**5540**	**3.86**	277	633	1430
Demand case (100%) | Cooling load of 12611 kW_{th} and total demand of 19200 kW_{th}											
	Recovered waste heat [kW_{th}]	Cooling Power [kW_{el}]	Cooling COP [-]	Heating load [kW_{th}]	Heating Power [kW_{el}]	Heating COP [-]	Total Power [kW_{el}]	Total COP [-]	$NO_{,el}$ [kg $CO_{2\,eq.}$ h^{-1}]	$NO_{,el}$ + Gas [kg $CO_{2\,eq.}$ h^{-1}]	$EU_{,el}$ + Gas [kg $CO_{2\,eq.}$ h^{-1}]
Scenario 1	0	2969	4.25	8600	8600	1.00	**11569**	**1.83**	578	1911	2641
Scenario 2	398	3013	4.19	8600	8216	1.05	**11229**	**1.89**	561	1835	2576
Scenario 3	2754	3276	3.85	11578	6050	1.91	**9326**	**2.59**	466	1404	2209
Scenario 4	4579	3487	3.62	17025	4472	3.81	**7959**	**3.72**	398	1091	1948
Demand case (200%) | Cooling load of 12611 kW_{th} and total demand of 27300 kW_{th}											
	Recovered waste heat [kW_{th}]	Cooling Power [kW_{el}]	Cooling COP [-]	Heating load [kW_{th}]	Heating Power [kW_{el}]	Heating COP [-]	Total Power [kW_{el}]	Total COP [-]	$NO_{,el}$ [kg $CO_{2\,eq.}$ h^{-1}]	$NO_{,el}$ + Gas [kg $CO_{2\,eq.}$ h^{-1}]	$EU_{,el}$ + Gas [kg $CO_{2\,eq.}$ h^{-1}]
Scenario 1	0	2969	4.25	16700	16700	1.00	**19669**	**1.49**	983	3572	4302
Scenario 2	398	3013	4.19	16700	16316	1.02	**19329**	**1.52**	966	3495	4236
Scenario 3	5109	3548	3.55	22656	11984	1.89	**15532**	**2.27**	777	2634	3506
Scenario 4	8759	3974	3.17	33549	8828	3.80	**12802**	**3.61**	640	2009	2985

Figure 3. Summarized results for the investigated scenarios with the different demand cases

An important factor in improving system performance and reducing GHG emissions is internal waste heat recovery. This can reduce the overall power consumption of electricity or fossil fuels required in the plant. The achieved heat recovery rate describes the ratio of recovered waste heat to the total available waste heat from the cooling processes. For the investigated scenarios and demand cases, the heat recovery rate vary from 0.0 % for Scenario 1 (S1) to 3.0 % for Scenario 2 (S2) to 11.7 % for Scenario 3 (S3) to 18.4 % for Scenario 4 (S4) for the demand case 50 %, from 0.0 % (S1) to 3.0 % (S2) to 20.3 % (S3) to 33.3 % (S4) for the demand case 100 % and from 0.0 % (S1) to 3.0 % (S2) to 37.0 % (S3) to 61.8 % (S4) for the demand case 200 %. For the demand cases investigated, it was thus possible to utilise the recovered waste heat further in the process for all scenarios and demand cases.

A deeper analysis of the results for the increasing system integration is presented in Figure 3, Figures 4 to 6 demonstrate the relative changes for the electrical power consumption, achieved COPs and GHG emissions for the investigated scenarios and demand cases. Here, the achieved values for S1 of each demand case are

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taken as a reference and the results of the remaining scenarios (S2 to S4) are presented as relative changes to the reference value.

The cooling power consumption increases starting from S1 for all scenarios. For S2, there is only a slight increase, and it remains constant for all demand cases. With increasing system integration for S3 and S4, the values increase more strongly. For the higher heat demand cases, the increase continues. These observations are caused by a larger share of the waste heat is recovered from the refrigeration system rather than rejected to the ambient at lower temperatures for increasing system integration and higher heating demands. The heating power consumption is decreased in comparison to S1 for all other scenarios. There is a small reduction for S2, whereby the reduction decreases as the heating demand increases due to the higher heating load. More significant changes are achieved for S3 and S4 with around 30 % and 50 % reduction compared to S1, respectively. These values are relatively constant and increase only slightly with increasing heat demand. For the total power consumption, likewise a reduction is achieved with increasing system integration. Here, the biggest changes are achieved from S2 to S3. For the increasing demand cases, the reduction for S3 and S4 increases further.

