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DECARBONISATION THROUGH INNOVATION

Industrial decarbonization with cascade heat pump systems – an analysis of the replication potential in Austria

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Abstract

Lately the role of industrial heat pumps in the transformation of energy provision significantly increased e.g. due to innovations and progresses in available refrigerants, technology, etc. First pilot plants, e.g. in the AHEAD project, are coming into operation. Thus, more real, industrial-scale operational data will be available in future. To significantly reduce industrial emissions a crucial step is the coming technology rollout. Therefore, this contribution assesses the rollout potential for cascade heat pump systems in the Austrian industrial sector.

Subsystems of the subsequently mentioned cascade system are considered in the analysis: chiller – hot water generating heat pump – steam generating heat pump – steam compressor. In general, with this combination temperature lifts greater than 100 K can be realized attracting a wide range of industrial production sites and needs. To determine the rollout potential for cascade heat pump systems the following approaches are combined: (i) Assessment of suitable industrial sectors for integration (e.g. paper, dairies, breweries, pharmaceutical industry, etc.), (ii) Localization and assessment of site-specific industrial energy consumption in Austria and, (iii) Derivation of future potential for heat pump cascade rollout with highly resolved industrial sites to determine the impact of this transition in Austria.

In this work generic integration concepts for the identified subsectors and performance indicators, e.g. prospective CO_2-emission reduction and an estimate for the installed capacity, are presented. This work serves as a strong planning foundation for different stakeholders – public bodies and funding agencies, technology suppliers, and engineering companies but also research and industry themselves.

Keywords: Industrial heat pump; Replication potential; Case study

1. Introduction

Heat pumps are emerging as a critical technology in global decarbonization efforts, with projections highlighting their pivotal role in the energy transition. According to the International Energy Agency (IEA) [1], industrial sectors with high thermal energy demands, such as food, paper, and chemicals, have significant potential to benefit from heat pump deployment, which could meet up to 30 % of their heating needs. Especially for sectors with heat demand at comparably low temperatures (< 200 °C) the integration potential can be considered as high. Despite this substantial potential, the current pace of heat pump installation remains inadequate relative to the ambitious climate targets.

To align with the IEA's *Net Zero Emissions by 2050* (NZE) Scenario, e.g. the global heat pump stock in buildings would need to almost triple by 2030 [2]. Achieving this scale will require policy support, technical

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innovation and extended research, particularly to reduce upfront costs, remove market barriers, improve energy performance and durability and develop products and systems using refrigerants with a lower climate and environmental impact. These barriers also apply in industrial contexts, where the potential for heat pumps has a big leverage, but heat pump integration might be more complex due to constraints of a manufacturing operation. The gap between heat pump potential and its current rate of adoption underscores the need for research into deployment strategies that can address these barriers.

The AHEAD (Advanced Heat Pump Demonstrator) project in Vienna [3] is pioneering in overcoming this gap by decarbonizing a pharmaceutical production site through the use of a steam generating high-temperature heat pump system on a full industrial scale. The system replaces traditional fossil-fuel-based steam generation at the site by utilizing excess heat and advanced heat-pump technology. The system shown in Fig. 1 operates in a cascading manner: Initially, it recovers low-temperature waste heat from the central chiller system, lifting the temperature to around 70 °C with a conventional heat pump. This system is also providing heat for the heating system on-site. However, operating hours of the heating system on-site are low compared to operating hours of the manufacturing process. During the period when heating is not required this heat (water at 70 °C) can then be further upgraded with an innovative high-temperature heat pump, generating steam at 120 °C. Finally, a steam compressor elevates the steam to 184 °C at 11 bara, meeting the requirements for the site's process steam system. The cascade realized in the AHEAD project furthermore uses 100 % natural refrigerants.

