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IntSGHP - Integration of steam-generating heat pumps in industrial sites (retrofit)

Source: Hot water supply at a Swiss dairy factory (Photo © F. Bless)

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Zusammenfassung

Der Bericht zeigt das vielversprechende Potenzial von dampferzeugenden Wärmepumpen (englisch: Steam Generating Heat Pump, SGHP) in industriellen Anwendungen auf und hebt dabei die signifikanten Energieeinsparungen und die Reduzierung der CO2-Emissionen hervor. Anhand detaillierter Analysen und Simulationen belegt die Studie, dass SGHP mit geschlossenem und offenem Kreislauf effizient in bestehende Systeme wie die der Anlagen von UCB Farchim und DSM integriert werden können. In UCB Farchim erwies sich die kombinierte SGHP als optimale Lösung, die trotz der hohen Temperaturerhöhungen ein solides Gleichgewicht zwischen Energieeffizienz und betrieblicher Machbarkeit bot. Umgekehrt profitierten die DSM-Verfahren am meisten von einem PEMS mit offenem Kreislauf, was die Anpassungsfähigkeit dieser Systeme an verschiedene industrielle Umgebungen belegt. Neben den Machbarkeitsstudien stellt der Bericht den Stand der Technik der aktuellen PMSG-Technologien dar und enthält detaillierte Informationen zu den verwendeten Kältemitteln. Dieser umfassende Überblick umfasst eine Zusammenfassung der auf dem Markt erhältlichen Produkte und Komponenten und bietet wertvolle Einblicke in die neuesten Fortschritte und Trends in der Branche.
Der Bericht stellt auch eine technisch-ökonomische Methode zur Bewertung der Realisierbarkeit der Integration von SGHP unter Berücksichtigung der Investitionsausgaben (CAPEX) und der Betriebsausgaben (OPEX) vor. Es wurde ein Excel-Tool entwickelt, das eine schnelle Bewertung der wirtschaftlichen und ökologischen Auswirkungen von Hochtemperatur-Wärmepumpen erleichtert. Darüber hinaus wurde ein kurzer Leitfaden erstellt, um Unternehmen, die an der Einführung dieser Technologien interessiert sind, zu unterstützen.

Zusammenfassend unterstreichen die Ergebnisse, dass SGHP nicht nur eine praktikable Alternative zur Dampferzeugung aus fossilen Brennstoffen darstellen, sondern auch zu erheblichen Kosteneinsparungen und Umweltvorteilen beitragen und somit einen bedeutenden Fortschritt in der nachhaltigen Industrietechnologie darstellen. Sie zeigen auch, dass, obwohl immer mehr Unternehmen SGHP anbieten, in der EU-Industrie noch keine installierten und in Betrieb befindlichen SGHP vorhanden sind.

Résumé

Ce rapport révèle le potentiel prometteur des pompes à chaleur génératrices de vapeur (SGHP en anglais) dans les applications industrielles, en mettant en évidence les économies d'énergie significatives et la réduction des émissions de CO2. Grâce à des analyses et des simulations détaillées, l'étude démontre que les SGHP à cycle fermé et à cycle ouvert peuvent être efficacement intégrées dans des systèmes existants tels que ceux des installations d'UCB Farchim et de DSM. À UCB Farchim, la SGHP à cycle combiné s'est révélée être la solution optimale, offrant un équilibre solide entre l'efficacité énergétique et la faisabilité opérationnelle malgré les élévations de température élevées. À l'inverse, les procédés de DSM ont tiré le meilleur parti d'une SGHP à cycle ouvert, ce qui démontre l'adaptabilité de ces systèmes à différents environnements industriels. Outre les études de faisabilité, le rapport présente l'état de l'art des technologies SGHP actuelles et fournit des informations détaillées sur les réfrigérants utilisés. Cette vue d'ensemble complète comprend un résumé des produits et composants disponibles sur le marché, offrant un aperçu précieux des dernières avancées et tendances dans l'industrie.
Le rapport présente également une méthode technico-économique pour évaluer la faisabilité de l'intégration de la SGHP, en tenant compte des dépenses d'investissement (CAPEX) et des dépenses d'exploitation (OPEX). Un outil Excel a été développé pour faciliter l'évaluation rapide des impacts économiques et environnementaux des pompes à chaleur à haute température. En outre, un bref guide a été créé pour aider les entreprises intéressées par l'adoption de ces technologies.

En résumé, les résultats soulignent que les SGHP offrent non seulement une alternative viable à la production de vapeur à partir de combustibles fossiles, mais qu'elles contribuent également à des économies substantielles et à des avantages environnementaux, marquant ainsi une avancée significative dans la technologie industrielle durable. Elles montrent également que, bien que de plus en plus d'entreprises proposent des SGHP, il n'y a toujours pas de SGHP installée et en fonctionnement dans l'industrie de l'UE.

Summary

This report reveals the promising potential of steam-generating heat pumps (SGHPs) in industrial applications, highlighting significant energy savings and reduced CO_2 emissions. Through detailed analysis and simulations, the study demonstrates that both closed-cycle and open-cycle SGHPs can be effectively integrated into existing systems such as by UCB Farchim and DSM facilities. At UCB Farchim, the combined-cycle SGHP emerged as the optimal solution, providing a robust balance between energy efficiency and operational feasibility despite high temperature lifts. Conversely, DSM's processes benefited most from an open-loop cycle SGHP, showcasing the adaptability of these systems to different industrial environments. In addition to the feasibility studies, the report presents the state of the art of current SGHP technologies and provides detailed information on the refrigerants used.
This comprehensive overview includes a summary of market-available products and components, offering valuable insights into the latest advancements and trends in the industry. The report also introduces a techno-economic method for evaluating the feasibility of SGHP integration, considering capital expenditures (CAPEX) and operating expenditures (OPEX). An accompanying Excel tool was developed to facilitate quick assessments of the economic and environmental impacts of high-temperature heat pumps. Additionally, a short guideline was created to assist companies interested in adopting these technologies.

In summary, the findings emphasize that SGHPs not only offer a viable alternative to fossil-fuel-based steam generation but also contribute to substantial cost savings and environmental benefits, marking a significant advancement in sustainable industrial technology. It also shows that although more and more companies are offering SGHP, there are still no SGHP installed and operating in EU industry.

Main findings

The findings of our study shed light on several key aspects relevant to the adoption of steam generating heat pump technologies within industrial settings:

- Readiness of Heat Pump Manufacturers: One significant finding indicates that manufacturers of heat pump systems are primed and technically prepared to meet the demand for steam generating heat pump solutions, demonstrating a readiness to support industrial decarbonization efforts.
- High Industry Interest: There exists a notable level of interest among industrial sectors in adopting steam generating heat pump technology. This interest underscores the recognition of HP as a viable solution for achieving decarbonization goals within industrial processes. This interest is sometimes there to the detriment of an in-depth study of their systems, which very often demonstrates the non-necessity of using steam as a heat carrier.
- Cost Barrier as Primary Challenge: Despite the enthusiasm for steam generating heat pumps, the primary obstacle hindering widespread adoption is the substantial initial investment cost. Consequently, many industries opt for cheaper decarbonization measures initially, delaying the integration of HP systems.
- Risk Due to Limited Case Studies: A significant risk factor identified is the lack of comprehensive case studies demonstrating the long-term operational efficacy of steam generating heat pump installations. This lack of empirical data poses a considerable challenge for industries assessing the feasibility and reliability of SGHP technologies.
- Complexity and Expense of Installation: The installation of steam generating heat pumps is inherently complex and expensive, requiring meticulous planning and organizational efforts. The intricate nature of SGHP installations necessitates thorough pre-project studies to mitigate risks and ensure successful implementation within industrial facilities.

These findings underscore the multifaceted considerations and challenges associated with the adoption of steam generating heat pumps in industrial contexts. Addressing these challenges will require collaborative efforts among stakeholders to navigate complexities, mitigate risks, and unlock the full potential of SGHP technologies in advancing industrial decarbonization initiatives.

Contents

Abbreviations

CAPEX:	Capital Expenditure
COP:	Coefficient Of Performance
GWP:	Greenhouse Warming Potential or Global Warming Potential
HP:	Heat Pump
HFO:	Hydrofluoroolefins
HTHP:	High-Temperature Heat Pump
IHX:	Internal Heat eXchanger
MVR:	Mechanical Vapour Recompression
NDA:	Non-Disclosure Agreement
ODP:	Ozone Depletion Potential
OPEX:	Operating Expense
SGHP:	Steam Generating Heat Pump
TFA:	Trifluoroacetic Acid

1 Introduction

1.1 Background information and current situation

The low price of gas led to an energy cost that was a negligible fraction of the product cost, and thus reducing gas consumption was often not a priority. Even the CO_2 levy of around 100 CHF per ton was too low to have a significant impact in most industrial sectors. The high investment cost of other solutions such as industrial heat pumps is due to being a newish technology and the need to be custom-tailored to a particular industrial process. Therefore, industrial heat pumps are not yet installed in large numbers and thus cannot benefit from the economy of scale cost reduction. The control of a heat pump is also harder than a simple fossil fuel burner which only produces heat. Heat pumps rely on a heat source to produce heat and thus are a more complex system.

The low supply temperature of a typical heat pump is due to heat pumps being mostly used as space heating devices where the temperature level is typically from 35 to 80°C. Therefore, the development of heat pumps was mainly targeted to this temperature range. However, many industrial processes require a temperature between 80°C and 200°C, which many heat pump products cannot reach due to technical difficulties (e.g., components not made for high temperature, oil deterioration, refrigerant critical temperature, etc.). In addition, there are also many industrial processes in need of low-pressure steam. Steam generating heat pump (SGHP) is a new technology that has not yet spread in the industry even though SGHP models already exist on the market.

However, the current global situation with the Ukrainian war and the awareness of climate change is pushing the government and industry to decarbonize the entire sector as quickly as possible. This geopolitical situation is helping the integration of high-temperature and SGHP technologies driven by renewable electricity.

1.2 Purpose of the project

The general purpose of the project is to help with the decarbonisation of the industrial sector. By increasing the deployment of HTHP and, in particular, SGHP in the industrial sector, many fossil-fuel boilers could be replaced. In addition, SGHP is a great technology to implement in industries that cannot reduce heating supply temperature in their processes and need low-pressure steam.

The interest in a renewable way to produce steam is currently skyrocketing, however the lack of good examples often reduces the motivation of the industries. In many cases low pressure steam is directly needed as a process fluid, in others it is used as a very effective heat carrier. Especially in the later cases using SGHP may not always be the optimum solution concerning CO_2 reduction and efficienfy (deeper process integration would alloweven better solutions). However, for retrofit cases, switching to a completely new process layout is often prohibited by a financial barrier. Therefore, even though some of these systems do not achieve an optimum solution, they are compromises which still significantly reduce the carbon footprint.

This project analyses three different processes in three Swiss industries in detail and designs the most suitable SGHP concepts. The project is also interested in how the industry deals with SGHP implementation to guide other sectors to a quick integration.

1.3 Objectives

The first objective is to develop SGHP concepts which best fit the processes defined by the three industrial partners. The global aim of this project is to develop tools and guidelines, using these three specific cases, that allow a better understanding of implementing SGHPs in a company, including the cost of integration and operation not just equipment and energy cost.

Another important goal is to disseminate the know-how gained in this project and the collaboration within this project to other industrial stakeholders in order to allow a faster uptake of the technology. In case certain procceses are not suited to SGHP integration, the gained information ist still very valid for the field

Finally, the hope is to convince the stakeholders of each industry to install SGHP where applicable.

2 Description of facilities

2.1 UCB Farchim

UCB Farchim is a global biopharma company focusing on neurology and immunology. Their business is strong, with total revenue growth to €5.8 billion in 2021. There are approximately 8,600 people in all four corners of the globe, inspired by patients and driven by science. The biotechnology production unit inaugurated in Bulle (FR) in October 2014 provides treatment for patients suffering from rheumatoid arthritis, psoriatic arthritis, ankylosing spondylitis, axial pondylarthritis, and Crohn's disease. The chemical and galenic synthesis production centers have been providing therapeutic solutions in the fields of allergies, respiratory diseases, and epilepsy for many years.[1]

The flows diagram of the Bulle factory on a plant level is the following:

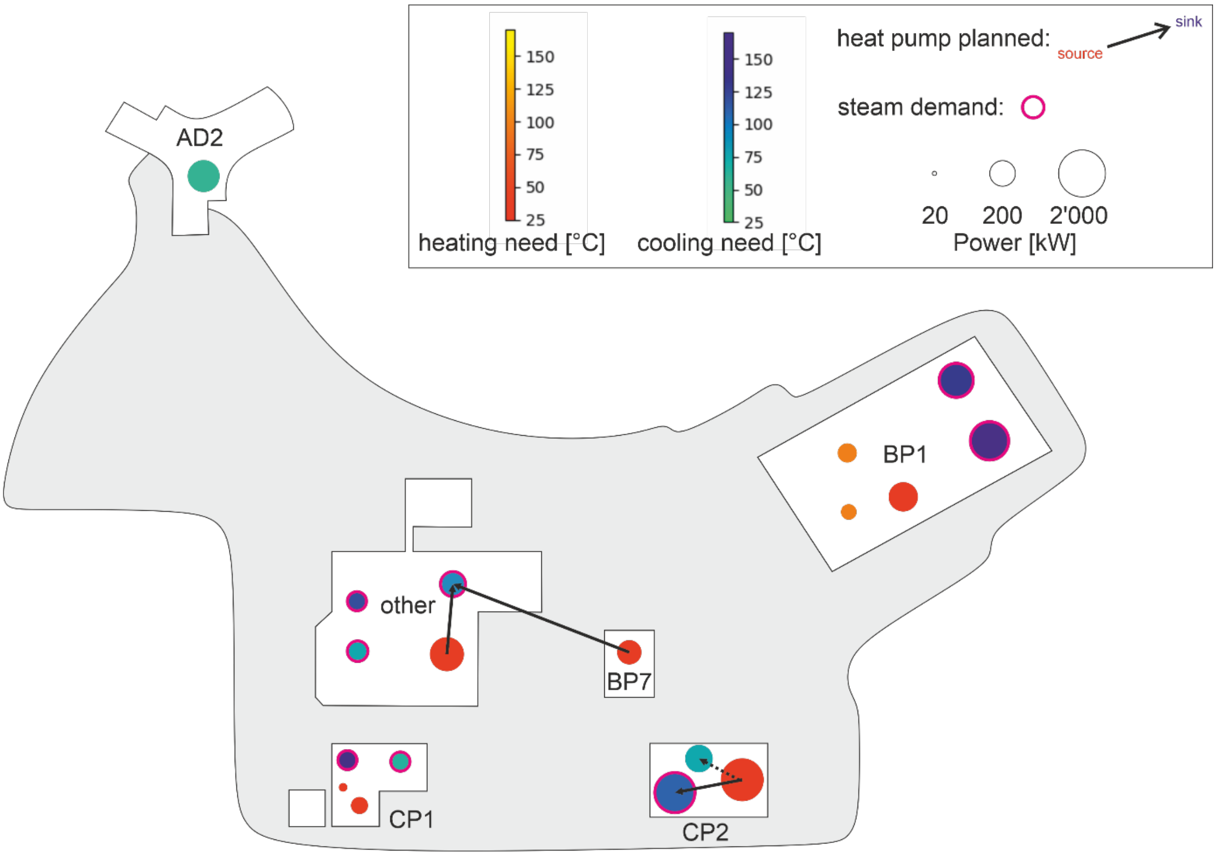


Figure 1: UCB Farchim site: heating & cooling demands in different buildings.

[1] From https://www.ucb.com/our-company/about-us (July 2022)

SGHP integration focuses on building CP2, where steam is needed at 110°C for a distillation process and waste heat is available. Two parallel processes run with a steam capacity demand of 640 kW. The source is the cooling used later in the process, which has the same capacity and a temperature of around 17°C to 20°C. A simplification of the process is given in Figure 2.

