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Generating hot water for food processing plant using waste heat, high temperature heat pump and storage

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ABSTRACT

This paper presents a novel concept to supply hot water to a food processing plant by upgrading surplus heat from a refrigeration system by means of a high temperature heat pump (delivering heat above 100°C). The system utilizes thermal storage and district heat as backup, replacing the currently used electric boilers. Savings for six different system solutions are presented, aiming to find the most sustainable and efficient solution. The savings for the best practice solution were about 41-49% of CO_2-emissions, 39-51% of electricity and 29-57% of district heat.

Keywords: High temperature heat pump, integrated system, combined heating and cooling, thermal storage

1. INTRODUCTION

The amount of surplus heat and heat demand in Europe are approximately equal (Persson, Möller et al. 2014) and corresponded to 25.3% of total energy use in EU in 2015 (Eurostat 2017) and 29.7% of electricity consumption in Norway in October 2017 (SSB 2017)). Many processes have large amounts of surplus heat, yet it cannot be utilized directly as the temperature is too low (Wolf, Fahll et al. 2014). Industrial heat often requires temperature above 100°C, which until a few years ago (about a decade) could not be obtained by the available heat pumps, at least not with acceptable CAPEX for the industry. Many recent studies have aimed to develop high temperature heat pumps, and these are now able to upgrade heat up to 180°C (Valmot 2015, Adler and Mauthner 2017, Bamigbetan 2017, Bantle 2017).

Another challenge to reduce the wasted surplus heat is that heat demands and surplus heat does not always occur simultaneously, or in the right proportions to utilize all heat for heating, or to cover the entire demand. Several retail stores have recently been rebuilt to reduce energy demand by 10-50% by applying integrated systems, storages, ejectors and efficient refrigeration cycles (Hanne Kauko, Kvalsvik et al. 2016). The potential savings for other industry fields with heating and cooling demands in similar ranges is thus enormous, yet not usually applied. There are examples of integrated systems, sharing energy like in industry clusters (Mo Industripark 2017).

The present investigation evaluates a local industrial food processing plant. The aim is to optimize the specific energy consumption and reduce the emission of climate gas near zero by using natural refrigerants. The study investigates whether a hybrid (ammonia/water) or propane/butane cascade heat pump were the better choice for the integrated heat pump system with respect to energy efficiency and how the cooling and heating could be performed efficiently, yet safe and cost effectively. The system must be able to supply sufficient heat and cold also when the thermal storages are empty. The design of the heat pump and thermal storages, how to connect the components and supply heat at three temperature levels and cooling at two temperature levels were the main challenges of the investigation.

2. METHOD

Energy demand, peak power, production times and temperature requirements for the processes were given. The main demands are heating and cooling of the building, the process heat demand at (supply-return temperature) 102-85°C, 67-40°C and 40-20°C, and the cooling demands for the storage (to be kept at 4°C) and

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the processes (must be cooled by ice water at 0.5°C). The different hour-by-hour demands cannot be published for confidentiality reasons.

Due to the challenge that surplus heat is not always available when needed, the simultaneity of the demands had to be included to see how much of the heating demand the surplus heat could cover. To make a holistic estimation of how an energy system would perform, the following procedure was used:

1. Develop hourly demand profiles for buildings and processes, based on supplied data and measured ambient temperatures for the region from 01.02.16-31.01.17 (Yr, NRK et al. 2017)
2. Evaluate different heat pump design in order to pre-select suitable energy solutions and their performance at the relevant operational conditions
3. Compare, how various energy systems will operate given hourly demand for one production year based on ambient climate condition (one cannot simple divide the heat demand by the COP, as this presupposes that there is always sufficient waste heat available, which will not always be the case).
4. Determine total electricity, district heat (DH) use and corresponding costs and greenhouse gas (GHG) emissions for selected cases.

The reference case was included in the evaluation in order to compare the performance and was based on technology considered as industrial standard solution.