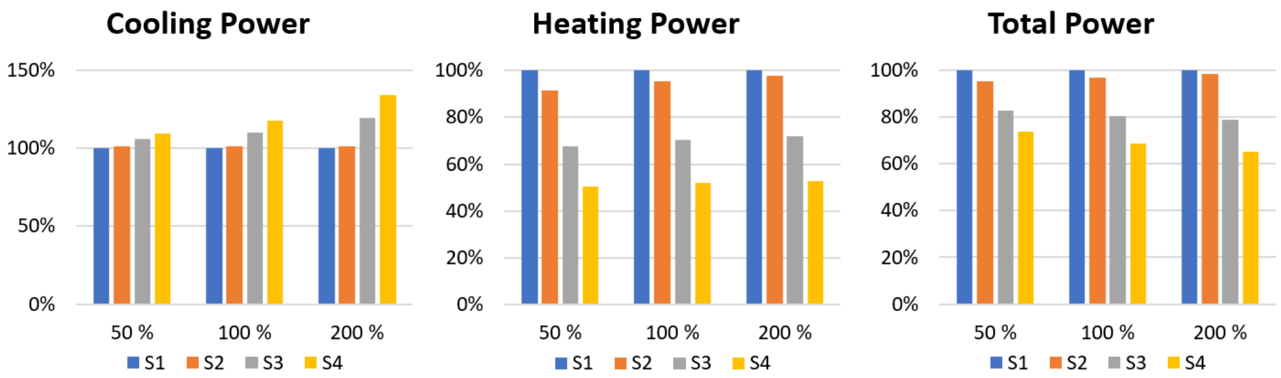

Figure 4. Relative change in cooling, heating and total power consumption (electrical) for the investigated scenarios and demand cases

The relative changes for the determined COPs behave inversely to the power consumption. Especially noticeable are the changes for S4, which change significantly in relation to S1, as well as for the cooling and total COP with increasing demand case.

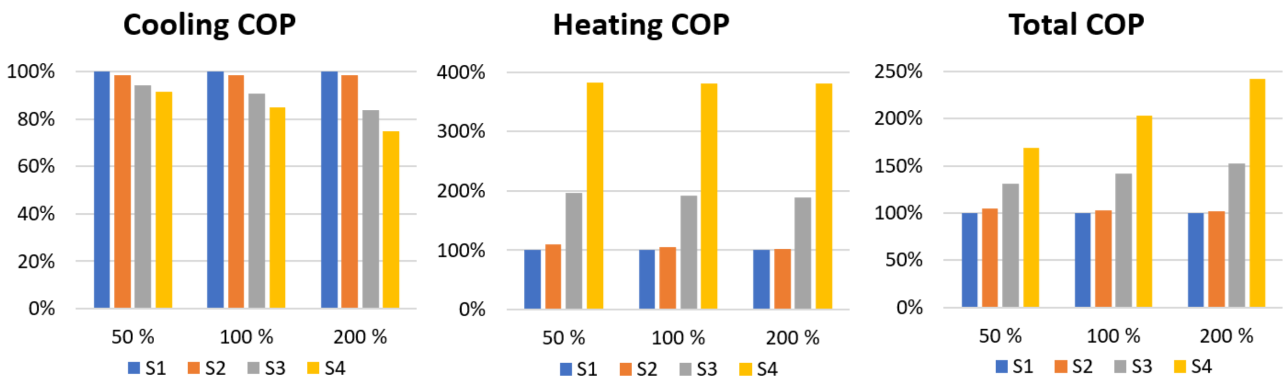

Figure 5. Relative change in cooling, heating and total COP for the investigated scenarios and demand cases

In terms of GHG emissions, a reduction is obtained with increasing system integration and waste heat recovery for all sites and scenarios. The greatest reductions of up to 45% less GHG emissions can be achieved for sites in NO using electricity and gas boilers. However, the potential GHG emission savings for S3 and S4 are considerable for all cases.

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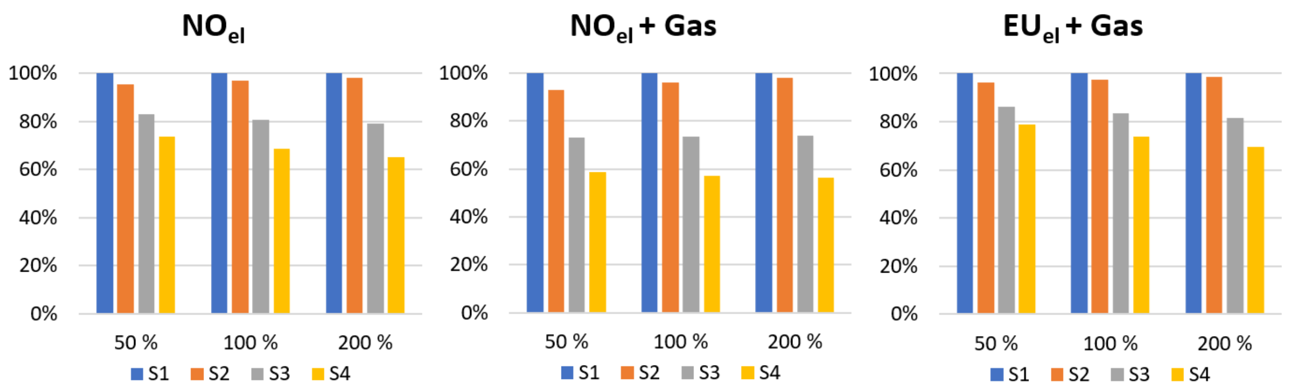

Figure 6. Relative reduction in GHG emissions for the investigated sites for all scenarios and demand cases