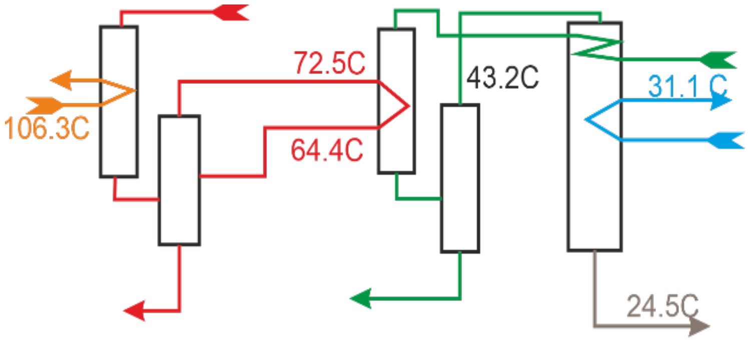


Figure 2: UCB Farchim: Simplified drawing of the distillation process in building CP2

The current system uses steam from the company steam network after a expension from 10 bar to the necessary pressure of around 1.5 bar.

In building CP2, there are 2 similar parallel production lines. The main energy consumers of these lines are the distillation. The heating and cooling needs of each line are summarised in Table 1.

Table 1: Details of UCB Farchim distillation process

Process demand	medium	power [kW]	temperature in [°C]	temp. out [°C]	pressure [bar(a)]	consumption [MWh/y]
Heating	water	462	106.3 (steam)	100 (liquid)	1.58	7600*
Cooling	water	461	22	31	1	300**

*consumption of natural gas in the steam boiler
**electricity consumption of the cooling towers

The saturated steam temperature is 110°C. Thus, the condensation temperature of a closed loop SGHP needs to be at approximately 115°C as a temperature difference is needed between the flows inside the heat exchanger. The evaporation temperature is around 17 °C (conservative estimation), giving a **temperature lift** of 115°C – 17°C = **98 K,** which is high for heat pump technology.

The choice of working on CP2 is based on two pinch analyses made in 2015 and 2021. In 2021 the steam of CP2 process was ignored because the authors did not realize at the beginning the potential of heat recuperation of the steam at 110°C. This is even more surprising knowing that in 2015 a previous Pinch analysis on this building CP2 was made. The study proposed three options to supply steam at the pressure level of the process. The first one was a heat pump between the condenser and the evaporator of the process exactly what is investigated now. The main difference was that to be able to find a potential industrial heat pump in 2015 and to have the best COP, the studies propose to modify the heat exchanger of the distillation column in order to be able to reduce the temperature of the heating fluid to 88°C (see annex 14.3). Unfortunately changing the heat exchangers was too expensive and risky for UCB Farchim. Thus, the option to replace the steam production from a gas boiler to a SGHP heat pump for this distillation process was studied. Pierre Krummenacher from HEIG-VD, who was one of the authors of both Pinch Analyses, also wrote that the theoretical best solution would be to use a compressor directly inside the process and to use the chemical solution as refrigerant, this technology has unfortunately not ever been tested and was thus rejected as an potential solution. To sum up:

Best theoretical solution	Optimal heat pump integration	Chosen Solution
Using a compressor directly in the process to distillate the chemical solution	Reducing the temperature difference between the heating fluid and the distillation solution	Integration of SGHP with unmodified process
+: carbon neutral solution +: Best efficiency as no heat exchanger may be required, the evaporation would be done by decreasing the pressure and thus the evaporating temperature -: Never being tested, distillation at a lower pressure by using a compressor may modify the process. The cooling demand would stay similar.	+: carbon neutral solution +: good efficiency by reducing the temperature difference between the heating fluid and the solution. -: New heat exchanger in the distillation column would need to be installed which is expensive.	+: No modification of the process +: carbon neutral solution -: Not the optimal possible efficiency. larger temperature lift and high temperature sink which means difficulty in the system (cascade or series HP) and in the choice of refrigerants. Also, the system goes from HTHP providing hot water to SGHP.
This solution would need a lot of time and effort to implement and would need a full R&D project to be tackled.	This solution would be easiest in terms of the heat pump system due to conventional temperature but is a problem of cost.	This solution is the best in terms of risk for the process but implies state of the art SGHP to be successful.

The table above summaries the possible options to replace the steam production from the current gas boiler. Another simple solution would be to replace the fuel of the boiler from gas to a renewable fuel such as wood, biogas, or hydrogen.

UCB Farchim is also in discussion with GESA (Gruyère Energie SA), which is located nearby and is developing a district heating network as a backup solution. GESA would like to lay their pipes through UCB Farchim to reduce their cost. It will also be beneficial for UCB Farchim in term of convenience. However, for now, GESA is using wood to produce heat at 90°C which is not the best option in terms of exergy loss. Therefore, even with a solution using 90°C heat to evaporate water + MVR for producing the process steam is efficient for UCB Farchim, in a larger view, it would be better to have used the wood to produce the process steam. The same goes if GESA is producing 90°C heat with hydrogen made from PV, which is one of their plans, as wood is getting scarer and will become even more scarce in the future. GESA is also looking to produce steam, using either wood or green hydrogen, for the industries in Bulle. This solution would be better in terms of exergy loss and easier for Farchim, even if the cost of steam will be higher than the current cost. They could replace the entirety of their own steam production from gas by the green steam from GESA. In this case, the comparison between using a SGHP vs green steam from GESA has to be made. Since the plan of GESA is still in development, a rough approximation can be made. The following table compares the three CO_2 neutral options of producing the steam. A life cycle assessment should be made to better compare the solutions:

Using GESA Steam 10bar from wood	Using GESA Steam 10bar from green H_2	Using SGHP with green electricity
Efficiency ~90% from the biomass boiler	Efficiency from El -> H2 is ~ 80% and then efficiency of the boiler ~90% = round -trip afficiency around 70%	Efficiency 200% (COP 2) to 300% (COP 3)

+ Simplicity, availability and established technology.	+ No scarcity + Can be combined as a grid storage	+ best efficiency, requiring ~3 time less electricity than the H_2 boiler.
- Scarcity of the wood in the future. - Waste of low temperature heat from UCB Farchim - Unknown timeplan of GESA	- Complex system (electrolysis, storage, H2 burner) and advance technology - Efficiency	- Higher electricity use than steam from wood - Advanced/ State of the art technology

Currently, both lines only run on weekdays and are shut down during the weekend. This means that every Monday morning the lines are started, it takes about 1 hour to reach a steady state and then the process runs constantly until Friday late afternoon. Thus, the heat pump will need to have an electrical back-up to produce the steam at the beginning of the week or to use the current system (steam from the 10 bar steam network) to start the process. The reason is that in order to run correctly the heat pump needs a heat source and that source is only available once the process has started. It would be also complicated to have steam storage for the entire weekend. First of all, the heat storage would have to be about 400kwh to be charged on Friday and discharged on Monday. Furthermore, since the heat pump creates the steam at a temperature close to what the process needs, the heat loss will likely reduce the temperature enough to make the steam less useful and consequently an additional heater will be needed anyway. Moreover, to charge the thermal storage, the heat source is needed, and it is not known if the heat source will be sufficient during the shutdown process to charge the storage. Thus, a thermal storage will be a very complex system, will take a lot of space, will be expensive, an extra heat will be needed anyway, all that to cover for the starting process which correspond to around 1% of the weekly operating time. A cold storage at the source could be a easiest option as it is easier and cheaper to store cold. Another idea would be to use the cooling tower as a heat source to be able to start the heat pump at the starting up of the process.

As the building BP1 needs steam at higher temperature, it is more practical to keep the steam network in place and to use the steam generated for BP1 to start the process until the heat pump received enough waste heat from the process to generate the desired steam.

2.2 DSM

DSM Nutritional Products is the world's leading supplier of vitamins, carotenoids, omega fatty acids, UV filters, and fine chemicals for the feed, food, pharmaceutical, and cosmetic industries. DSM Nutritional Products can look back on a long tradition as a pioneer in developing new products, new formulations, and attractive application areas for all industrial sectors.

Their customers are global, regional and local feed and premix companies as well as producers in the areas of food, beverages, infant nutrition, nutritional supplements, pharmaceuticals, personal care, flavors and fragrances.

As part of the Nutritional Products business unit, headquartered in Kaiseraugst, the Sisseln site belongs to the Dutch DSM Group. Around 1,000 of DSM's global 25,000 employees work there.

The DSM site in Sisseln produces vitamins, pharmaceuticals, substances for the cosmetics industry, carotenoids, folic acid, and many other high-quality products.[2]

A full plant-level flow diagram is unfortunately not available. DSM has already recuperated most of the waste heat. Their main current issue is reducing the cooling capacity provided by water from the Rhein river while increasing energy efficiency. The process analysed within this project is a distillation process with a heat sink temperature of 115°C and a source temperature of 45°C with a heating

[2] https://www.dsm.com/sisseln/en_US/Ueber_uns.html (July 2022)

capacity of 2.3 MW. It is one of the larger energy consumers at the given plant, with significant physical distance to other heat sinks and heat sources.

A simplified flow diagram of the process is shown in Figure 3.

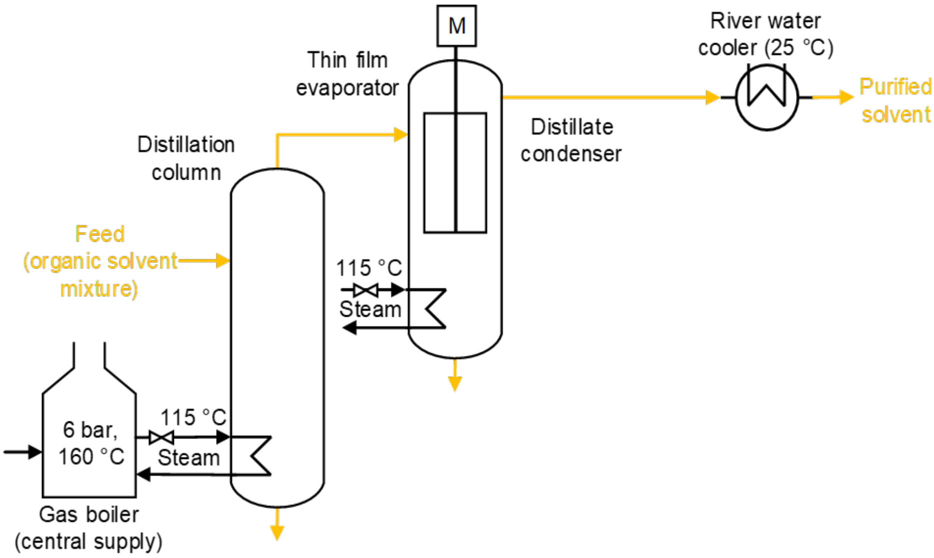


Figure 3: DSM: Simplified schematic of the distillation process.

The heating and cooling needs of the distillation process are summarised in the table below:

Table 2: Details of DSM distillation process

Process demand	medium	power [kW]	temp. inlet [°C]	temp. out [°C]	pressure [bar(a)]	consumption [MWh/y]
Heating	Water	2'300*	110-115 (steam)	90 (liquid)	1.74	
Cooling*	Water		40			

*1900kW Acetone evaporation + 250kW Acetone pre-heating + 380 kW additional heating (hot water)

The process has been continuous until now. During the summer, the line is shut off due to too high temperatures of the heat sink Rhein.

The saturated steam temperature is 110°C. Thus, the condensation temperature needs to be 115 °C or higher as a temperature difference is needed between the flows inside the heat exchanger. The distillate needs to be cool down to at least 45°C which gives an evaporation temperature for the heat pump at around 40°C or 45°C, giving a temperature lift of 115°C – 40°C = 75 K.

This temperature lift is quite high for heat pump technology.

2.3 Nestlé

The first meeting with the representatives of Nestlé was made on 11 January 2022. An NDA between OST and Nestlé has been signed during the first months of 2022. Starting this summer, Nestlé is doing a Pinch analysis of their Konolfingen factory with the Beat Wellig group at HSLU. As Beat Wellig is in the advisory group of IntSGHP, the authors contacted him and he agreed to discuss the result of the Pinch Analysis as long as the respective NDA with Neslté covers this case. As of the writing of this report, the Pinch Analysis is just finished but due to reason of NDA will not be summarize in this report.

Another interesting activity which happened at Nestlé is the organisation of an internal workshop on decarbonization of the Konolfingen factory. The workshop lasted one week and has been conducted in

August 2022. The internal workshop has allowed the Nestlé production site of Konolfingen to make their masterplan which is their energy plan for the next year in order to transform the site to a carbon neutral. The results are a modification of the main heating and cooling network of the site. The reduction of the temperature of the highest heating network and the addition of a new network with a different temperature level. For the process still requiring steam, a steam generating heat pump is planed using the network with the highest temperature as the heat source but this part of the masterplan is not planned to be made in the next 5 years.

Nestlé hasn't proven to be a very interesting case study for this project with a duration of around 2 years. However, they are highly interested to know more about the high-temperature and steam-generating heat pump as these technologies will be installed in many of their factories worldwide. It, however, seems clear for the authors that Nestlé will not be the first company to install such modern technologies and are waiting to see how the first demonstration projects will work before installing them on their sites.

Therefore, it is important to have Nestlé on the loop, to be able to share with them the advancement of these technologies and to help them modernize all their factories with the most efficient solutions the quickest as possible as their potential of reducing CO_2 production is huge.

3 Procedures and methodology

Information of the different industrial plants came from our direct contact at DSM and UCB Farchim. The industrial partners always replied promptly when more information was needed.

Information on heat pumps and components came from scientific literature (e.g., peer-reviewed papers, magazines, conference proceedings, and online presentations), our own experience at OST, and via direct exchange with manufacturers.

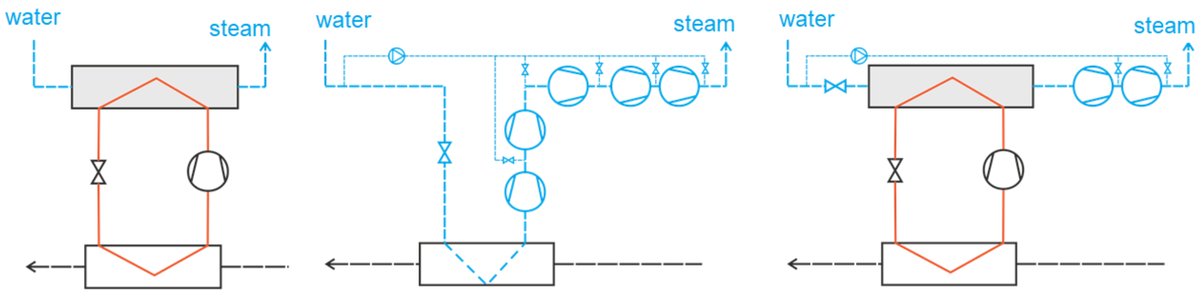
Heat pump cycle simulations were made using Coolpack and/or EES (Engineering Equation Solver) software. The details of these models are given in the following sections.

The global methodology can be described as follows: an assessment of the entire plant is performed using Pinch Analysis if such study has been done, otherwise the plant's energy flows are obtained and used. Then a first step consisting of finding all the heat recuperation potential is performed which is easy to do, if a grand composite curve is available. For each process where low-pressure steam is needed, a potential of using a SGHP is evaluated, looking for potential heat sources. If a process is found with a suitable heat source, more details are requested as to whether the process is a constant or a batch process and to verify the temperature and capacity of both the steam and the cooling needs. It is also important to discuss the possibility of reducing the temperature difference between the heating/cooling fluid and the product. Different heat pump designs (centralised, decentralised, closed-loop, open-loop, choice of refrigerant, etc.) are made as described as in this report.