2.1 Market available system solution

All costs and savings should be compared to the standard, conventional alternative. This should be the best of available, cost effective, market available technology. As high temperature heat pumps (HTHPs) are not standard technology, a conventional solution involves that process heat demands would be covered by Nordic electricity mix (mostly renewable), lower heat demands by DH and the cooling demand covered by an indirect cooling system with superheat after evaporation, using glycol for distribution. This is based on information from the industry and an offer from a consultant firm. CO_2 is regarded to be the most energy efficient solution for cooling in Nordic countries today, and has also become a standard, commercial, available, conventional solution. Thus, a reference case with a CO_2 cooling system (evaporating at -9.3°C, 27.0 bar), rejecting heat to the ambient, and heating with electricity and DH was chosen as reference.

2.2 Market ready system solutions

Direct cooling with CO_2, no additional glycol or water loops, has become a standard cooling solution, reducing the need for heat exchangers compared to the conventional solution. Innovative features include:

- Direct heating with CO_2, avoiding extra temperature lift and achieving lower return temperature
- Thermal storage tanks for balancing demands and peak shaving.
- Investigate the use of CO_2 at higher pressure to also heat tap water and other demands at intermediate temperature directly.
- HTHP as top cycle, using either a butane/propane cascade or a two-stage hybrid heat pump to supply heat at the highest temperature levels (from 85 - 102°C), take out the desired amount of heat at the intermediate temperature level.

2.3 Evaluated cases

Based on the suggestions in section 2.2, it was decided to evaluate the following cases, shown in Figure 1:
Case 1: Reference case: CO_2 -HP cooling (-9.3°C), indirect cooling for all systems, DH for building heating and electrical heating of processes.
Case 2: Indirect cooling with CO_2 – HP (-10°C) and delivering heat directly, condensing at +20°C (superheat used for heating, the rest delivered to HTHP) and heating by a propane/butane cascade with COP=2.2.
Case 3: Direct cooling with CO_2 -HP (-1.5°C) and delivering heat directly, condensing at +20°C (superheat used for heating, the rest delivered to HTHP) and heating by a propane/butane cascade with COP=2.2.
Case 4: Direct cooling with CO_2 (-1.5°C) and delivering heat directly or indirectly, condensing at +27°C and heating by a propane/butane cascade with COP=2.2 (making the return temperature 20°C).
Case 5: Direct cooling with CO_2 (-1.5°C) and delivering heat directly at both the two lowest temperature levels, by having a cycle reaching 67°C after compression and heating by a propane/butane cascade with COP=2.2 (making the return temperature 20°C).
Case 6: Direct cooling with CO_2 (-1.5°C) and delivering heat directly or indirectly, condensing at +27°C and heating by a water/ammonia heat pump with COP=2.31 (making the return temperature 20°C).

Case 6 is equal to case 4, apart from the choice of HTHP. Cases 4, 5 and 6 allowed indirect heating which is preferred by the industry as this means water instead of high-pressure refrigerant in the heating system.