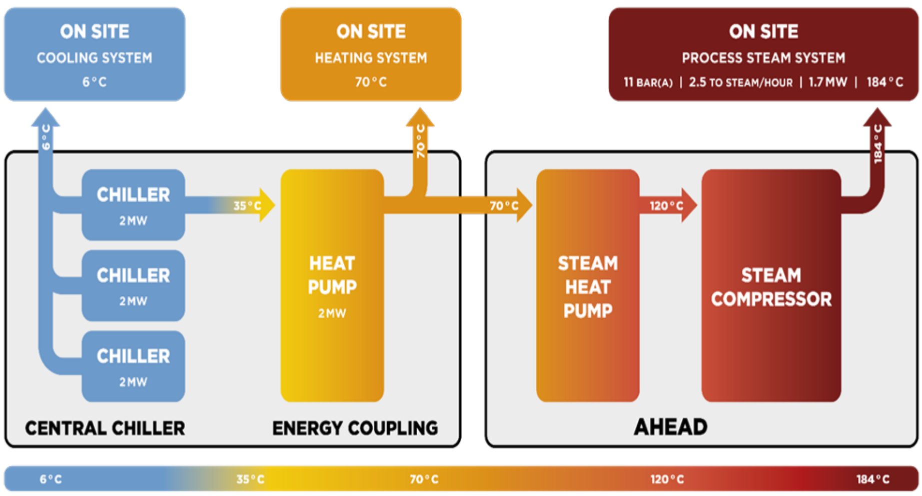

Figure 1. Cascade heat pump system of the AHEAD project (Source: Takeda)

Building on lessons learned from AHEAD, the next crucial steps involve optimizing performance and, more importantly, planning the widespread rollout of such systems across Austria's industrial sector and beyond. Previous studies assessing replication and market potential for industrial high temperature heat pumps, e.g. by Kosmadakis [4], Koller et al. [5] and Marina et al. [6], have often relied on aggregated national or sectoral data, e.g. energy or overall product amounts, to estimate the overall heating and cooling demand. In the following, the applied approaches are shortly described.

Kosmadakis [4] employed a top-down approach to estimate the potential for heat pump deployment in European industries. The study mapped the availability of waste heat for heat pumps at both the industrial branch and country levels. This involved estimating the waste heat and its temperature levels suitable for use by heat pumps, alongside the industrial heat consumption within temperature bands from 100 °C to 200 °C. By matching these two heat flows for each industrial branch, the study identified the potential for waste heat recovery through heat pump technology, with non-metallic minerals, food, paper, and non-ferrous metals emerging as the most promising sectors.

Koller [5] extended Kosmadakis's approach by incorporating country-specific energy prices and CO_2 pricing, which allowed for the calculation of minimal COPs to ensure economic feasibility. This refinement provided a more accurate estimate of the economic potential and market feasibility for heat pumps across different EU countries on industrial scale.

Marina et al. [6] used a bottom-up approach. Their methodology involved gathering process data, specifically focusing on the heating and cooling profiles of individual industrial processes in the food, paper, chemical and refining sectors, including temperature levels and energy use per unit of product. They then assessed the applicability of heat pumps for each process and determined their thermodynamic performance. The findings from the individual process level were upscaled to the sector and EU level using data on typical plant capacities and relevant production statistics for each sector.

These studies provide insights into the broad feasibility of heat pump technologies, but their analysis lacks in granularity needed for more targeted recommendations at the site-specific level. Especially, they do not include an insight into required industrial heat pump capacities for the future. In contrast, the present study adopts a methodology, going down even on site-level resolution. Specifically, it estimates final energy consumption below 200 °C at the individual facility level, using employee numbers as a proxy for energy demand. This granular approach provides a more detailed assessment of the heating and cooling needs at the facility level, allowing for a more accurate identification of localized market opportunities and strategic deployment priorities for heat pumps in Austria. By using facility-specific data, this study is able to provide targeted insights into where heat pumps can be most effectively deployed as well as a valuable insight into required capacities, something that is not possible in macro-level studies that rely on aggregate sectoral or national data.