4. DISCUSSION

An extensive investigation of the developed scenarios for the different demand cases was carried out. The achieved performance parameters of the energy system are used to evaluate and compare the heat recovery strategies of the investigated food processing plant. The results have shown that the increased application of heat pumps combined with the recovery of available waste heat can lead to a significant increase in system efficiency. Despite the increased power consumption of the cooling processes due to the raised condensation temperature, the overall electrical power consumption and GHG emissions are reduced. Thereby, the integrated system is more efficient when compared to the use of electric or gas heaters, regardless of the increased heat load due to the internal heat lift. Here, even minimal integration and waste heat recovery as in Scenario 2 resulted in GHG emission reduction of up to 7.1 %, although the COP was not considerably improved. Overall, the difference in the CO_2 equivalent values of the energy sources used is decisive for the saving of GHG emissions. With a growing share of renewable energy sources in the electricity mix, GHG emissions could be further reduced in the future and the utilisation of high temperature heat pumps to supply the thermal demands is favourable.

During the investigation of the scenarios, the influence of the cooling to heating load ratio was examined. For this purpose, the cooling load was kept constant while the required thermal heating load was varied. The results indicated that a complete integration with the coverage of the heat demand by waste heat recovery is appropriate for both proportionally smaller and larger heating loads. In fact, the usability of the supplied power via the compressors even enables the supply of larger heating loads. Therefore, the heating load was covered by waste heat recovery for all demand cases investigated. The recovery rate of available waste heat from the cooling processes ranged from 0 % in the reference scenario up to a maximum of 61.8 %. In the case of a low recovery rate due to a lack of heating demand, the connection with other consumers such as a district heating network or other nearby consumers might be a suitable approach to increase the system efficiency and capacity utilization. For further evaluation of the scenarios, the investigation of demand cases with insufficient amounts of waste heat from the cooling processes would be of interest. In this case, suitable heat sources for supplying the heat loads must be identified and utilized.

Differences and fluctuations in the thermal demands can occur depending on the operation time (time of day, day of the week, season) as well as process control and workload. Fluctuations and/or time-shifted occurring demands are manageable through the utilization of thermal energy storage tanks. The use of efficient thermal energy storage tanks can enable decoupling of the supply and demand between the temperature stages and are also important in the case of uneven distribution of demands. In the conducted calculations, the demand for the building heat was assumed to be constant and the heating load for cleaning and cooking was equally divided. Therefore, the investigation of uneven demand distributions between process stages is recommended for further exploration. The required loads and total COPs are expected to change due to the uneven distribution of heating demands between the process stages. However, the performance parameters are still expected to improve compared to the reference scenario. If process stages are omitted entirely, system modifications with higher temperature lifts for each heat pump stage can be implemented.

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For the current study and in the calculation of the applied COPs, only solutions with natural refrigerants currently available on the market were considered. Further improvement of the achievable sink temperatures and attainable system efficiencies are the subject of many ongoing research activities. For this reason, it can be assumed that the application range for high temperature heat pumps using natural refrigerants will be available in the future for higher temperature levels of up to 150 °C or more. It is therefore appropriate for further studies to include higher temperature levels and investigate the effects on the system performance. In addition, by considering losses during heat exchange and storage, more detailed investigations can be carried out in relation to the applied heat pump solutions and demand cases. Nevertheless, the conducted study and demonstrated methodology can help to sensitize potential end-users and operators to the benefits of using waste heat recovery through the integration of heat pumps and thermal energy storage tanks for various industrial applications such as the food processing industry.

5. CONCLUSIONS

The objective of this study is to analyse and evaluate different strategies for low-temperature waste heat recovery from a CO_2/NH_3 cascade refrigeration system on the example of food processing plants with the aim to demonstrate the potential of integrated heat pump systems and to raise the awareness of potential users and operators for this issue. Within the scope of the investigation, an energy analysis with system comparison was carried out based on selected performance parameters. For this purpose, the energy supply system for serving all the defined demands was further interconnected by integrating heat pumps and thermal energy storage tanks, so that the available waste heat from the cooling processes can be recovered to supply the heating demands. A methodology for calculating the defined scenarios with different demand cases based on available heat pump solutions using only natural refrigerants was developed. The increasing system integration led to heat recovery rates of the available waste heat from the cooling processes of up to 61.8 % throughout the investigated scenarios and demand cases. As a result of the increasing system integration and heat recovery rates for all demand cases, improvements were achieved for all investigated performance parameters, such as total power consumption, total system COP and GHG emissions. The results indicated that the integration of heat pumps, even with comparatively low CO_2 equivalent values of the employed energy sources, such as electricity in Norway, can lead to potential reductions in GHG emissions of up to 35 %. Considering the growing share of renewable energy sources in the electricity mix of many countries, the recovery of available waste heat through heat pumps provides great potential for reducing GHG emissions and energy savings. The conducted study can serve as a basis for further work. In this context, a detailed investigation of the requirements based on fluctuating demands and the consideration of losses can be of interest. To increase the confidence of the results, the modification of the system design with increased temperature levels and a more detailed calculation of the employed heat pump systems can be of interest.

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