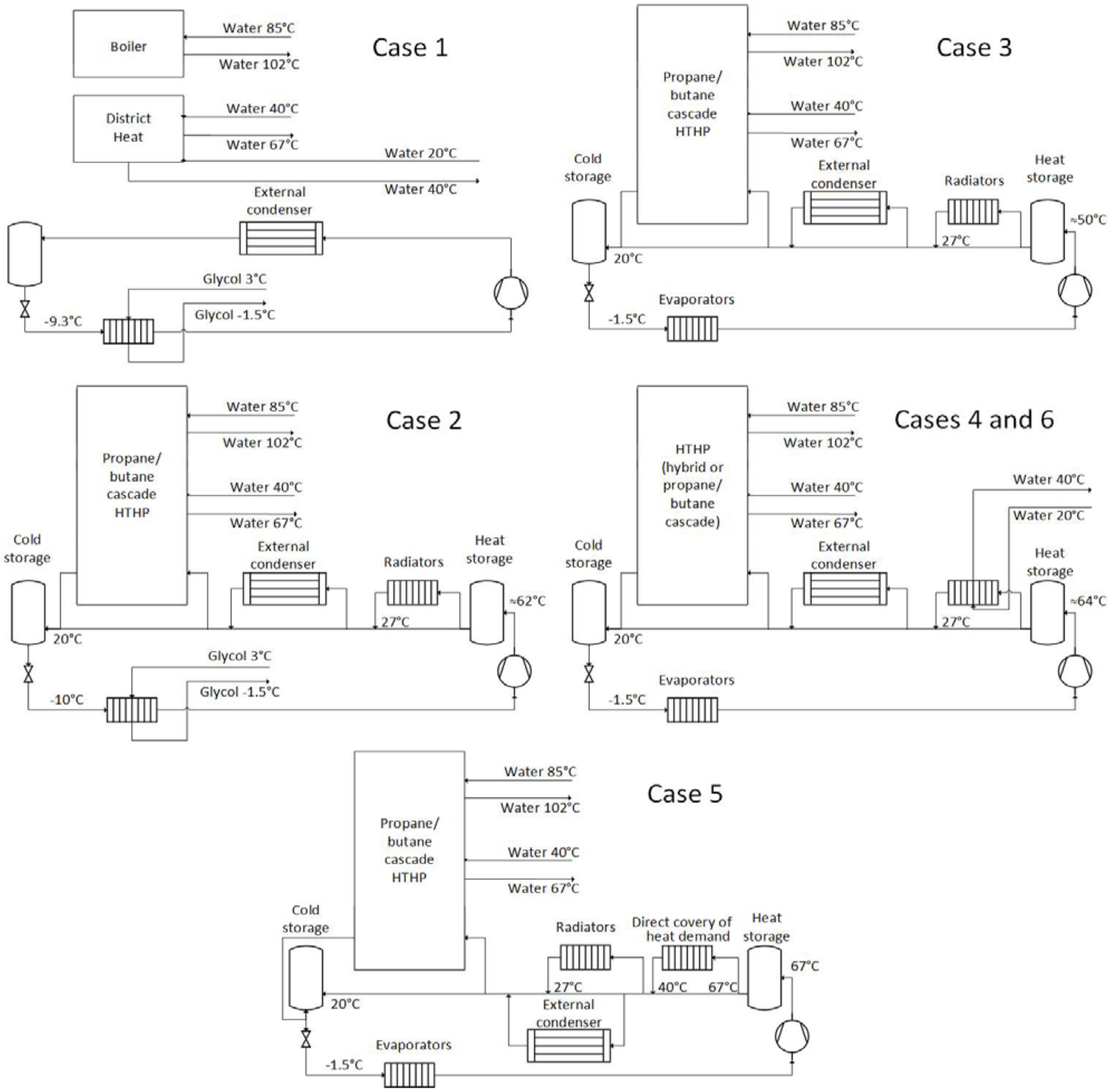

Figure 1: Overview over the system solutions for cases 1-6: Evaporators and radiators symbolize direct supply of cold/heat, whereas indirect heat flow is visualized by inclusion of a secondary fluid.

2.4 Demand profiles

Total demands (per day and year) as well as installed power and operational hours for most demands (food production processes, building, tap water and similar) were given. Using the installed power, operational hours and total daily demand, artificial demand profiles could be made for the food processing. These demands were distributed during the typical working hours of each day, apart from weekends. The demand profiles were also compared to those at an existing plant. Building demands were found from IDA ICE (EQUA 2010), based on the size and shape of the building and ambient conditions.

2.5 Case simulations

2.5.1 Reference case

Surplus heat in a conventional solution (case 1) would be rejected to the ambient, and the heating/cooling demand of the building would depend on the ambient temperature, thus the COP is not constant. To make the variation of COP with ambient temperature realistic, the reference refrigeration solution was modelled and simulated for one production year. For all other cases, the operational temperatures were constant. A model of a CO_2 heat pump was made in Dymola (Dynamic Modelling Laboratory 2015, see (Dassault Systemes 2002, Richter 2008, Gräber 2009)), and the cooling demands and ambient temperature read from an input file. Electrical heating was assumed to have 100 % efficiency in all cases, and was thus given directly from the demand profile.