2. Approach

2.1. Site identification and quantification

A first step towards the determination of the rollout potential for cascade heat pump systems in the Austrian production sector started with a domain and knowledge-based identification of relevant industrial branches, that can include the overall cascade of the AHEAD systems or at least parts of it. While the overall cascade of the AHEAD system, see Fig. 1, includes (1) chillers, (2) a hot water generating heat pump, (3) a high temperature heat pump (here for steam generation) and (4) a mechanical vapour compression unit, in the following also cascades including at least two of those four, but at least the high temperature heat pump, are considered. From this approach three sectors of major relevance could be identified.

After this identification of relevant subsectors, which was done on detail level of categories and subcategories of the NACE Rev.2 classification sector C (production of goods), a database including about 35,000 sites from the Austrian production sector was consulted. The procedure of how this database was derived can be described as follows: A combined top-down and bottom-up approach was established to derive all sites of the Austrian production industry with an automatized data pipeline. On the one hand, all sites for all sectors and all Austrian communities were disaggregated from the workplace counting data set of 2021. Employee-specific energy consumption data per sector is generated based on Austria’s final energy usage statistic. On the other hand, site specific information about CO_2 emissions, used fuel amounts, etc. is derived from different publicly available data sets. All types of information are combined to determine (i) a data set with highly spatially resolved industrial sites and (ii) an estimation of their energy demands. Details of the according approach of deriving this *industry map* are presented in Knecht et al. [7].

2.2. Determination of potential for cascade heat pump systems

As the *industry map* includes not only sites with relevant industrial energy demand but also very small sites with less than five employees, some filtering criteria were applied to the database to determine those sites of high relevance for industrial scale high temperature heat pumps. The following filtering approach was performed: The dataset is filtered by selecting sites with at least 5 employees and a minimum thermal energy demand of 1 GWh for temperatures below 200 °C. The constraint of at least 1 GWh was related to the order of magnitude the heat pump in the AHEAD systems is designed for. The cascade of steam generating heat pump and steam compressor can provide 1.7 MW of thermal power (see Fig. 1). A process demand of 1 GWh corresponds to 1 MW power demand for 1000 full load hours per year or to 200 kW for 5000 full load hours. Thus, far smaller systems and sites with significantly lower energy demand are not considered of further relevance in this study.

However, as interim step and to derive further information it was also determined how many sites with at least 100 MWh of thermal energy demand in the respective final energy demand category (process heat below 200 °C) occur in the Austrian industrial sector. This energy demand correlates to a thermal power demand of 100 kW for 1000 full load hours per year. The evaluation of this number shall give an indication of how many sites are significantly smaller than the previously introduced size of the AHEAD system.

For the remaining industrial sectors, the resulting sites with more than 1 GWh of process heat demand below 200 °C were then categorized into discrete ranges of thermal energy demand in the next step. The following ranges were considered: (i) 1-10 GWh/a, (ii) 10-20 GWh/a, (iii) 20-30 GWh/a, (iv) 30-40 GWh/a, (v) 40-50 GWh/a, (vi) 50-100 GWh/a and (vii) >100 GWh/a.

To assess an upper bound for the number of heat pump cascades to be rolled in Austria for all energy demand ranges the following steps were performed:

- An average energy demand per site was derived from the range. For the smallest range (1-10 GWh/a) 5 GWh/a was assumed and 250 GWh/a for the biggest range (>100 GWh/a). For all further ranges, the mean of the range was assumed, e.g. 15 GWh/a for the second smallest range.
- With an average of 5000 full load hours a thermal capacity was determined for every range.
- In the next step three typical heat pump cascade capacities were defined.
    - It was assumed that systems with an overall heating capacity of 2 MW, similar to the AHEAD system, could be included. For any site with a thermal capacity demand below 10 MW integration of multiple AHEAD systems was assumed.
    - For any site with a thermal demand between 10 and 20 MW cascade systems with a thermal capacity of 10 MW were assumed.
    - For sites with more than 20 MW thermal demand cascade systems or multiples of those with 20 MW thermal capacity were assumed.