3.1 Heat pump models

3.1.1 Different heat pump cycles

There are three different main heat pump cycles: closed-cycle, open cycle, the combination of both cycles also named the combined-cycle. The definition of "open cycle heat pump" in this document is, when the refrigerant is used directly in the process. The advantage of the open cycle is that it only needs one heat exchanger (the evaporator) and it can be more efficient as the produced heat is the final product, often water vapor. It is directly used and thus it reduces the need of producing a higher temperature. The three different cycles are shown in the figure below[3]:



where a) is the closed-cycle, b) the open-cycle, and c) the combined cycle. The combined cycle can be the optimal solution especially when the temperature lift is high and the delivery temperature is above the critical temperature of many refrigerants. Indeed, the limitation of the closed-loop in the case of high-temperature delivery (>= 100°C) is the reduced number of suitable refrigerant with a critical temperature above the desired temperature. The limitation of the open loop cycle comes with a high temperature lift which requires multiple pressure stages with the efficiency decreasing for each stage. Another limitation is to evaporate the product, often water, at low-pressure. The combined-cycle can solve both limitations by reducing the number of steam compressors and by reducing the temperature in the close-cycle heat sink.

3.1.2 Closed-loop model

The closed-loop heat pump model for a steady state heat pump is made using energy balance. Figure 4 shows a schematic of a heat pump on the left and the log(p)-h diagram on the right. The right hand-side diagram can be use to describe how the model is made.

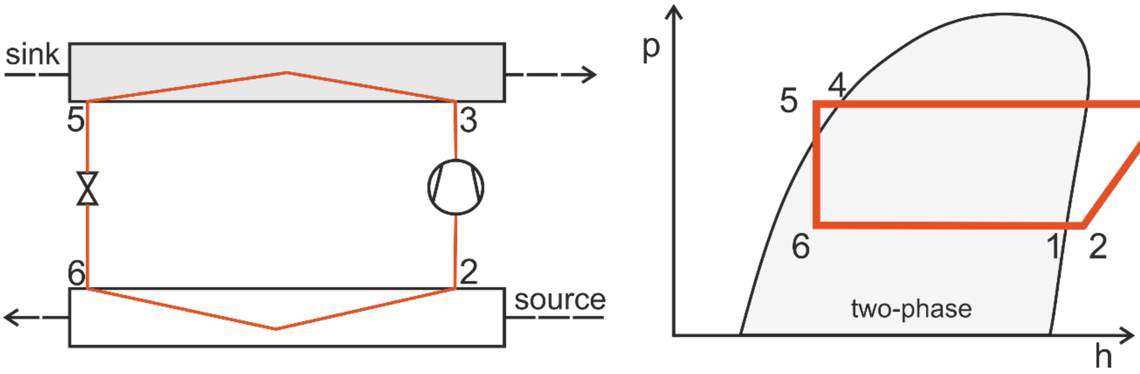


Figure 4: closed-loop heat pump schematic and log(p)-h diagram.

On the log(p)-h diagram, the horizontal line in the two phase dome represent a constant temperature of the refrigerant: condensation temperature on the higher pressure and evaporation on the lower pressure. The pressure and enthalpy for each state is depending on the refrigerant, here shown in orange. Each state is fully defined by its pressure and enthalpy. For our model, the condensation pressure (points 3,4, and 5) as well as the evaporation pressure (points 1,2, and 6) are full defined

[3] Bless F., Arpagaus C., Bertsch S.S., Schiffman J.: Theoretical analysis of steam generation methods - Energy, CO2 emission, and cost analysis, Energy, 2017, 129, 114-121

from the heat sink and source. The heat sink and source temperature is given by the specific cases. For simplification a temperature difference (also called Pinch point) between these temperature and the condensating and evaporating temperatures is fixed, which in reality depends on the properties of the heat exchanger used. This model uses 5K, meaning that the condensating temperature is 5K higher than the heat sink temperature and the evaporating temperature is 5K lower than the heat source temperature, which is a conservative design in this capacity range.
Thus the states 1 and 4 are defined using the properties of the refrigerant as the boundary of the two-phase is known for the used refrigerants. To calculate the state 2 and 5, the super-heating, respectively, sub-cooling is fixed. In reality, both are coming from the sizing of the heat exchangers, refrigerant charge and the control of the expansion valve. In this model a simple fixed temperature gap is given, which again is a save assumption, since the effects on performance are usually low. Both over-heating and under-cooling are fixed to 5K.
The expansion of the refrigerant (between state 5 and 6) is assumed to be isenthalpic, meaning that the enthalpy of state 6 is the same as the one in state 5, thus fully defining state 6.
The last state to be defined is 3 which is after the compressor. To estimate state 3, the isenstropic efficiency (η_{is}) of the compressor is needed. It is calculated using the following equation

$$\eta_{is} = (h'_3 - h_2)/(h_3 - h_2)$$

where h_i is the enthalpy at state i and h' is the enthalpy of state 3 if the compression would be isentropic (i.e. same entropy at state 2 and 3). Thus as h'_3 is fully defined, h_3 can be calculated using (η_{is}). The isentropic efficiency depends on the compressor and the pressure ratio. In this model it was fixed to 70%.
The COP can be calculated using the ratio of the enthalpy differences:

$$COP = {}^{(h_3 - h_5)}\!/\!_{(h_2 - h_6)}.$$

The cooling capacity (Q_c) can also be calculated as a ratio of the heating capacity (Q_h) as follow:

$$Q_c = Q_h \cdot \left(1 - \frac{1}{COP}\right).$$

This model is simple in the way that no heat loss and pressure loss are considered. No internal heat exchanger is modelled which can improve the COP. The error is approximately 10%.

Once the simulation runs and gives results, the pressure ratio between the condensating pressure and the evaporating pressure can be calculated to determine if multiple compression stages are necessary due to the limitations of a real compressor. Finally the massflow of the refrigerant can be calculated using the heating capacity:

$$Q_h = \dot{m} \cdot (h_3 - h_5).$$

3.1.3 Open-loop model

The open-loop model is similar to the closed loop model. In this case the refrigerant very ofteh is water but other refrigerant such as chemical product could also be envisioned. Similar assumptions are made as with the closed loop heat pump. One additional limitation is the maximum compression ratio of water compressors (usually centrifugal). This value can also be given in terms of temperature gap when the saturation temperature is used. For water compressor most of the current steam compressors can achieve a temperature lift of 15K which corresponds to a pressure ratio between 1.5 and 2 depending on the input temperature. State of the art mechanical vapour recompressor blower are able to go higher than 20K (Piller Compressor) and a prototype of a rotary vane machine is aiming to 50 to 60K (toCircle) which will be a game changer in the MVR branch.The open-loop cycle can be

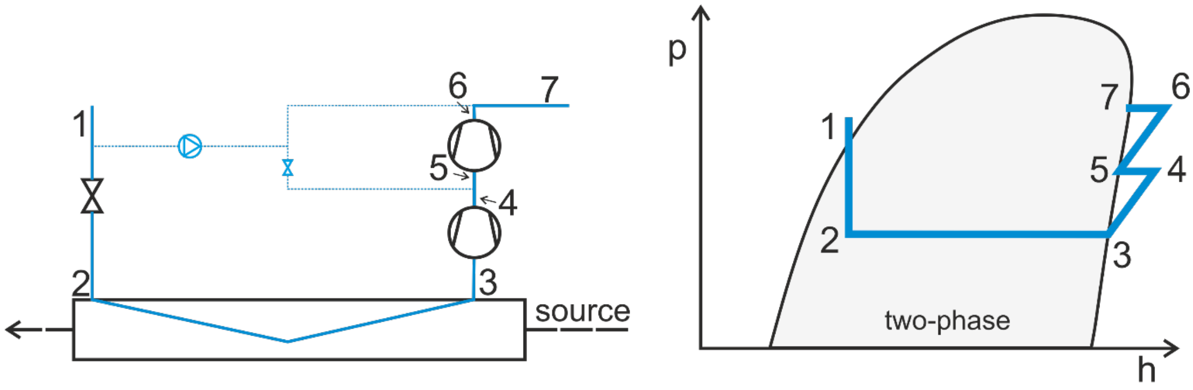


Figure 5: Schematic and log(p)-h diagram of an open-loop cycle heat pump.

represented as shown Figure 5.

One main difference for this model is to simulate the inter-cooling between any compressor step. The intercooling is made using the input water (the work of the inter-cooling circulating pump is neglected, due to low power needs for fluid compression). Inter-cooling is necessary to avoid highly super-heated steam which is at too high temperatures to be handled by existing compressors.

The additional difficulty in the simulation is that after each intercooling step, the water mass flow increases. The states described in Figure 5 are calculated as follows:

State 1 is the input state of the refrigerant, here water and its temperature and pressure are known. The required steam temperature is given by the industrial process and fixes the pressure of the states 6 and 7 as saturated pressure at this temperature. Similarly to the closed-loop cycle, the pressure of state 2 and 3 is the saturated pressure at the evaporation temperature of the water. This temperature is given by the source temperature minus the temperature difference or Pinch point (here fixed to 5K). Isenthalpic expansion is assumed between state 1 and 2.
The number of compression stages is calculated knowing the total pressure ratio and the maximal compression ratio value of the compressor simulated which is 2.5 (using a state of the art compressor). Once the number of compressions stages is known, the compression is distributed equally to all compressors. The same isentropic efficiency for the compressors is assumed, here fixed to 70%.

The following steps are computed for each compression stage:

- The pressure of state 4 is the previous state pressure times the pressure difference per compression step calculated previously. Using the same equation as in section 4.1.2, the state 4 can be fully obtained using the isentropic efficiency.
- State 5 is the value at the border of the two-phase dome for the same pressure as state 4

As explained above, the inter-cooling is made using the water injection method which is more efficient and cheaper than using heat exchangers between the compressors (see Bless et al. 2018). The amount of water added to the steam is calculated in order to cool the steam down to its saturated temperature and can be calculated as follow:

$$\dot{m}_{steam} \cdot (h_4 - h_5) = \dot{m_{wi}} \cdot (h_5 - h_1),$$

where $\dot{m}_{wi}$ is the mass flow of the water injection. The massflow of the steam increases after each cooling step.

The COP is more complex to calculate and requires to calculate the electrical power of each compressor which depends on the mass flow.

$$W_{el,i} = \dot{m}_i \cdot (h_{3+i} - h_{2+i})$$

where i is the number of compression step. COP is thus

$$COP = \dot{m}_{steam,7} \cdot {(h_1 - h_7)} / {\sum_i W_{el,i}},$$

the mass flow can be removed as each increase of mass flow is depending on the input mass flow. Thus a general COP (without any indication of the heating power) using only enthalpy can be calculated.

3.1.4 Combined cycle

The combined cycle is calculated using the closed-loop cycle and the open-loop cycle, a schematic is shown in Figure 6.

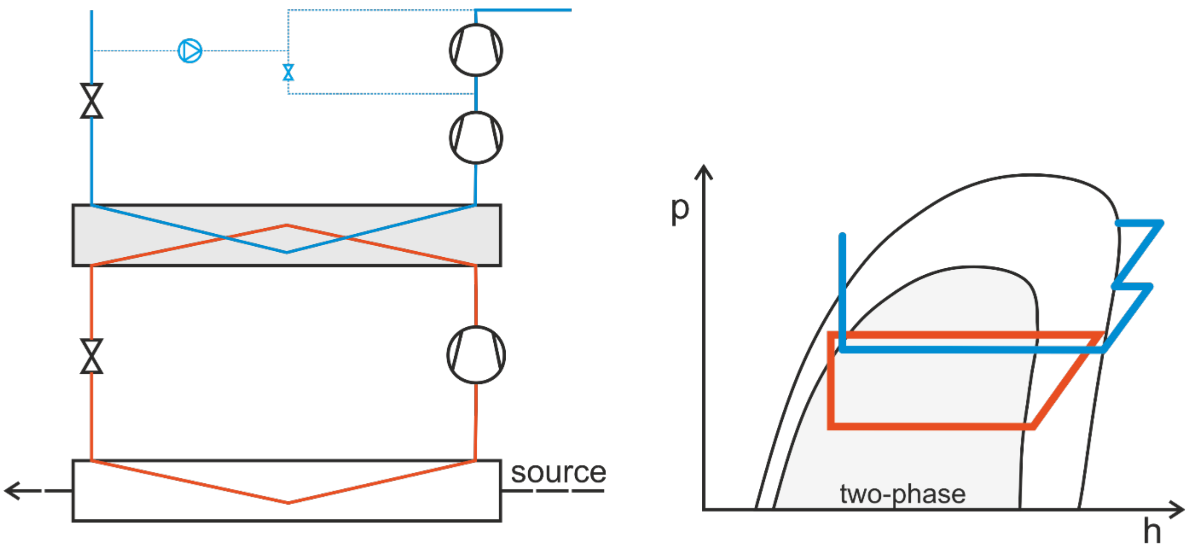


Figure 6: Schematic and log(p)-h from a combined cycle.

The first step is to decide the intermediate temperature (evaporating temperature for the open-loop cycle). Then the open loop simulation runs. A fixed mass flow is chosen to calculate the energy required to evaporate the water. Then, the close-loop cycle is run with the heating capacity equal to the energy calculated from the open-loop. Finally the COP is calculated with the heating capacity of the open-loop

$$(Q_{steam} = \dot{m}_{steam} \cdot (h_7 - h_1))$$

divided by all the compressors work:

$$COP = Q_{steam}/\sum W_{el}.$$

3.2 Refrigerants

The refrigerant in a heat pump is one of the main components and influences all the sizing and type of the components. For high temperature 80°C and higher, only a few refrigerants are able to reach such a high condensation temperature. To select a refrigerant, one must also consider current and future regulations. Refrigerants with an ozone potential (ODP) are already banned in Switzerland, and refrigerant with a global warming potential (GWP) are also regulated[4]. This exact allowable limit of GWP also depends on the total heating capacity of the system and the type of industrial process. The main future-proof choices are natural refrigerants and hydrofluorolefin (HFO) refrigerants: HCFO-R1233zd(E), HFO-R13336mzz(Z), R600 (n-butane), R600a (iso-butane), R717 (ammonia) and R718 (water). Although all the refrigerants have no (or insignificant) ODP and low GWP, each has its advantages and disadvantages. Here are some properties of them:

[4] https://www.bafu.admin.ch/bafu/en/home/topics/chemicals/info-specialists/chemicals--regulations-and-procedures/refrigerants.html

Refrigerant	Advantage	Disadvantage
R718 (water)	• high heat capacity, high heat transfer • no need for special safety measures • no need for high-pressure piping • cheap refrigerant • high efficiency for many applications	• high-pressure ratio for low temperature increase, which means multiple compressors in series with intercooling are necessary • lack of commercial components
R717 (ammonia)	• large volumetric heating capacity	• low-pressure ratio, may need 2 stages compression due to temperature at the compressor outlet, high specific heat • high-pressure components are required • toxic, which implies safety measures • limited in maximum temperature
Hydrocarbon: R600a (iso-butane), R600 (n-butane), R290 (propane), etc.	• low-pressure ratio • cheap refrigerant	• highly flammable, which implies safety measures around the heat pump
HFOs (Hydrofluorolefine): R1233zd(E), R13336mzz(Z), etc.	• good thermal properties for high temperature applications • low GWP • many components available	• expensive refrigerant • ODP of R1233zd(E) not zero • May form trifluoroacetic acid (TFA) which is particularly toxic for aquatic organisms even at low concentrations.

At first sight HFO refrigerants seem to be the best solution as they do not require safety measures and lead to systems with low investment cost. However, their long-term future authorization cannot be known. There is still research to determine how much HFOs degrade into trifluoracetic acid (TFA) in the atmosphere. TFA is toxic to aquatic life and is not biodegradable. It can be that HFOs would be banned in the future due to their degradation into TFA or for other reasons. Hydrocarbon refrigerants need ex-protection measures that add to the cost but are common in industries. Ammonia also needs safety measures due to its toxicity and flamability. It is a standard refrigerant often used in chillers and in high-power industrial heat pumps up to about 90°C supply temperature. **It does not seem that a perfect refrigerant exists for steam generating heat pump, meaning that any choice would have some advantages and drawbacks.**
The table below shows some refrigerants properties discussed above.