2.5.2 Cases 2-6

For cases 2-6, the system temperature levels were fixed, and thus the COPs would be close to constant. The calculation of the yearly performance was based on:

1. Refprop (Reference fluid thermodynamic and transport properties database, see (Nist 2013)) to determine the COP at the respective temperature levels with the chosen fluids, assuming minimum temperature differences of 7 K. Dymola was used for simulation of a hybrid HTHP for case 6, as this is more advanced and thus more efficient for calculations on this complex type of heat pump.
2. Pressure losses were included as a constant value in all calculations, reducing all COPs by 8%.
3. Temperature levels for the refrigeration system can be constant in an integrated system. Required power for cooling was found by dividing the cooling demand on the cooling COP. The surplus heat was lifted to higher temper depending on the demand, and used at the next temperature level if required. If there was a need for heat at a higher level, the heat was lifted to this level by the HTHP. Otherwise, it was assumed rejected to the ambient.

Cases 2-6 still require external condensers to balance the excess heat of the system with the ambient. Other cases with hybrid HTHP were considered, but showed deficient performance.

3. RESULTS

The total need for electricity, district heat and corresponding costs (50 € MWh^{-1} for both electricity and DH) and GHG–emissions (110 kg CO_2-eq. MWh^{-1} for electricity (BKK 2017) and 20 for DH (Otterlei 2014)) were found for each case and compared. Results for all cases are shown in Table 1 through Table 3 and Figure 2.

Table 1: Results for the heating solutions, total heat demand was 2.88 GWh/year

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Solution at 20-40°C	DH	Condensation at 20°C		Condensation at 27°C	Condensation at 70 bar	Condensation at 27°C
Solution at 40-67°C	DH	Propane/butane				Hybrid
Solution at 85-102°C	El	Propane/butane				Hybrid
DH [GWh]	1.35	0.58	0.94	0.84	0.96	0.85
Electricity [GWh]	1.52	0.56	0.53	0.55	0.48	0.54
GHG emissions [tons CO_2-eq. yr^{-1}]	195	73	77	77	72	76

Table 2: Results for the refrigeration solution, the total cooling demand was 2.47 GWh/year

Case:	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
CO_2 evaporating temperature [°C]	-9.3	-10	-1.5			
Condensation condition	Varied with ambient	20°C	20°C	27°C	70 bar	27°C
Electricity [GWh yr^{-1}]	0.48	0.67	0.45	0.58	0.61	0.58
GHG emissions [tons CO_2-eq. yr^{-1}]	53	74	50	64	67	64

Table 3: Results for cooling and heating solutions together

Case:	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
CO_2 evaporating temperature [°C]	-9.3	-10	-1.5			
Heating at 20-40°C	DH	Condensation at 20°C		Condensation at 27°C	67-20°C	Condensation at 27°C
Heating above 40°C	El and DH	Propane/butane				Hybrid
District heat [GWh yr^{-1}]	1.35	0.58	0.94	0.84	0.96	0.85
Electricity [GWh yr^{-1}]	2.01	1.23	0.98	1.14	1.09	1.12
GHG-emissions [tons CO_2-eq. yr^{-1}]	248	147	126	141	140	140
Costs [k€ yr^{-1}]	168	90	96	99	103	98