2.3. Emission reduction

Finally, it was determined how much reduction in scope 1 CO_2 emissions could be achieved under the assumption that heat pumps, replacing steam boilers fired by natural gas with an efficiency of 90 % and direct emission factor of 201 g/kWh [8], would provide the overall thermal energy demand. Thus, the energy demand per site and range was assumed as described in Section 2.2. This energy $e_{s,r}^{\text{process}<200\,°\text{C}}$ for sector s and range r was considered for every sector and range with the boiler efficiency η_{boiler} and the emission factor em_{CO2} according to the following equation:

$$Saving_{CO2} = \sum_{s\,\in\,sector} \sum_{r\,\in\,range} \frac{e_{s,r}^{process<200°C}}{\eta_{boiler}} \cdot em_{CO2} \tag{1}$$

3. Results and Discussion

3.1. Assessment of relevant industrial products for the application of the AHEAD system

In the following, an overview of assessing the relevance and applicability of the AHEAD system for different industrial products and thus sectors is shown in Tab. 1. Based on this assessment six (sub)sectors have been identified as sectors with highest interest for the integration of further AHEAD systems. For the further result representation in Section 3.2. they have been aggregated to the following three groups:

- **Food and beverages**, resulting from several groups and classes (C10.1, C10.2, C10.5, C10.6.2, C10.7, C10.9 and C11.0.5) of the two divisions *manufacture of food products* (C10) and *manufacture of beverages* (C11) – here typically the full cascade system including chillers would be applicable.
- **Chemistry, pharmaceuticals and rubber**, resulting from several groups and classes (C20, C21.1, C21.2, C22.1, C22.2) of the three divisions *manufacture of chemicals and chemical products* (C20), *manufacture of basic pharmaceutical products and pharmaceutical preparations* (C21) as well as *manufacture of rubber and plastic products* (C22) – here, as well, typically the full cascade system including chillers would be applicable.
- **Pulp and paper** resulting from the division *manufacture of paper and paper products* (C17) – here typically only stage two to four of the AHEAD system is applicable as no significant cooling demands occur and the most promising initial heat source considering temperature and energy for the cascade would be humid excess air from the paper drying process.

Table 1. Overview of NACE Rev.2 divisions, process heat demand and typical excess heat potentials

NACE Rev.2 divisions	Relevance for roll out of AHEAD in Austria	Industrial process heat demand	Typical excess heat potentials
C10 – Manufacture of food products	High: high number of sites, high relevance for meat and fish processing, dairies, starch (products), farinaceous products, animal feed	Often steam and hot water demand	Cooling processes
C11 – Manufacture of beverages	Medium: similar to food sector, lower number of sites, high relevance for breweries	Often steam and hot water demand	Cooling processes
C12 – Manufacture of tobacco products	Low: low number of sites	---	---
C13 – Manufacture of textiles	Medium: interesting process demand but low number of sites	Often steam and hot water demand	Compressed air systems and drying
C14 – Manufacture of wearing apparel	Low: low number of sites and lower overall thermal energy demand	Low	Compressed air systems
C15 – Manufacture of leather and related products			
C16 – Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	Medium: often direct firing integrated in production process	(in)direct firing and heating of products	Humid air from drying
C17 – Manufacture of paper and paper products	High: suitable process heat demand and high relevance in Austria	Mainly steam demand	Humid air from drying
C18 – Printing and reproduction of recorded media	Low: low thermal requirements	---	---
C19 – Manufacture of coke and refined petroleum products	Low: low number of sites but with relevant energy demand and heat pump integration potential in refineries. Needs to be assessed site-specific	Several steam consumers in refineries	Cooling processes
C20 – Manufacture of chemicals and chemical products	Medium to high: high steam demand and cooling needs	Often steam and hot water demand	Cooling proceses
C21 – Manufacture of basic pharmaceutical products and pharmaceutical preparations	High: high steam demand and cooling needs	Often steam and hot water demand	Cooling processes
C22 – Manufacture of rubber and plastic products	Medium to high: high steam demand and cooling needs	Often steam and hot water	Cooling processes, exhaust air
C23 – Manufacture of other non-metallic mineral products	Low to medium: heat pumps relevant for brick drying but no direct steam requirement and low number of applicable sites	Hardly significant demand of process heat < 200 °C	Partly – humid air from drying, kiln exhaust gases
C24 – Manufacture of basic metals	Low: unsuitable temperature levels	No significant demand of process heat < 200 °C	Cooling processes
C25 – Manufacture of fabricated metal products, except machinery and equipment	Low: unsuitable temperature levels	No significant demand of process heat < 200 °C	Cooling processes
C26 – Manufacture of computer, electronic and optical products	Low: unsuitable temperature levels	No significant demand of process heat < 200 °C	Conditioning of air, cooling processes
C27 – Manufacture of electrical equipment	Low: unsuitable temperature levels	No significant demand of process heat < 200 °C	Conditioning of air, cooling processes
C28 – Manufacture of machinery and equipment n.e.c.	Low to medium: unsuitable temperature levels	Often thermal oil	Conditioning of air, cooling processes
C29 – Manufacture of motor vehicles, trailers and semi-trailers	Low: unsuitable temperature levels	Often thermal oil	Conditioning of air, cooling processes
C30 – Manufacture of other transport equipment	Low: unsuitable temperature levels	Often thermal oil	Conditioning of air, cooling processes
C31 – Manufacture of furniture	Low: unsuitable temperature levels	---	---
C32 – Other manufacture	Low: too generic for assessment	---	---
C33 – Repair and installation of machinery and equipment	Low: too generic for assessment	---	---