Refrigerant	Critical Pressure [bar]	Critical Temperature [°C]	Pressure ratio for 70°C/ 120°C	Density gas @ 70°C	Cp Gas @ 70°C	Flammable	Toxicity	GWP	ODP
R717 (ammonia)	83.2	132.3	2.8	26.4	4.7	(slightly)	yes	0	0
R600a (iso-butane)	36.4	134.7	2.6	28.4	2.3	yes	no	<5	0
R600 (n-butane)	38.0	152.0	2.7	20	2.2	yes	yes	<5	0
R718 (water)	220.6	373.9	6.4	0.2	2.0	no	no	0	0
R1336mzz(Z)	29.0	171.3	3.4	21	21.0	no	no	2	0
R1233zd(E)	35.7	165.6	3.1	27	27.0	no	no	1	~0.00034

4 Results and discussion

4.1 UCB Farchim

To sum up the UCB Farchim case, the distillation process line has around 460kW of heating and cooling needs, the steam used as a heat supply has a saturation temperature of around 110°C and the cooling temperature is around 25°C.

The models of different types of heat pump cycle described in section 3.1 were used to calculated the potential COP of each cycle. After analysis of the distillation data, it was establish that it is a steady-state process, thus the creation of a complex digital twins is not necessary. The steady state heat pump model is enough to simulate the heating system as the heat sink and heat source temperature are constant.

First of all, the refrigerant had to be selected. Research has shown that transcritical cycles are not the most efficient for steam production since they require large temperature gradients on the heat sink side[5]. Therefore, only a few refrigerants can reach such a high condensation temperature. As seen in section 3.2, there isn't a perfect refrigerant. In this particular case, the near future-proof choices are natural and hydrofluorolefin (HFO) refrigerants, eventhough the HFO refrigerants may not be future-proof in EU: HCFO-R1233zd(E), HFO-R13336mzz(Z), R600 (n-butane), R600a (iso-butane), R717 (ammonia) and R718 (water). Hydrocarbon refrigerants need ex-protection measures that add to the cost but are common in industry. The particular plant at UCB Farchim even has ex-protection in certain areas of the plant. Ammonia needs even higher safety measures due to its toxicity. Therefore, at first all the refrigerant are taken into consideration when doing the simulation for this case. UCB Farchim wanted first to have an idea of all the possible options without restricting their selection of refrigerant.

4.1.1 Closed-cycle heat pump simulation

Starting with the closed-loop cycle, the heat pump model was made with the following additional assumption:

- 1 compression step
- 5K superheating unless for R1336mzz(Z), which needs a superheat of 17K to avoid 2-phase compression.

As written in section 3.1.2, the cooling capacity of the heat pump is lower than its heating capacity. However, the distillation process requires the same heating and cooling capacity. Thus, there is still a need for a cooling tower with the cooling power corresponding to approximately the compressor input power.

The advantages and shortcomings of a closed-loop heat pump cycle in comparaison to a standard heating system are:

- PRO:
  - \+ electrification of heat, high potential of reducing CO_2 emission possible
  - \+ higher efficiency than other electrical (or hydrogen) systems meaning reduced energy consumption
  - \+ less dependent on gas price and gas production
  - \+ electricity could be produced and/or stored by the company to be totally independent and reducing the electricity price variation.

[5] Bless, F.; Arpagaus, C.; Bertsch, S.: Theoretical Investigation of High-Temperature Heat Pump Cycles for Steam Generation, 13th IEA Heat Pump Conference, Jeju, Korea, 11-14 May 2020, postponed to 26 -29 April 2021.

- + Zero-CO2 possibility using renewable electrical power
- CONS:
  - higher CAPEX
  - 'new' technology, not a lot of systems installed to analyse the durability of the heat pump for short and long-term
  - smaller power range and temperature range variation that cannot be easily modified to fit other needs in the future (compared to fossil boilers).
  - for the refrigerant R1336mzz(Z): its thermodynamic properties force a high overheating to avoid wet compression, which does not suit the process temperatures and requires an additional internal heat exchanger.

The COPs calculated are given in the following table:

Refrigerant	COP 17°C/115°C	Cooling reduction [%]	Remark:
R717 (ammonia)	**2.41**	58	Compressor outlet temperature is 312°C (1 stage) + high pressure -> intercooling or economizing needed
R600a (iso-butane)	**2.16**	54	
R600 (n-butane)	**2.29**	56	
R718 (water)	**2.38**	58	Needs multistage compressor + very low evap. Pressure, which manufacturers try to avoid
R1336mzz(Z)	**2.36**	58	Needs an internal heat exchanger, otherwise 2-phase compression, HFO refrigerant
R1233zd(E)	**2.40**	58	HCFO refrigerant

4.1.1.1 Sensibility analysis with R1336mzz(Z)

This sensibility analysis is conducted using the refrigerant R1336mzz. Using one of the refrigerants listed in the previous section will lead to very similar effects. The idea is to show the effect of small variations of the heat sink and heat supply temperatures on the COP of the system. This study was done to show the impact of reduced temperature lift on the effiency of the overall saystem to judge potential modifications of the distillation process.

Analysis of a slight variation of the evaporation temperature on the COP.

Temp cold outlet	Evap	Cond	Lift	COP	COP Change
°C	°C	°C	°C	-	%
20	15	115	100	2.30	-2.5
22	17	115	98	2.36	0
24	19	115	96	2.42	2.5
26	21	115	94	2.49	5.5
28	23	115	92	2.56	8.5

Analysis of a slight variation of the condensing temperature on the COP.

Temp hot outlet	Evap	Cond	Lift	COP	COP Change
°C	°C	°C	°C	-	%

115	17	120	103	2.32	-1.7
110	17	115	98	2.36	0
105	17	110	93	2.41	2.1
100	17	105	88	2.46	4.2
95	17	100	83	2.52	6.8

This theoretical study was shown to UCB Farchim to make them aware of the effect on the efficiency depending on the process temperature. However, the control engineers are not ready to modify the process control. The startup is all made by hand and has been working great since months and there is no motivation to try another process control even if it could lead to a more efficiency on the heat pump without knowing the effect on the product.

4.1.2 Open-cycle heat pump simulation

To simulate an open-loop cycle heat pump, the water needs to be expanded to around 20 mbar (which has a saturated temperature of 17°C) in order to cool the process. Once the water is evaporated, multiple compression steps in series are required to attain a saturation temperature of 110°C.

To calculate the COP, the heat pump model described in section 3.1.3 was made with the additional assumptions:

- hot water returns at 90°C as saturated destillate
- compressor isentropic efficiency fixed to 70% with a compression ratio of a maximum of 3 (which is technically high for turbomachinery).

The **COP of** such system was calculated to be **2.80**. The details of this simulation are given in the appendix. Four or more Intercooling stages (water injection) have to be implemented, each after a compression step. The reduction of the cooling need for the cooling tower is around 64%, and therefore higher than for any closed cycle system.

PROS:

- high efficiency
- water as refrigerant is non-toxic, non-flammable, and, cheap, already used by UCB Farchim.
- only needs 1 heat exchanger

CONS:

- newish technology, not a lot of know-how by manufacturers yet. An option would be to build the system by Farchim itself with the help of a steam compressor manufacturer
- Low evaporation pressure (only 20 mbar) which can be technically challenging and leads to very high volumetric flow rates.
- Would need at least four water compressors with a high pressure ratio at different working pressure, meaning different steam density for each compressor

4.1.2.1 Sensibility analysis with the open-loop cycle

This sensibility analysis is made for the open-loop cycle using water as a refrigerant. It shows the effect of small variations of the hot and cold temperatures on the COP of the system.

Temp cold outlet	Evap	Final	Lift	COP	COP Change	Compressions info
°C	°C	°C	°C	-	%	Pressure ratio (# steps)
20	15	110	100	**2.76**	-1.4	2.43 (5)
22	17	110	98	**2.80**	0	2.93 (4)

24	19	110	96	**2.86**	2.2	2.84 (4)
26	21	110	94	**2.91**	4.0	2.76 (4)
28	23	110	92	**3.00**	7.2	2.67 (4)

Analysis of a slight variation of the evaporation temperature on the COP.

Analysis of a slight variation of the condensing temperature on the COP.

Temp steam outlet	Evap	Lift	COP	COP Change	Compressions info
°C	°C	°C	-	%	Pressure ratio (# steps)
120	17	103	**2.64**	-5.6	2.52 (5)
115	17	98	**2.73**	-2.6	2.44 (5)
110	17	93	**2.80**	0	2.84 (4)
105	17	88	**2.90**	3.6	2.81 (4)
100	17	83	**3.02**	7.9	2.69 (4)

4.1.3 Combined cycle heat pump simulation

As the cooling temperature is low, the open cycle using water as refrigerant will have to evaporate the water at a very low pressure (around 20 mbar). In order to take advantage of the currently available technology, a combination of closed and open cycle can be used. The system will look like the schematic shown in the figure below.

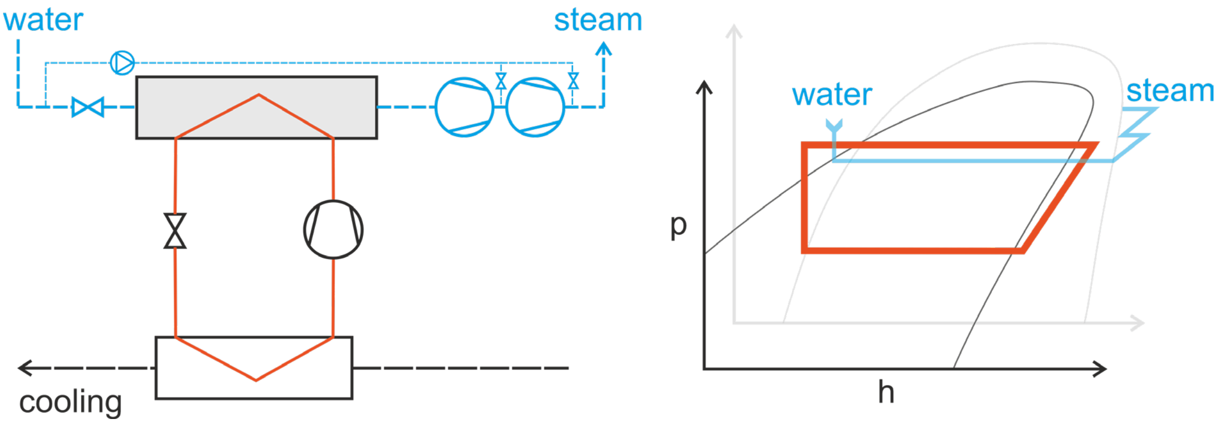


Figure 7: Combined cycle heat pump.

A standard heat pump is used with an evaporating and a condensing temperature of 20°C and approximately 70°C respectively using Ammonia. This system then evaporates the water at 65°C and steam compressors will further increase the steam pressure to the desired 110°C saturation temperature. The total combined **COP is 2.92** assuming compressors with 70% isentropic efficiency and with high pressure ratio. The details can be seen in the appendix. It is surprising that the effiency is slightly above the open-loop with water heat pump cycle which has a COP of 2.8. Reason is the optimal use of the refrigerants combination in the cylce. Firstly, the heat pump temperature is well below the critical temperature of the refrigerant where the COP tends to decline. Secondly, having only two steam compression steps reduces the complexity compared to the four steps of the open-loop cycle heat pump using water as refrigerant.

The reduction of the cooling needed by the cooling tower is around 66% which is similar to the open-loop cycle system.

The condensing temperature of the heat pump can be different. The choice of 70°C was made as many industrial heat pumps with these temperatures were found on the market[6], however, depending on the refrigerant and the compressors, another intermediate temperature may result in an even better efficiency.
After discussion with the some steam compressors and heat pump manufacturer, it is clear that the intermediate temperature will have to be optimise depending on the refrigerant(s) used in the heat pump, the refrigerant compressors and material available on the market and the efficient, minimal pressure section, and pressure ratio of the steam compressors.

PROS:

- high efficiency
- no need of high temperature heat pump, standard heat pump is feasible
- increase of the water evaporation pressure which makes it easier to find a suitable steam compressor
- two heating temperature levels are available. If the heat pump heating capacity is higher than the steam evaporation needed, heating at 70°C is available for other processes in the plant, reducing the exergy losses.

CONS:

- “new” technology, not a lot of know-how by manufacturers yet. An option would be to build it by Farchim itself with the help of an industrial heat pump manufacturer and a steam compressor manufacturer
- two systems have to be well controled together (heat pump & steam compressors) increasing the complexity of the control system
- would need two water compressor stages or more with the same pressure ratio but different working pressure meaning different steam density.

4.2 DSM

To sum up the DSM case, the distillation process line has around 2.3 MW of heating need, the steam used as a heat supply has a saturation temperature of around 110°C and the cooling temperature is around 45°C.

The models of different types of heat pump cycle described in section 4.1 were used to calculated the potential COP of each cycle. We were informed that it is also a steady-state process similarly to the UCB Farchim case.

First of all, the refrigerant had to be selected. DSM is only looking for natural refrigerants and would thus like to avoid synthetic HFOs because of uncertainty and environmental concerns in the future.

4.2.1 Closed-cycle heat pump simulation

The tendency toward natural refrigerants, preferably water vapor is wished by DSM. This refrigerant does not need special permits, and the steam network can be centralized and energy transported via pipes to the various production buildings. On the other hand, DSM prefers to avoid ammonia due to its toxicity and also hydrocarbons due to their flammability and risk of explosion. It seems that at the end of the decision, a trade-off is needed between availability, environment, and cost.

[6] https://www.gea.com/en/products/refrigeration-heating/gea-blu-red-fusion.jsp

A simulation made in collaboration with the industry partner of the closed-cycle using water as refrigerant was performed using the model described in section 3.1.2. Additional assumptions are the following:

- Two-stage cycle with two compressors steps (3.48 pressure ratio and 5.2 pressure ratio)
- Evaporating temperature of 45°C (0.096 bar)
- Condensation temperature of 115.9°C (1.74 bar)
- Intermediate process water pressure of 0.5 bar (81.33°C)
- Isentropic efficiency of 70%
- Constant flow rate

The result shows a **COP of 3.06.** However, the low pressure (0.096 bar) and the high-pressure ratio of 5.2 are hindrances to finding a real steam compressor to build such a heat pump (see section 4.3.3). Furthermore, as DSM is interested in using water (R718) as a refrigerant, an open-cycle heat pump would be a better option. Although it uses the same compressors and the low-pressure is the same, it reduces one large heat exchanger (condenser) and has a higher COP.

4.2.2 Open-cycle heat pump simulation

In principle, a 2-stage water vapor compression from 96 mbar to 500 mbar and then to 1.74 bar is technically feasible. However, the combination of high delivery volumes (45,000 m3/h) and low vacuum suction pressure (96 mbar, absolute) is a major challenge for most compressor manufacturers. There are only a few suppliers who can offer a technical solution. Multistage centrifugal fans or roots blowers seem to be the best compromise, with water injection interposed to cool the hot gases as described in section 3.1.3. Between 4 and 12 compressors would be needed depending on the type (calculation based on market available compressors). A simple calculation using 8 steam compressors steps gives a **COP of 3.29** which is better than the COP of the closed cycle (3.06).
Depending on the stability of the process, an additional intermediate steam storage tank must be installed in order to compensate for the short-term fluctuations in heat generation. The advantages and disadvantages are similar to those of the UCB Farchim case.

PROS:

- high efficiency.
- multiple heating temperature level available. Steam could be used at each compressor stage for different processes.
- water as refrigerant is non-toxic, non-flammable, and, cheap.
- reduced need of an heat exchanger compared to the closed cycle system which is a gain of place, efficiency and cost.