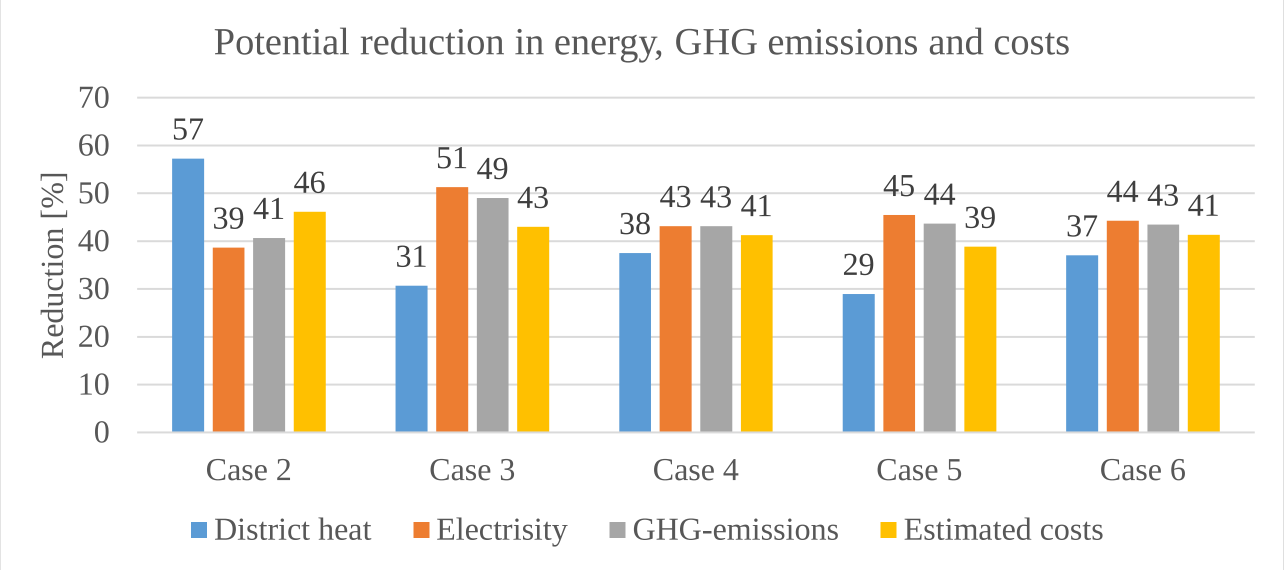

Figure 2: The relative reductions in demand for DH and electricity, and in GHG-emissions and costs for cases 2-6 compared to case 1 (reference case)

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4. DISCUSSION

All proposed solutions reduce the electricity demand by about 45 % (39-51%) and the DH demand by about 30% (29-57%). In terms of cost, the best solution is actually case 2, which involves indirect rather than direct cooling and condensation at 20°C. However, it also has the lowest savings of electricity. The larger cost savings presumably occur because the prices of electricity and DH were assumed to be equal, and due to a higher degree of superheat when compressing from a lower pressure level, less DH was required for this case, as seen in Figure 2. Quite often is DH a bit cheaper than electricity. However, performing a sensivity analysis of this value, see Table 4, case 2 is surprisingly competitive at price. First when the DH price is reduced to 35 € MWh^{-1} is it no longer the best solution, and the differences are always so small that no clear cost difference can be said to be found.

Table 4: Parametric analysis of how the yearly total running costs [$k€yr^{-1}$] for the different cases change with DH price

€ MWh^{-1} DH	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
50	168	90	96	99	103	98
45	161	88	91	94	98	94
40	154	85	86	90	93	90
35	148	82	82	86	88	86
30	141	79	77	82	84	81

From an environmental point of view, case 3 is the best solution as it has the lowest GHG emissions. It is also the best in terms of total amount of electricity required. This case included CO_2 evaporating at -1.5°C and condensing at 20°C and a propane/butane cascade HP. However, a critical question is whether the heat at the high-pressure side of the refrigeration system can actually be utilized for heating. Condensing at 20°C means that the heat from the refrigeration system to cover building demands must be used directly, which the industry is very reluctant to do. In addition, most of the heat is available *at* 20°C, not above, as most demands require. 35 %, 29 %, 49% and 46 % of the heat was superheat and could be used at nearly linear, gliding temperature above 20°C for cases 2, 3, 4 and 5, respectively. This was included in the calculations, decreasing the amount of required DH a bit compared to if it was not included. However, it might be necessary to condense at 27°C or higher to meet industrial requirements.