3.2. Sectoral distribution and range of thermal energy demand for industrial sites in Austria

This section shows the results for identified sites in the three aggregated industrial sectors from Section 3.1.. First, Tab. 2 gives an overview of the number of sites with more than five employees and more than 0.1 GWh process heat demand below 200 °C, which is the final energy demand category most relevant for further AHEAD systems. In a second stage it was evaluated and is shown how many of these sites (from step one) have up to 1 GWh of process heat demand per year as well as those with more than 1 GWh. The latter are especially relevant for the AHEAD system rollout as the order of magnitude of the system components is at least comparable to the currently installed system in Vienna, see also explanation in Section 2. From this analysis we can see that only a small share of the first filtered sites (with more than five employees and 0.1 GWh) has an energy demand high enough to be suitable for the AHEAD system. Especially for *food and beverages* more than 88 % (1806 out of 2042) were excluded from the roll out potential analysis due to a too low process heat demand below 200 °C. For Chemistry, pharmaceuticals and rubber still more than 44 % (165 out of 373) were not further included, while in *pulp and paper* one can see a different picture: Only 15 percent (17 out of 115) were not further included.

Table 2. Sectoral distribution of identified sites for the filtering criteria steps to derive relevant sites with a significant thermal energy demand of at least 1 GWh per year

Sector	Sites with > 5 employees and > 0.1 GWh for process heat below 200 °C	Sites with 0.1 – 1.0 GWh for process heat below 200 °C	Sites with > 1 GWh for process heat below 200 °C
Food and beverages	2042	1806	236
Pulp and paper	115	17	98
Chemicals, pharmaceuticals and rubber	373	165	208