CONS:

- compressing low-pressure vapour at high volume is a fairly new technique, not a lot of know-how by manufacturers yet, only large scale compressor available on the market (luckily fitting the needs of DSM quite well).
- would need multiple water compressors or more with the same pressure ratio but different working pressure meaning different steam density.

Contrary to the UCB Farchim case, an open-loop cycle will have more advantage here as the temperature lift is lower and more steam compressors are available at this high power range. This case also does not require a combined cycle to surpass the difficulty seen in the UCB Farchim case with a very low evaporating temperature.

4.3 Summary of market available products and components

4.3.1 High-Temperature Heat Pumps (HTHP) (>100 °C)

Commercial steam-generating heat pump (SGHP) technologies and vapor compressors are increasingly available on the market. Figure 8 shows an overview of some suppliers of industrial HTHPs structured by maximal supply temperature. The products deliver more than 90 °C but vary in thermal capacity, compressor technology, and refrigerant. Only a few companies offer products in the MW-scale (e.g., Friotherm AG, Switzerland).

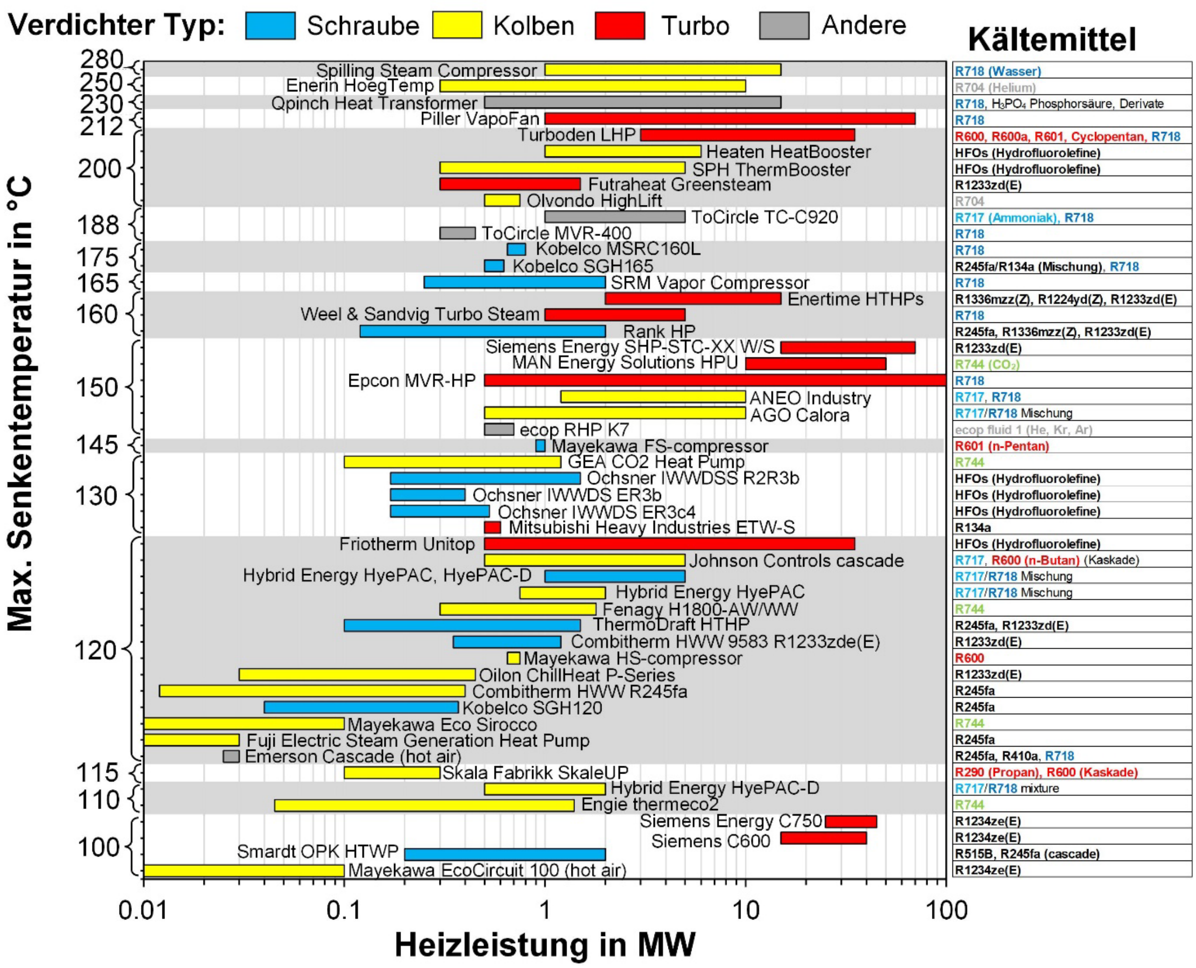


Figure 8: List of commercial HTHPs taken from (Arpagaus, Hochtemperature Wärmepumpe Buchs, version 2, 2023-2024).

Since 2018 the market of industrial HTHPs has been evolving rapidly as industry is increasingly interested in implementing heat pump technologies. Thus, this list of HTHPs shown in Figure 8 increased with new products from manufacturers like SPH Sustainable Process Heat (Germany), Heaten AS (Norway), MAN Energy Solutions (Switzerland), Johnson Controls (Denmark), Turboden (Italy), Olvondo (Norway), Fuji Electric (Japan), Mayekawa (Japan), ecop Technologies (Austria), and others (Arpagaus et al. 2022, Bless et al. 2022).

Table 3 shows a non-exhaustive list of HTHP suppliers with heat sink temperatures >120 °C suggesting the technical feasibility of SGHP (steam-generating heat pump) and MVR (mechanical vapor recompression). The compressor technologies include mainly piston, screw, and centrifugal compressors.

Table 3: Overview of some HTHP suppliers (not an exhaustive list) with heat sink temperatures >120 °C showing technical feasibility of SGHP and MVR made by OST-IES after many private market analysis. TRL: Technology Readiness Level.

HTHP supplier	Compressor type	Working fluid (Refrigerant)	Max. capacity [MW]	Max. supply temp [°C]	TRL
Spilling (DE)	Piston	R718	15	280	9
Enerin (NO)	Piston	R704	10	250	6
Piller (DE)	Turbo	R718	70	212	8 to 9
Olvondo (NO)	Piston (double acting)	R704	5	200	9
Turboden (IT)	Turbo	Application specific	30	200	7 to 9
ToCircle (NO)	Rotary vane	R717+R718	5	188	6 to 7
Kobelco (JP)	Twin-screw	R245fa/R134a + R718	0.4	175	9
SRM (SE)	Screw	R718	3	165	5
SPH (DE)	Piston	HFOs	5	165	7 to 8
Heaten (NO)	Reciprocating	HFOs	6	165	7 to 9
Weel & Sandvig (DK)	Turbo	R718	5	160	4 to 9
Siemens Energy (DE)	Turbo	R1233zd(E)/R1234ze(E)	70	160	9
ECOP (AT)	Rotational heat pump	ecop fluid 1	0.7	150	6 to 7
Rank (ES)	Screw	R245fa, R1336mzz(Z), R1233zd(E)	2	150	7
Epcon (NO)	Centrifugal fans, blowers	R718	30	150	9
MAN Energy Solutions (CH)	Turbo with expander	R744	50	150	7 to 8
Mitsubishi Heavy Industries	Two-stage centrifugal	R134a	0.6	130	9
Fuji Electric (JP)	Reciprocating	R245fa	0.03	120	9
Emerson (US)	Scroll and EVI scroll	R245fa, R410a, R718	0.03	120	6
Mayekawa (JP)	Reciprocating	R744	0.1	120	8 to 9
Fenagy (DK)	Reciprocating	R744	1.8	120	5 to 6
Johnson Controls (DK)	Reciprocating	R717+R600 (cascade)	5	120	7 to 8

4.3.2 Steam Generating Heat Pumps

Figure 9 illustrates some large-scale SGHPs (>1 MW heating capacity) that provide high supply temperatures between 115 and 174 °C. The main difference between HTHP and SGHP is the condenser of the heat pump which evaporates the water. Some HTHP can be transformed into SGHP by heating high-pressure water and using an additional component, the flash tank (see section 4.3.4), to create steam. There is also increased interest in so called shell and plate heat exchangers as condensers that can be used to directly evaporate water. There aren't many SGHP heat pump prototypes and thus there are no best practice examples with respect to sizing and design. Also, there is still a lack of know-how on the combination of SGHP and steam storage.

Friotherm (CH)	Turboden (IT)	MAN Energy Solutions (CH)	Mitsubishi MHPS (DE)	Siemens (DE)	Ochsner (AT)	Kobelco (JP)
FRIOTHERM Heat Pump	LHP30 LHP150	ETES	D-GWP	Large-scale	IWWDSS R2R3b IWWHS ER3b TWIN	SGH 120/165
R1233zd(E) + R718 (Water)	R601 + R718 (n-Pentane + Water)	R744 (CO_2)	R600a + R718 (Iso-Butane + Water)	HFOs	Öko (R245fa) R1233zd(E) (HFOs)	R245fa + R718
25 MW	**2.7 MW 14.4 MW**	**5 to 100 MW**	**4.3 MW**	**4 to 70 MW**	**Up to 750 kW TWIN 2.4 MW**	**Up to 624 kW Cascade 2.5 MW**
137 °C	115 °C	150 °C	174 °C	150 °C	130 °C	165 °C

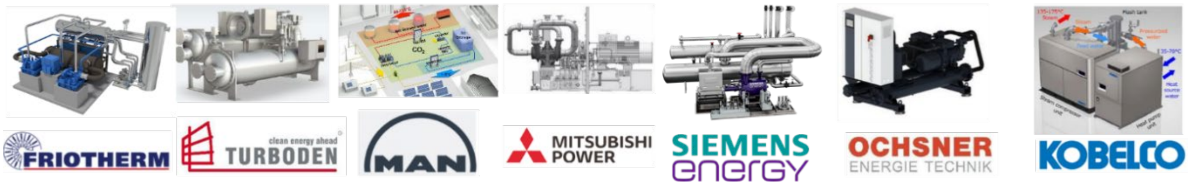


Figure 9: Examples of Large Scale HTHPs with heating capacity in the MW-scale and providing steam, list made by OST-IES throughout different market analysis projects.

4.3.3 Steam Compressors

Table 4: Comparison of roots blowers and centrifugal fans (based on experience from EPCON, Norway)

	Roots blowers	Centrifugal fans
Efficiency	45 to 55%	80 to 85%
Max. recommended temperature lift per unit	15 K	10 K
Max. outlet temperature	125 to 130 °C	150 to 160 °C
Capacity	not recommend above 1000 kW delivered energy	Min. capacity 500 to 800 kW delivered energy, depending on temperature
Maintenance cost	high	lower
Availability	lower	higher
Price	lower (typically 1/3 compared to centrifugal fans for small capacities)	higher (typically 3 times compared to roots blowers for small capacities)

Mechanical vapor recompression (MVR) is a very efficient technology to increase steam pressure and temperature. Thus, research for steam compressors is very active, with many manufacturers developing new products. Table 4 compares the typical characteristics of the two types of MVR equipment (based on direct information from EPCON[7]). Roots compressors are normally only used for small scales below 600 to 800 kW, where other options are limited. But the selection also depends on the temperature lift and temperature range. This situation will normally favour roots blowers for small capacities, both for investment reasons and operating below minimum capacities for centrifugal fans. So far, EPCON delivered mainly MVR fans (95% of the cases) and only 5% roots blowers, naturally because most of the cases are at a quite large scale.

[7] EPCON Website https://www.epcon.org/ (visited September 2023)

Table 5: List of steam compressors either available on the market or in development for potential use in SGHPs with MVR application.

Manufacturer (country)	Type	Remarks	Capacity, suction pressure	Temperature	Mass/volume Flow
Piller (DE)	Multi-stage MVR blowers, VapoFan 2-stage	Water injection, efficiency up to 86%	Up to 5 MW_el, VapoFan 90 kW_el, minimum suction 200 mbar, temperature lift 10 K per stage	up to 140 to 150 °C	up to 400'000 kg/h, 200 to 5'000 kg/h (VapoFan)
EPCON (NO)	MVR-HP, IHP-MVR-4S-66, MVR fans in series, MVR roots blowers	Open and closed cycles, distillation processes	0.65 to 4.5 MW_th, 50 to 1'250 kW_el, minimum suction 200 mbar	98, 112 to 150 °C	up to 6'600 kg/h
AERZEN (CH)	Rotary blowers, GM 240S, DeltaBlower	Several 2-stage blowers in series	Minimum suction 300 mbar, discharge 2 bar	up to 120 °C	3'600 kg/h 15'000 m3/h
Continental Industrie (DE)	Multistage centrifugal blowers, Type 600	96 to 500 mbar feasible with turbo blowers	Suction 150 to 540 mbar, pressure increase 0.2 to 1.4 bar	up to 120 °C	13'000 to 45'000 m3/h
Hoffman & Lamson (by Gardner Denver) (USA)	Multistage centrifugal blowers	-	Minimum suction 500 mbar	-	3'400 to 70'100 m3/h air and other gases
Howden (CZ)	Roots blowers, Turbo blowers	Vapor compressor, MVR	2080 RGS-J (750 kW) 2022 RGS-J (653 kW)	up to 243 °C	13'000 to 46'000 m3/h 3'000 to 3'900 kg/h
Spilling (DE)	Pistons	30 to 100% control range	Suction 2 to 20 bar, discharge 35 to 65 bar	up to 280 °C	3'000 to 15'000 kg/h
Kaeser Kompressoren (CH)	Vapor recompression blowers OMEGA 83PB	Water injection, No multistage	Minimum suction 500 mbar, discharge 2 bar	up to 120 °C	5'580 to 10'000 m3/h
Atlas Copco (DE)	Screw compressors Series ZA6	Oil-free, air or water cooled	Customized solutions	-	up to 7'200 m3/h
Johnson Controls (EDF) (FR)	2-state radial compressor (PACO Prototyp TRL 6)	Water injection, parallel arrangement possible	110 kWel, 600 kW_th, minimum suction 600 mbar	up to 130 °C	about 2'500 m3/h
DBS (UK)	TurboClaw MVR	Protoype status	Capacity 500 kW, pressure ratio up to 1.8, temperature lift 15 to 25 K per stage	-	100 to 800 m3/h
ToCircle (NO)	Two phase rotary vane compressor with water injection	Protoype status	500 kW to 5 MW, pressure ratio up to 5.5, temperature lift 50 K per stage	-	1'000 to 8'000 m3/h

Even though typically centrifugal and rotary compressors are used for steam compression, there are other alternatives on the market. As an example, Figure 10 shows an installation drawing of a 2-cylinder compressor from Spilling (Germany). The compressor system compresses from 3.5 to 15.5 bara (approx. 245 °C) and delivers 1.2 t/h steam. The costs of 710 kEUR include accessories and commissioning (i.e., drive motor with frequency converter for variable speed flow, control cabinet,

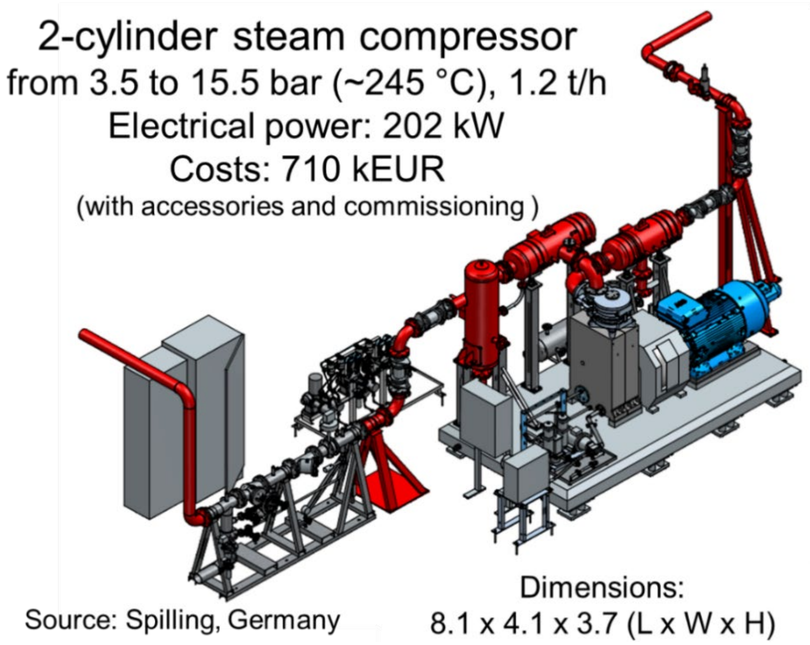


Figure 10: Examples of Large Scale HTHPs with heating capacity in the MW-scale and providing steam (Picture courtesy by Spilling Technologies GmbH, Germany)

equipment for automatic start-up, injection cooling, engineering). Operation at sub-atmospheric conditions is not recommended.