Another challenge of utilizing surplus heat at a constant temperature is that hybrid heat pumps, having gliding temperature, cannot easily be applied. To condense the CO_2 completely at 20°C, the HTHP must extract heat below 20°C, which requires very low inlet temperature case for hybrid heat pumps. Investigations showed that heat extraction by from both 20 and 27°C are feasible, but the COP at 20°C was unacceptably low. The temperature profile of the propane/butane cascade, which extracts heat at constant temperature, matches the heat source far better. However, if the indirect heating solution is chosen by the industry, the hybrid heat pump would be well suited, otherwise not. As, direct heating with CO_2 means supply pipes at much higher pressures, the industry is much more reluctant to try it, and this situation is thus very likely. This was the main reason to include investigations of cases with condensation at 27°C.

If direct heating with CO_2 is not accepted, this excludes the best solution in terms of GHG emissions, and also case 2, the cheapest alternative. Of cases 4, 5 and 6, case 5 achieved the lowest GHG-emissions, but the difference between case 5 and cases 4 and 6 in terms of electricity and GHG-emissions is very small and not significant. The differences in costs and district heat demand on the other hand are significant; case 5 is the most expensive solution. Cases 4 and 6 are thus more interesting for the industry, condensing CO_2 at 27°C and using the cascade and the hybrid heat pump in that order. These are also not significantly different from each other, hence; no conclusion on which HTHP is better for this plant can be made.

Considering cooling separately, lifting the evaporation level and apply CO_2 for direct cooling is very beneficial, saving 0.22 GWh of electricity, 33%. Direct heating only saved 0.02 GWh of electricity, 3.6%, and has a much smaller impact on the environment. The surplus heat always exceeded the heat demand, hence, condensers on the roof will be necessary in all cases. All calculations assumed that to the return temperature of CO_2 was

20°C, which will not be true in periods with high ambient temperature and no heat demand. At these conditions, the COP will therefore drop a bit. However, this will not occur often. The ambient is rarely above 15°C, the average temperature in May-September is 14.8°C, and the average for every month in June-September is 15±0.3°C. Designing the condensers for a temperature difference of 5°C, there will also be many days when heat is rejected to ambient at lower ambient temperature, achieving a better COP than assumed. The effects were thus considered to partially cancel each other, and omitted from all cases in this comparative investigation.

The power demand for a refrigeration system rejecting heat to the ambient, normally at about 10°C, will have a much better yearly performance than the systems which have return temperature of 20°C all year, thus, the improvement of the system by using HTHP, must include this effect. From Table 1, it is clear that the disadvantage in condensing at 20°C instead of rejecting to ambient was about 0.19 GWh yr^{-1}. This was subtracted when comparing HTHPs with boilers.

In many cases, there was a small imbalance between heat available and heat required at the lowest temperature level. Having the ability to store it for just some hours reduced the demand for DH considerably. Thus, the results presume that it is possible to store heat.

5. CONCLUSIONS

Large savings in electricity (39-51%) and the DH demand (29-57%) are obtainable with efficient, integrated heating and cooling solutions. No significant difference between the propane/butane cycle and the hybrid cycle was found in this study. CO_2 heat pump was used for cooling. The evaluation of the different solutions depends on the weighting of the different outcomes. Based on costs, case 2 is the most efficient, based on environment, case 3 is preferable, or, if direct heating with CO_2 is unacceptable, the best practice solutions are cases 4 and 6, with no significant differences. The most promising solutions involve direct cooling and heating with CO_2 at -1.5 and 20°C in combination with any of the HTHPs, achieving 31% reduction in DH demand, 51% lower electricity demand and 49% lower GHG-emissions. If indirect heating is required, condensation at 27°C gives 37-38 % reduction in DH demand, 43-44 % lower electricity demand and 43 % lower GHG-emissions. Overall, the solutions are about equally good, as the uncertainty is higher than the differences. Obtainable savings are expected to be in the same range as in this study. All solutions show promising results with respect to industrial implementation.

As the source's temperature is partially constant, it is thermodynamically better with cooling at constant temperature as well, and also higher certainty that a propane/butane cascade can guaranty the low return temperature for CO_2. However, more detailed studies on this is required.

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