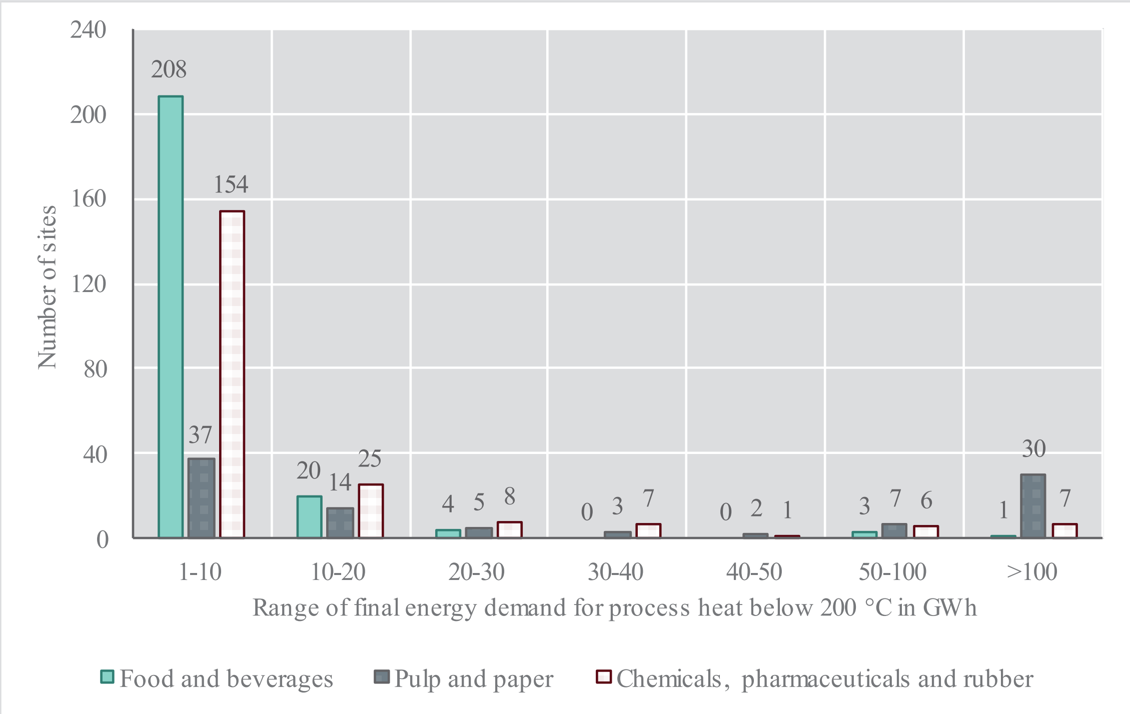

Figure 2. Overview of number of sites with more than 5 employees and final energy demand for process heat below 200 °C with at least 1 GWh per year for three identified sectors based on the industry map data base by Knecht et al. [7].

In Fig. 2 the sectoral distribution is visualized for the defined energy demand ranges. From this, a continuation of the trend already shown in Tab. 2 is visible. Especially in the sectors *food and beverages* as well as *chemicals, pharmaceuticals and rubber* a high share of sites can be found in the rather small energy demand ranges. However, for *pulp and paper* 30 of the remaining 98 sites have at least 100 GWh of annual process heat demand below 200 °C or more. This result is already a strong indication of the suitability of different sectors for the rollout of the AHEAD system and its adaption needs. Especially for large sites with far higher energy demand, adaptions will be probably necessary. This is also underlined by the evaluation shown in Fig. 3. This includes an evaluation of the number of cascade heat pump systems in Austria. It is distinguished whether the full four stage cascade (for *food and beverages* as well as *chemicals, pharmaceuticals and rubber*) or a three-stage cascade without chillers (for *pulp and paper*) will be necessary. For sites with higher energy consumption, it is also considered that larger thermal capacities for the cascade might be required (see Section 2.2.). For smaller sites, multiple cascades similar to the original size of the AHEAD system are considered. This results in a high number of up to 522 cascades with four stages and 2 MW heating capacity. Due to a lower number of sites in the pulp and paper system only 92 three stage cascades with 2 MW heating capacity were identified. Furthermore, systems with 10 MW heating capacity are of minor importance in the Austrian heat pump roll out. Nevertheless, the assessment for 20 MW heat pump cascades shows a higher need with 33 of four stage cascades and 97 three stage cascades based on this analysis.