4.3.4 Flash Tank

Figure 11 shows a HTHP from Combitherm (Germany) with 3 refrigeration circuits run by screw compressors providing 1'060 kW hot water of 120 °C (Type HWW 3/9573 R1233zd(E)). The price for such an HTHP, including control components, electric panel, and functional testing, is roughly 300 kEUR. The hot water is discharged at 120 °C and converted into steam in a flash tank. A rough indicative price for the flash tank module is 185 kEUR. The flash tank system may have some advantage in terms of weight as the heat exchanger can be reduced as pressurise is heat without evaporate. However, for industrial cases, the main drawbacks are the lack of !compensenting/inertial! Volume in case the steam demand has some quick variation.

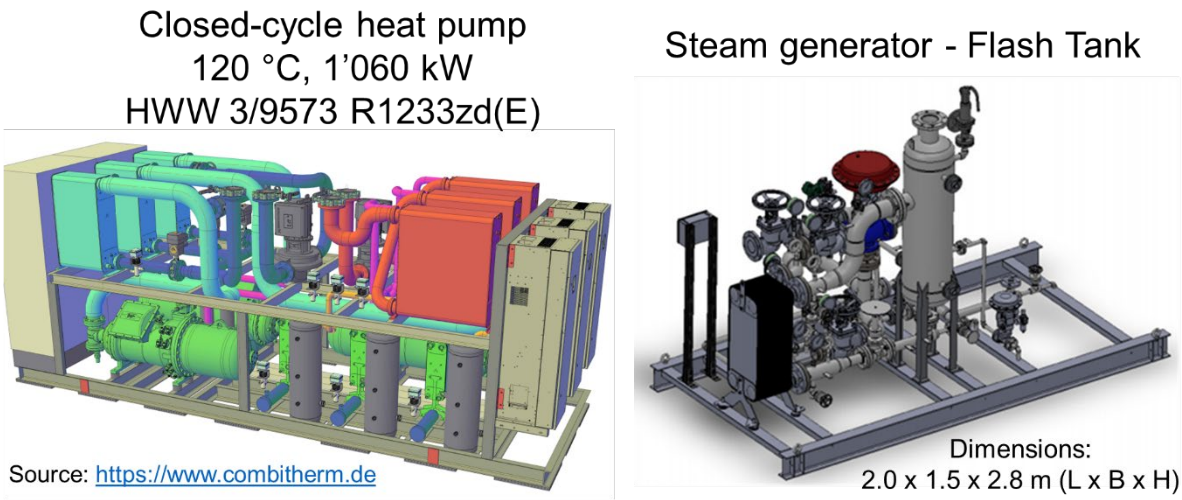


Figure 11: Closed-cycle heat pump with R1233zd(E) refrigerant providing hot water up to 120 °C and steam generator (flash tank) (Pictures courtesy by Combitherm GmbH, Germany)

4.3.5 High-Temperature Heat Pumps (HTHP) (>100 °C) able to produce steam.

Recently the IEA Annex 58 released a list of high-temperature heat pumps with sink temperature higher than 100°C on their website[8]. This temperature allows any of these heat pumps to, in theory, produce steam by the addition of a flash tank. In Appendix are copies of the lists entiteld “overview of development of supplier technologies” as well as the "overview of demonstration cases table" (section 11.4 & 11.5). It has to be noted that all information has been provided by the supplier without third-party validation. The information was provided as an indicative basis and may be different in final installations depending on application-specific parameters.

These tables from the IEA Annex show how the topic of hight-temperature heat pumps with temperature high enough to produce steam is an important topic in many european countries.

[8] https://heatpumpingtechnologies.org/annex58/task1

4.3.6 Steam storage

A steam accumulator module is a possible solution in combination with SGHPs for storing a defined quantity of energy available as expansion steam during pressure reduction. In addition, such an accumulator is used for covering short-term peak loads, e.g., if the capacity of a steam generator like a SGHP is exceeded briefly.

Figure 12 shows a steam accumulator SAM from Bosch, which consists of an horizontal cylindrical container with a built-in steam nozzle pipe. Typically, the steam accumulator is filled to 50% with water and is heated to the charging pressure with steam. Then, the accumulator is emptied by opening the shut-off devices on the consumer side. The greater the water content of the accumulator, the greater the re-evaporation heat.

Figure 12: Steam accumulator module SAM from Bosch

4.3.7 COP – Efficiency and cost of SGHPs

Cost of high-temperature heat pumps are hard to find due to their rarety and the fact that companies do not give the price of their product easily. However, thanks to many project done by OST-IES, we collected a small number of costs for different temperature lifts and heating capacities and we are able to make the following price trends presented at the High-Temperature Heat Pump Symposium of this year (2022) in March in Copenhagen by Cordin Arpagaus (Figure 13).

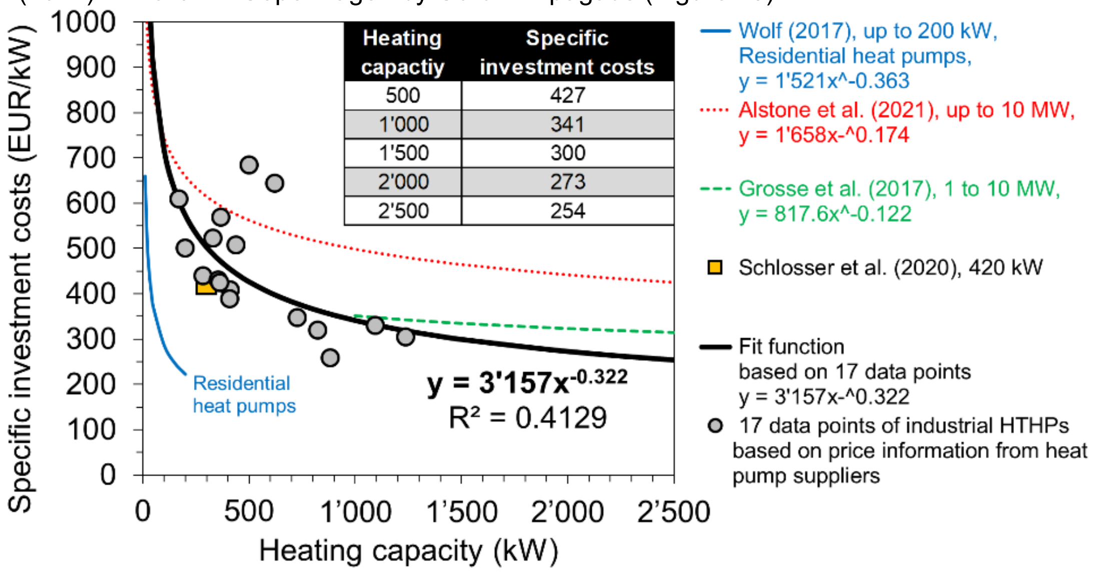


Figure 13: Specific investment cost for industrial HTHPs (excl. planning and integration) (Arpagaus et al. 2022)

It is also important to note that due to the geo-politic situation the prices of material and of systems are rising since the beginning of the Ukrain conflict. That is seen in the following graph where new data recently collected from two manufacturers is added.

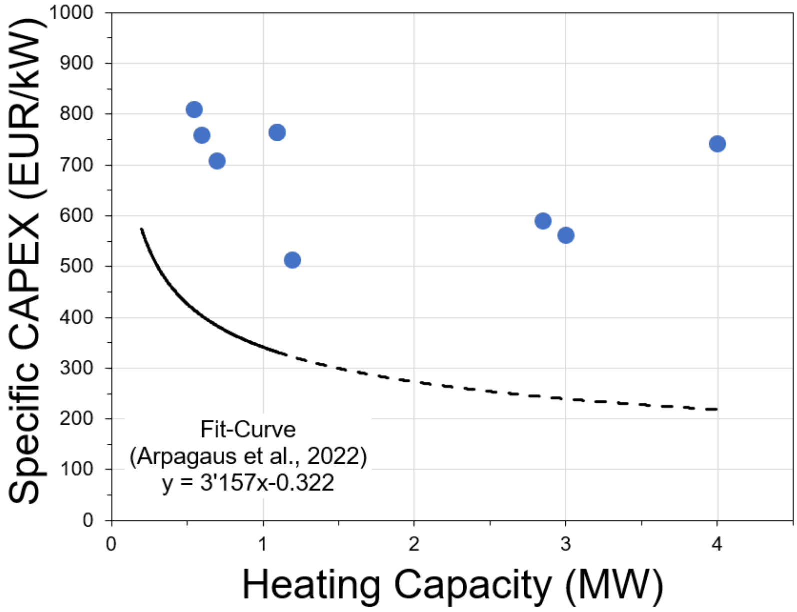


Figure 14: Similar plot as Figure 13 with additional data collected in 2022-23.

Another reason may be simply that these new manufactuers are more expensive than the average, but a cost increase has also been seen with many heat pump suppliers.

The following plot shows the COP vs the temperature difference of the new data compare with the previous fit by Arpagaus et al. 2022.

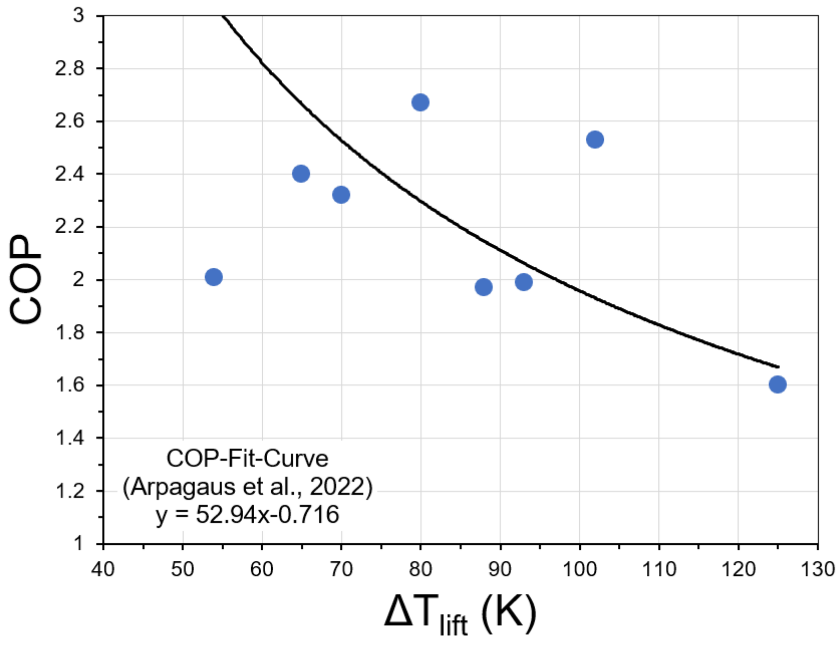


Figure 15: COP vs Temperature lift for the new data collected in 2022 and the fit based on previous studies.

Figure 15 shows that the new data points are similar in terms of efficiency compared to the previous data on which the fit was based. Thus, it shows that the technologies are not necessarily new advanced systems which would have explained the higher specific cost.

4.4 Techno-economic method to calculate the feasibility for the SGHP integration (in comparison to the current fossil-fueled steam-generating system)

In order to analyse the techno-economic feasibility of any SGHP, it is important to obtain some values of the case studied. This section is also reported in the SWEET DeCarbCH Deliverable 5.3.1[9].

The COP is the main parameter to describe the efficiency of a vapor compression heat pump. The Carnot COP ideally defines it by dividing the temperature of the heat sink (process heat demand) ($T_{h,out}$) by the temperature lift between the sink and the source ($\Delta T_{lift} = T_{h,out} - T_{c,in}$). A first COP estimate is obtained by multiplying the COP_{Carnot} by the 2nd Law efficiency (η_{2nd}). A 2nd Law efficiency of 0.45 is reasonable for several industrial HTHPs, as shown by (Arpagaus, 2018, 2020; Arpagaus et al., 2018) (Eq. 1), resulting in COPs between 2 and 6 depending on ΔT_{lift}. Eq. (2) describes the corresponding power function of the COP fit with an R^2 value of 0.78.

Based on regression analysis of literature data, Schlosser et al. (2020a) and Jesper et al. (2021) developed a more advanced fitting formula for water/water HTHPs using HCFO, HFC, or HFO refrigerants as a function of $T_{h,out}$ and ΔT_{lift} (Eq. 3). Moreover, Schlosser et al. (2020 & 2020) presented a COP correlation explicitly for water/steam VHTHPs (Eq. 4).

$$COP = \eta_{2nd} \cdot COP_{Carnot} = 0.45 \cdot \left(T_{h,out} + 273.15\right)/\Delta T_{lift} \text{ with } \Delta T_{lift} = \left(T_{h,out} - T_{c,in}\right) \quad \text{Eq. (1)}$$

$$COP = a \cdot \Delta T_{lift}{}^{b} = 68.455 \cdot \Delta T_{lift}{}^{-0.76} \text{ with } R^2 = 0.78 \quad \text{Eq. (2)}$$

$$COP = a \cdot \left(\Delta T_{lift} + 2 \cdot b\right)^{c} \cdot \left(T_{h,out} + b\right)^{d} = 1.9118 \cdot \left(\Delta T_{lift} + 2 \cdot 0.044189\right)^{-0.89094} \cdot \left(T_{h,out} + 0.044189\right)^{0.67895}$$

valid between $80\,°C \le T_{h,out} \le 160\,°C$ and $25\,K \le \Delta T_{lift} \le 95\,K$ with $R^2 = 0.95$ Eq. (3)

$$COP = a \cdot \left(\Delta T_{lift} + 2 \cdot b\right)^{c} \cdot \left(T_{h,out} + b\right)^{d} = 8.898 \cdot \left(\Delta T_{lift} + 2 \cdot 0.042214\right)^{-0.52137} \cdot \left(T_{h,out} + 0.042214\right)^{0.16395}$$

valid between $110\,°C \le T_{h,out} \le 160\,°C$ and $25\,K \le \Delta T_{lift} \le 70\,K$ with $R^2 = 0.77$ Eq. (4)

Figure 16 shows the variation of the COP with temperature lift (ΔT_{lift}) using the COP fit curves (Eqs. 2, 3, and 4). In addition, 32 data points from industrial SGHPs are plotted based on quotes from European heat pump suppliers and data from the Japanese Kobelco SGH120 and SGH165 models (Kaida, 2021, 2019). The power function $COP = 52.94 \cdot \Delta T_{lift}{}^{-0.716}$ (black line) (Eq. 5) represents the 32 data points and COP correlations well ($R^2 = 0.8826$). The COP decreases from about 3.8 to 2.0 with an increase in temperature lift from 40 to 100 K. In this study, this power function (Eq. 5) is used

[9] https://www.sweet-decarb.ch/results/deliverables

for the COP calculation of the case studies. Overall, a temperature lift of up to about 100 K seems technically feasible.