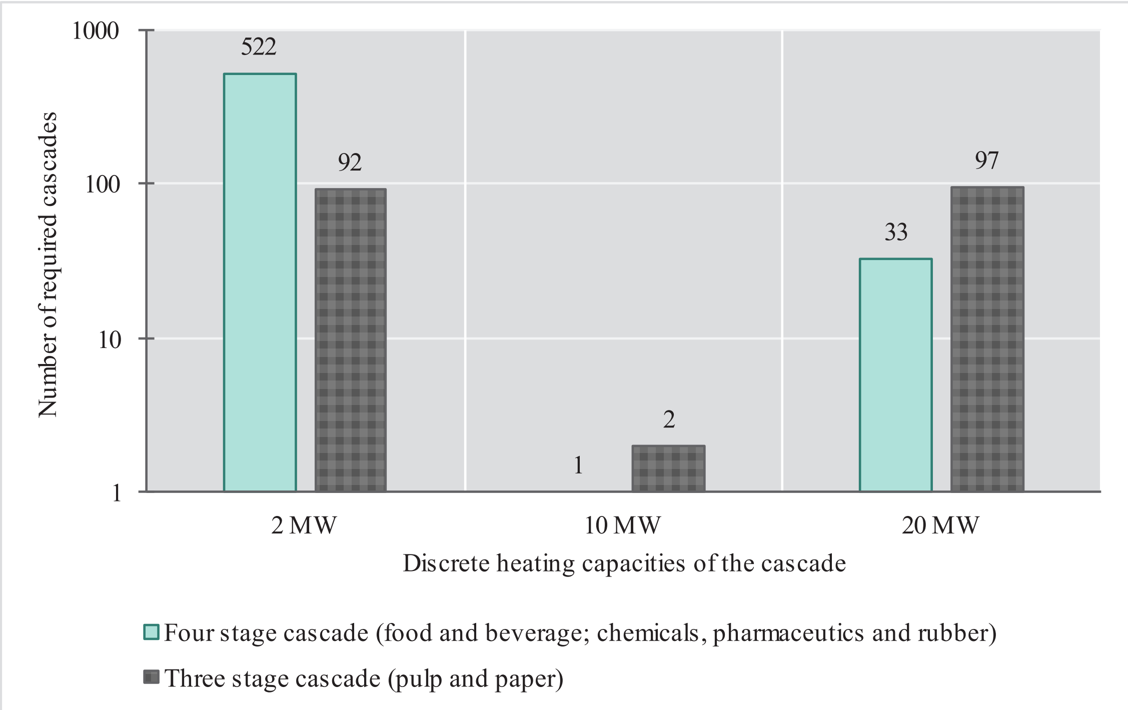

Figure 3. Number of required cascade heat pump systems with different heating capacities to cover 100 % of the decarbonization potential

3.3. Emission reduction

With a calculation based on Section 2.3. an annual saving potential of scope 1 emissions by replacing natural gas fired steam boilers of up to 3236 kilotons per year could be determined if the full potential can be covered. This equals to nearly 46 % of Vienna's total CO2 emissions in the year 2023 [9].

Furthermore, the analysis on single cascade level revealed the following. A cascade heat pump system with 2 MW heating capacity and 5000 full load hours per year leads to an annual reduction of 2.24 kilotons when replacing natural gas fired boilers with 90 % efficiency by heat pump systems for the supply of process heat below 200 °C. Cascades with 10 MW and 20 MW heating capacity reduce emissions by 11.2 and 22.4 kilotons per year, respectively.

4. Conclusion

The analysis done in this work reveals a potential future focus of work for manufacturers of heat pump cascade components. For the three aggregated sectors it could be shown that a significant share of sites might be too small in terms of process heat demand to replicate such cascade heat pump systems. However, for cascades with 2 MW heating capacity an upper bound of more than 600 units in total could be identified in Austria. While there is hardly any need for cascades with 10 MW heating capacity, a relevant demand could be identified for systems with 20 MW heating capacity. Focusing on smaller heating capacities, similar to the AHEAD system already in operation, an emphasis should be laid on the sectors *food and beverages* as well as *chemicals, pharmaceuticals and rubber*. As the sector *pulp and paper* holds a big emission reduction potential by integrating cascade heat pump systems due to its high energy consumption values it is also of high relevance. Here, cascades with higher heating capacities are of greater importance compared to the other sectors and should be the focus of joint work from researchers, suppliers and industrial operators. For further integration also the learned lessons from the AHEAD project and optimized operation of the existing system is of high relevance and should be considered in future roll out work.

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