$$COP = 52.94 \cdot \Delta T_{lift}^{-0.716} \text{ with } R^2 = 0.8826 \qquad \text{Eq. (5)}$$

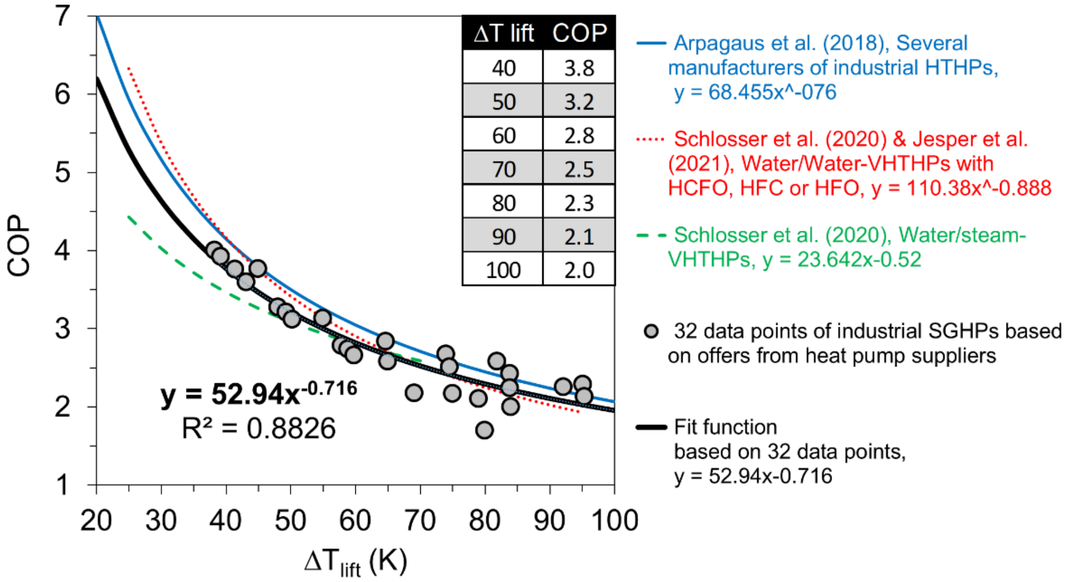


Figure 16: COP fit curves for industrial HTHPs from literature and SGHPs from 32 data points.(Arpagaus et al. 2022)

For the techno-economic model this approach was used since it is significantly easier to implement than the models described in chapter 4. Those, earlier described, more detailed thermodynamic heat pump models consider the influence of refrigerant (e.g., HFOs, NH3, CO_2, R600), compressor efficiency (e.g., screw, piston, turbo compressors), cycle optimizations (e.g., multistage, economizer, MVR combination), temperature glide, capacity, etc. However, they need expert know-how which is usually not available during a first techno-economic analysis.

While the efficiency of the heat pumps strongly depends on the application (i.e., heat sink and source temperatures), a fixed efficiency of 90% (η_{fuel}) is assumed for fossil-fuel-fired heat generation (gas/oil).

4.4.1 Cost model

A cost model was developed for the economic evaluation of the SGHP. For a retrofit case, it is assumed that the gas(oil) boilers are already in operation today and that the investment is depreciated. The gas boilers remain for production reliability, redundancy, start-up operation, and to cover peak loads. First, the investment costs of the industrial SGHPs are evaluated. Then, the operating costs are calculated considering efficiency and energy prices (gas, oil, electricity) and possible refunds of CO_2 taxes. Next, a maintenance factor is used to estimate the additional maintenance costs of the SGHPs, which is based on experience in the field of large-scale refrigeration. After that, the payback period of the heat pump investment is evaluated for decision. Finally, the discount rates are considered to calculate the discounted payback period.

Although this cost model is relatively simple, it provides a useful initial overview and is valuable for obtaining preliminary information before starting a project related to the integration of a steam-generating heat pump. This perspective is shared by USB Farchim and DSM.

4.4.2 Investment cost

The specific investment costs include the capital costs of the heat pump itself but not the costs associated with planning, integration, and labor. Therefore, a cost multiplication factor ($f_{inv,hp}$) is usually applied to account for planning and integration. The investment cost for a SGHP (C_{inv}) follows from Eq. (10) and considers the multiplication factor ($f_{inv,hp}$).

$$C_{inv,HP} = c_{inv,HP} \cdot \dot{Q}_h \cdot f_{inv,hp} \qquad \text{Eq. (10)}$$

4.4.3 Operating cost and net annual cost savings

The operating costs for a SGHP include the electricity cost for running the heat pump calculated by the electricity consumption and the electricity price and a fixed annual maintenance factor based on the capital cost. For simplicity, energy price growth rates are neglected, and constant operating conditions are assumed at the nominal heating capacity.

Eq. (11) is used to calculate the annual fuel cost savings (C_{fuel}), Eq. (12) calculates the annual electricity cost (C_{el}) to operate the HTHP, Eq. (13) calculates the annual additional maintenance cost for the HTHP ($C_{maintain}$), and Eq. (14) determines the carbon tax refund (C_{CO2}) due to the reduction of CO_2 emissions.

$$C_{fuel} = \left(\dot{Q}_h \cdot t \cdot c_{fuel}\right)/\eta_{fuel} \qquad \text{Eq.(11)}$$

$$C_{el} = \left(\dot{Q}_h \cdot t \cdot c_{el}\right)/COP \qquad \text{Eq.(12)}$$

$$C_{maintain} = f_{maintain} \cdot C_{inv,hp} \qquad \text{Eq. (13)}$$

$$C_{CO2} = \dot{m}_{CO2,savings} \cdot c_{CO2\,tax} \qquad \text{Eq. (14)}$$

where $\dot{Q}_h$ is the heating capacity, t the annual operating time of the HP and boiler, c_{fuel} the fuel (gas, oil) price, c_{el} the electricity price, η_{fuel} the efficiency of the gas(oil)-fired boiler, COP the efficiency of the HTHP, $f_{maintain}$ the maintenance factor, $c_{CO2\,tax}$ the carbon tax, and $\dot{m}_{CO2,savings}$ the annual CO_2 emissions savings by replacing fuel energy with electrical energy. Finally, Eq. (15) describes the net annual cost savings ($C_{savings}$) (in CHF/year) by use of the SGHP replacing the fuel-driven boiler.

$$C_{savings} = C_{fuel} - C_{el} - C_{maintain} + C_{CO2} \qquad \text{Eq. (15)}$$

Table 6 shows the typical lifetime for heat pumps and different interest rates (discount rates) for investment decisions. The discount rates from the industrial partners are confidential and therefore not disclosed. A lifetime of 20 years seems most reasonable. Interest rates range from 5% to 15%, depending on the investor's risk tolerance (see the discussion in the following section on the payback period). Typical annual operating times are between 4'000 to 8'400 hours for heat pumps, which agrees with various techno-economic studies presented in the literature review (Table 6).

Reference	Gas boiler efficiency (η_{fuel})	Interest rate (discount rate) (i)	Operating hours (t)	System lifetime (T)	Maintenance factor (% of capital cost) ($f_{maintain}$)
	[%]	[%]	[h]	[years]	[%]
Schlosser, Wiebe, et al. (2020)	87	12	6'000	20	2.5
Schlosser, Jesper, et al. (2020)	96	7	6'000	20	1.5
Jesper et al. (2021)	96	7	3'500	20	1.5
Kosmadakis et al. (2020)	90	5	7'000	20	4
Meyers et al. (2018)	n.a.	6.4	2000	20	2.5
Wang and Zhang (2019)	n.a.	10	7'000	15	6
Arnitz et al. (2018)	90	n.a.	3'500	n.a.	n.a.
Wolf (2017)	n.a.	15	4'000	20	2.5
Vieren et al. (2021)	n.a.	8.4	n.a.	15	n.a.
Brückner et al. (2015)	n.a.	10	4'000	25	n.a.
Cox et al. (2022)	80	15	7'300	20	5
Zuberi et al. (2018)	n.a.	10.5	n.a.	15	n.a.
Range	**80 to 96**	**5 to 15**	**2'000 to 7'300**	**15 to 25**	**1.5 to 6**
Average values	**90**	**10**	**5'410**	**20**	**3.2**

Table 6: Literature values as input parameters for payback calculation.

4.4.4 Payback period

Payback calculations are commonly used in practice for financial investment decisions. For example, the simple (static) payback period (PP) calculated according to Eq. (16) assesses the trade-off between the investment costs versus the expected annual cost savings resulting from the heat pump investment. The Discounted payback period (DPP) is simply the period after which the cumulative discounted cash inflows cover the initial investment (Bhandari, 2009). DPP can therefore be interpreted as a period beyond which a project generates economic profit, whereas PP gives a period beyond which a project generates accounting profit. The shorter the payback period, the more economical the project. If the annual net savings are assumed constant each year, the DPP is calculated by Eq. (17) (Bhandari, 2009; Kosmadakis et al., 2020) using a risk-adjusted discount rate (i).

$$Payback\ period\ (PP) = C_{inv} / C_{savings} \quad \text{Eq. (16)}$$

$$Discounted\ payback\ period\ (DPP) = -ln\left(1 - \left(C_{inv} \cdot i / C_{savings}\right)\right) / ln(1+i) \quad \text{Eq. (17)}$$

Discount rates are typically between 5% for a relatively safe project up to 15% for high-risk ones.

Payback periods demanded by the industry are typically in the range of 2 to 5 years (De Boer et al., 2020). For payback periods over 5 years, there is a discussion about how high the residual risk is for the product or the impact on the process. It has to be noted that often if the project is the replacement of utilities and not process then a higher payback time is also acceptable.

4.4.5 CO_2 emissions reduction and energy savings

Compared with natural gas, which has an emission factor of 0.201 kg CO_2 per kWh of useful heat[10] the electricity mix produced in Switzerland entails relatively low emissions, with about 57% hydropower (0.0296 kg CO_2/kWh)[11]. By contrast, the average consumer electricity mix is more emission-intensive with 0.128 kg CO_2/kWh[11] due to the more fuel-based imported electricity.

The CO_2 emission reduction by replacing a fuel-driven boiler with an industrial SGHP is calculated according to Eq. (18):

$$E_{CO2,reduction} = \dot{Q}_h \cdot t \cdot \left(\frac{f_{CO2,fuel}}{\eta_{fuel}} - \frac{f_{CO2,el}}{COP} \right) \qquad \text{Eq. (18)}$$

where η_{fuel} is the efficiency of the fuel-fired boiler, and $f_{CO2,fuel}$ and $f_{CO2,el}$ are the CO_2 emissions factors for fuel and electricity. For the fuel-fired boilers, an efficiency of 0.9 is assumed, the average value of compared literature values.

A further reduction in CO_2 emissions is controlled by a CO_2 levy on fossil fuels, which is 120 CHF/tCO_2 in Switzerland since 2022[12]. The CO_2 tax creates incentives for economical energy consumption and the increased use of low-CO_2 energy sources. Together with a more favorable electricity to fuel price ratio ($p_{el/fuel}$) this can significantly increase the applicability (market attractiveness) of industrial SGHPs.

However, many of the large and energy intensive industries in Switzerland have the avantage of an exemption from the CO2 levy[13]. This can have a huge impact on our calculation scheme.

4.4.6 Interactive document

Using this techno-economic method, an easy to use Excel file has been created in order to estimate the paypack time of two simple cases: replacing a boiler with a heat pump or installing a boiler vs a heat pump. The Excel file is provided in three languages (English, German, and French) and produces a short A4 report using information provided by the user and the calculation methods shown in this chapter. A first version of this file is handed in with this report. A printscreen of the file is shown in the appendix and the last version can be downloaded online[14]

[10] https://www.bafu.admin.ch/dam/bafu/en/dokumente/klima/fachinfo-daten/CO2_Emissionsfaktoren_THG_Inventar.pdf.download.pdf/Faktenblatt_CO2-Emissionsfaktoren_01-2022_DE.pdf

[11] https://www.bafu.admin.ch/bafu/en/home/topics/climate/questions-answers.html

[12] https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/reduction-measures/co2-levy/redistribution.html

[13] https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/reduction-measures/co2-levy/exemption.html

[14] https://www.sweet-decarb.ch/fileadmin/downloads/Tools/HeatPump_IntegrationCalculation_Example.xlsx.

5 Status and Future Projects of UCB and DSM

For the UCB Farchim and DSM cases, the information gathered is sufficient to design a concept of SGHPs. Simulation of closed and open-cycle heat pumps have been made for both industrial processes, for the case of UCB Farchim a combined cycle simulation was also performed. For the two processes different optimal heat pump solutions could be found and recommended.

UCB Farchim were really interested for the most efficient solution which was the combined cycle. However, after discussion with some companies, it was clear that the risk were too high for UCB Farchim as no combined cycle heat pumps have been installed in industry at the time of the project. Furthermore, it would need a perfect collaboration between the steam compressor company and the heat pump manufacturer, as no company could be found that has enough competence in both technologies, which increases the risk of delay and problem. Thus UCB Farchim chose to focus on the closed-cycle heat pump which would allow to work with one company, eventhough no system producing steam has been installed in industry in the EU yet. The refrigerant selection for UCB Farchim was chosen to be natural if possible to have the highest chance to be future-proof, and UCB Farchim was looking for a Swiss heat pump manufacturer for convenience and best support after installation. Walter Wettstein AG which is a Swiss company specialised in industrial chiller systems is working only with natural refrigerant and is building its knowledge in high temperature heat pump. Walter Wettstein AG developed a whole concept for the distillation process of UCB Farchim. This project has brought UCB Farchim in contact with Walter Wettstein and the design of a cascade steam generating heat pump using natural refrigerant was established. On June 2023, the stakeholders of UCB Farchim choose not to continue with the steam generating heat pump project due to the high capital costs estimated by different companies. The reason was that the allocated project was planned to be around 1 Mio Swiss franc and that the solution which necessited not only the heat pump but also the construction of a small building with its own cooling and heating and some piping between the heat pump and the process was more than twice the planned budget. In addition, the risk of using a new technology was deemed too high. However, the steam generation heat pump installation for the heating and cooling of this distillation process is not definitely cancelled and UCB Farchim will internally review the solution further, since pay back rates of the project might change with altering boundary conditions.

DSM was really focused on using water as refrigerant to avoid any toxicity of the ammonia refrigerant or flammability of the hydrocabones refrigerants.That reduces the concept to either a closed-loop heat pump using water as refrigerant or using an open-loop. Using the open-loop, the heat pump gains in efficiency and lowers cost due to the removal of the condensator. DMS has contacted different companies to compare their options and found that a manufacturer of mechanical vapour recompressors can offer the best option in terms of efficiency, cost, and risks. However, the financial department of the DSM did not accept to pay for this solution for now, due to structureal changes in the company. In order to make sure no patent on this design would be applied, DSM and OST wrote a conference proceeding for the DKV 2023 in Hannover in order to publish the heat pump concept. That action means that the solution interests DSM and they would like to implement it in the future.

Information on the newest high-temperature heat pumps and components available on the market has been found through direct contact with companies, participation in the IEA HPT Annex 58, and online search and summarized in this report.

An estimation of price trensd of high-temperature heat pumps and steam generating heat pumps has been made using information gathered in different national and international OST-IES projects. Finally, an Excel document and an online tool were prepared, tested and validated using the collected values.

During the project it could be observed that the novelty of such technology leads to industry hestitating in installing efficient solutions that have not been proven by several companies before. It is very important for them to see a working case study, in the best case in Switzerland made by a Swiss company. In this sense, the authors of this study suggest that the companies use the existing SFOE funding to financially help the installation and monitoring of the first industrial steam generating heat pumps via the P&D funding for example. That should help mitigate the financial risk for industry and increase the spread of this efficient steam production method.

6 Outlook and next steps

The adoption of steam generating heat pumps (SGHP) within industries presents a promising avenue for decarbonization efforts, despite initial hesitations primarily rooted in cost considerations. While cost and environmental impact are significant factors, the anticipation of future decarbonization benefits emerges as a key motivator driving the uptake of HP technologies.

A notable observation is that many industries, although their processes must not necessarily be reliant on steam, face considerable complexities and risks associated with altering process temperatures or heat exchanger systems. The transition from conventional steam-based systems to heat pump technologies introduces intricacies and expenses, highlighting the need for careful planning and execution.

To facilitate the adoption of steam generating heat pumps, a comprehensive guideline has been developed (refer to Appendix 11.7 for details). This guideline serves as a roadmap for industries embarking on projects involving HP, offering insights into the implementation process and potential challenges. This guideline is currently used for case studies and extended with new learnings. It also has impacted IEA HTPAnnex 58.

Furthermore, the integration of HP systems holds the promise of overcoming certain limitations related to cooling processes while simultaneously reducing water consumption. These advantages underscore the potential of HP technologies in optimizing industrial operations and resource utilization.

Looking ahead, the next crucial step involves the initiation of demonstration projects aimed at showcasing the real-world efficiency and integration of steam generating heat pumps. These projects will serve as compelling case studies for interested companies, enabling them to evaluate the practical benefits and feasibility of HP adoption. By analyzing the performance and outcomes of these demonstration projects, valuable insights can be obtained to inform future implementations and enhance industry-wide adoption efforts.

The successful execution of demonstration projects hinges on securing necessary resources, including financial support. Given the high cost and perceived risk of steam-generating heat pumps—stemming from the lack of field testing and from missing experience - financial assistance would likely be necessary to initiate such projects. Therefore, it is crucial that companies like UCB Farchim or DSM use the subsidies allocated by SFOE via their P&D programme to support promising technologies in order to demonstrate them and enable the realisation of the first installations. These Funds help to de-risk new technologies.

For companies, to invest funds into a steam-generating heat pumps requires an increased willingness to take risks and often a willingness to make investments that cannot be amortised quickly. Company internal carbon reduction goals and emphasising multiple benefits bejond the carbon reduction help in implementation.

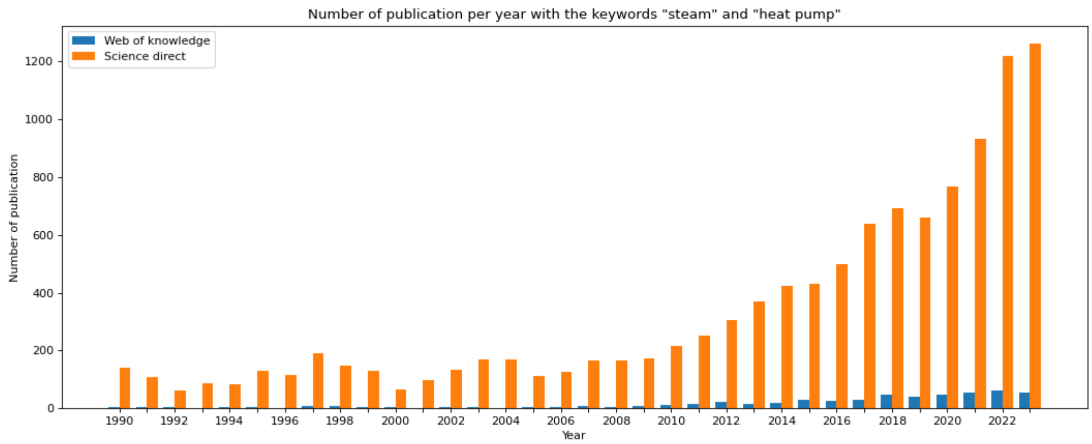
Such investments not only demonstrate a commitment to sustainability but also pave the way for transformative advancements in industrial energy management and decarbonization.

7 National and international cooperation

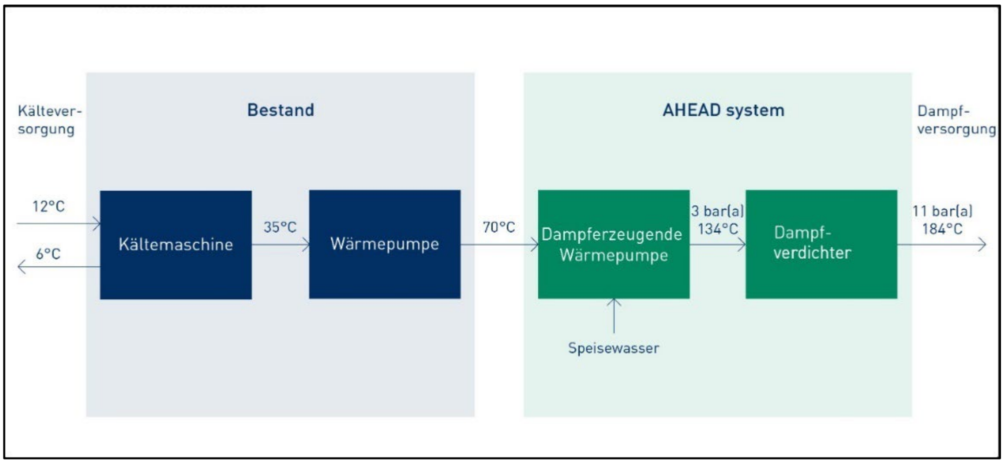
Cooperation with the HSLU group from Beat Wellig to be able to look at their Pinch Analysis for the Nestlé Konolfingen factory. Collaboration with DeCarbCH, mostly WP5 in terms of technology, WP4 to know more about the Swiss sectors, and WP2 to better understand the social aspect and the non-technological barrier to SGHP integration. There is also a lot of collaboration between IntSGHP and IEA HTP Annex 58 and the Swiss project HTHP-CH as they tackle similar research questions. Furthermoore, direct funded projects by OST-IES benefit from the methodologies developed in IntSGHP and IntSGH also benefits from increased market know-how.

7.1 International news

- In the literature, it can be seen that the amount journal papers with the keyword "steam" and "heat pump" are rising the last couple of years as shown on the graph below.



- In Europe there are also different projects involving integration of steam generating heat pump into industries such as the AHEAD project from nefi with the following system: chiller, heat pump, SGHP, and steam compressor in series:



- As previously mentioned, the IEA Annex 58 is focusing on high temperature industrial heat pump which include steam generating heat pump systems.
- In India, a small 60kW low-pressure SGHP was developed, installed, and analysed recently [Koundinya2023].

8 Communication

One presentation on IntSGHP project has been given at the WP-Tagung 2022 in Burgdorf (link to pdf) and one presentation on Steam Generating heat pump and the IntSGHP project has been given at the Symposium Optimisation Energétique 2022 in Yverdon but has not been made public. An short article with interview of the Swiss industrial partner from IntSGHP and HTHP-CH have been written by Cordin Arpagaus and Frédéric Bless. The article was sent and will be published in the HTP Magazine Issue 3/2023. Furthermore, a conference proceeding on the DSM study has been accepted, presented, and published for the DKV Tagung 2023. It can also be noted that a P&D for the USB Farchim study has been written and is attached to this document but the project has not being approved in 2023 by UCB Farchim due to its high cost.

Furthermore a webinar on steam generating heat pump has been made with great success. A workshop on high-temperature heat pump was co-organised with the HTHP-CH project.

8.1 Webinars on steam generating heat pump

The 1st of March 2023, the first steam generating heat pumps webinar was organised using Microsoft Teams. The webinar provided valuable insights into the latest advancements in steam generating heat pumps was organised by OST-IES. The webinar was recored and the videos are be available on SWEET DeCarbCH YouTube channel[15]. The webinar was hosted by Frédéric Bless, scientist at OST in the field of steam generating heat pumps, and featured presentations from five leading EU-manufacturers in the field (spilling, piller, toCircle, EPCON, SPHeat). The presentations provided a comprehensive overview of the technology, including its benefits and applications, a few implementation examples, as well as the latest research and development trends in the field. This webinar is aimed at professionals in the heating and cooling industry, as well as anyone interested in learning more about the future of energy-efficient heating solutions. Attendees had the opportunity to ask questions and engage in the Q&A with the experts. Jürg Schifmann, Prof at EPFL, was planned to talk about the advancement of oil-free steam turbo-compressor but he unfortunately could not join the webinar and his talk was replaced by a half hour Q&A with the presenters. The webinar was free to attend and open to all. The recording of the webinar is also available on YouTube, open to anyone and without advertisement. The presentations can be download on the SWEET DeCarbCH website[16]. Just below 75 people participated at the life webinar and the video (as of May 2024) have been viewed between 430 and 1200.

In 2024 a second webinar was organised with presenters from ETHZürich, Atlas Copco, ANEO, DTU, TNO, Well & Sandvig, Teknologisk Institut, Enerin, and OST. With more than 540 registrations and a peak of 430 paticipants during the webinar, the webinar was a success. The presentations and videos are also available online[17].

[15] https://www.youtube.com/watch?v=_D1IC1-byi0&list=PLMOVLV6qhK4Ynn0NYchFG9ZLVpMrJMXem
[16] https://www.sweet-decarb.ch/events/event/webinar-on-steam-generating-heat-pumps
[17] Webinar on Steam Generating Heat Pumps: SWEET DeCarbCH (sweet-decarb.ch)

8.2 High-Temperature Heat Pumps Workshop

The 24th of March 2023, the team of HTHP-CH (Aramis project number SI/502336[18]) organised a day workshop in Bern and IntSGHP helped with the organisation, one of the presentation, and one of the breakout session. The morning was used for the project team member to present the latest advancements for heating applications over 100°C, energy integration methodology, case studies, and discussed about the various facets of this decarbonization solution for the industry. then discussions in smaller group on specific themas were organised the afternoon. There were many opportunities of networking during the day. This day has, therefore, allowed to expand knowledge, connect with others industry professionals in many diverse field. The presentations were recorded and are available on demand. The presentation can be download on the SWEET DeCarbCH website[19]. The HTHP-CH report will contain the summary of this one-day workship, therefore it will not be summarise here but the reader are kindly forward to the Aramis database of the HTHP-CH project to read it[20].

9 Publications

The IntSGHP project has been promoted on several websites and conferences:

- DeCarbCH Newletter July 2022 (Link DecarbCH website: https://www.sweet-decarb.ch/news/article/intsghp-integration-of-steam-generating-heat-pumps-in-industrial-sites-retrofit)
- Description of IntSGHP project on OST website (Link: https://www.ost.ch/de/projekt?tx_base_project_single%5Bproject%5D=886&cHash=c928638cde1d7c7aa2e8a1910cece943)
- Presentation of IntSGHP project at the WP-Tagung 2022 in Burgdorf (Link to presentation: https://www.sweet-decarb.ch/fileadmin/downloads/Presentations_File/Frederic_Bless_IntSGHP_WP_Tagung_2022.pdf)
- Presentation together with Pierre Krummenacher at the Symposium Optimisation Energétique 2022 at HEIG-VD (6 september 2022) entitled “La recompression mécanique de vapeur et ses applications”
- And it was as well presented at the SWEET DeCarbCH Site Visit in Bern, the 19th October 2022.
- Some part of the IntSGHP research was presented in Dinan for the Colloque Pôle Cristal the 7th November 2023.
- Some part of the IntSGHP research was presented at the two ENAW annual forum in Bern the 7th of November and in Sion the 16th of Novembre.
- Web-based and excel-based tool to estimate payback time of heat pump installation available online (https://www.sweet-decarb.ch/fileadmin/downloads/Tools/HeatPump_IntegrationCalculation_Example.xlsx.)

[18] https://www.aramis.admin.ch/Projektsuche/
[19] https://www.sweet-decarb.ch/events/event/high-temperature-heat-pump-event
[20] https://www.aramis.admin.ch/Grunddaten/?ProjectID=49514

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- Arpagaus, C.: Hochtemperatur-Wärmepumpen: Potenziale und Einsatzmöglichkeiten für die Bereitstellung von Prozesswärme in der Industrie, VEA-Veranstaltung: Wie die Dekarbonisierung gelingen kann: Einsatz alternativer Energien und Technologien im Unternehmen, 5. April 2022, Online Seminar
- Arpagaus, C., Bless, F., Bertsch, S.S.: Techno-Economic Analysis of Steam-Generating Heat Pumps in Distillation Processes. 3rd High-Temperature Heat Pump Symposium, 29-30 March, 2022, Copenhagen, Denmark, https://hthp-symposium.org
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- https://www.bosch-thermotechnology.com/global/en/ocs/commercial-industrial/steam-accumulator-module-sam-669559-p/ (Februar 2022)
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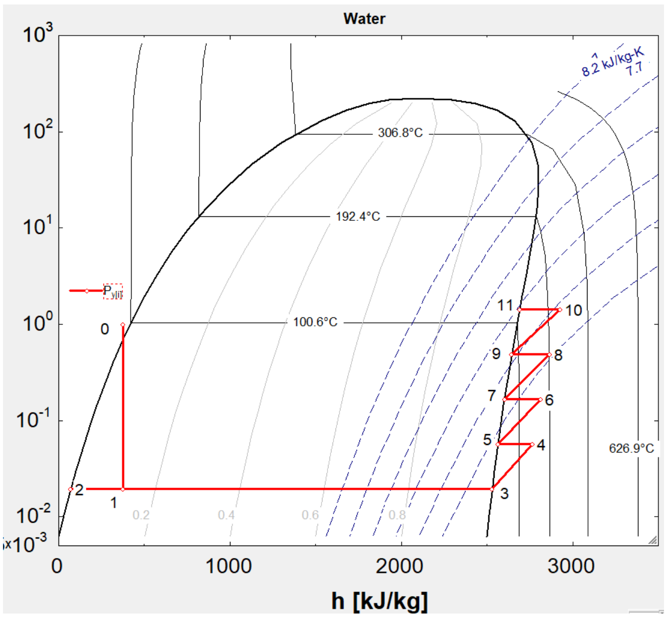
11 Appendix

11.1 Open-loop cycle using water as refrigerant: simulation details.

Results simulation with a unit water mass flow of 1 kg/s at the inlet.

Step (figure below)	Pressure ratio [-]	ΔTemperature [T]	ΔEnthalpy [kJ/kg]	Massflow [kg/s]	Q [kW]
0 → 1	1/50	-73	0	1	0
1 → 3	1	0	2117	1	2155
3 → 4	2.93	125	235	1	235
4 → 5	1	-107	-202	1.09	-221
5 → 6	2.93	131	250	1.09	273
6 → 7	1	-110	-212	1.20	-255
7 → 8	2.93	139	266	1.20	318
8 → 9	1	-114	-224	1.20	-294
9 → 10	2.93	147	284	1.32	373
10 → 11	1	-117	-237	1.32	-344
0 → 11	1.434	20	2314	1.45	3355

To calculate the COP, the total electrical power from each compression steps has to be divided by the power needed to heat the water from the initial state to the final state.
Electrical power = 235 + 273 + 318 + 373 = 1200 kW
COP = 3355 kW / 1200 kW = 2.80



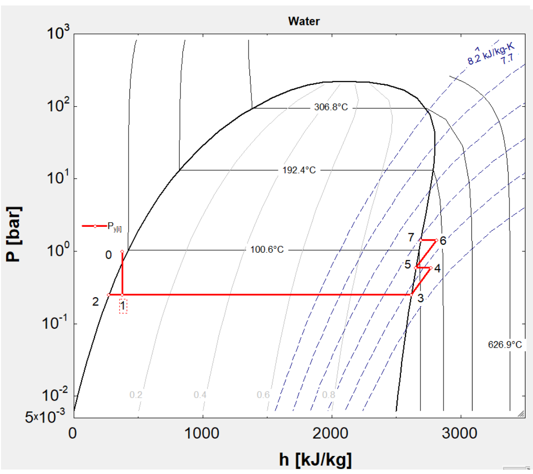
11.2 Combined cycle using water as refrigerant: simulation details.

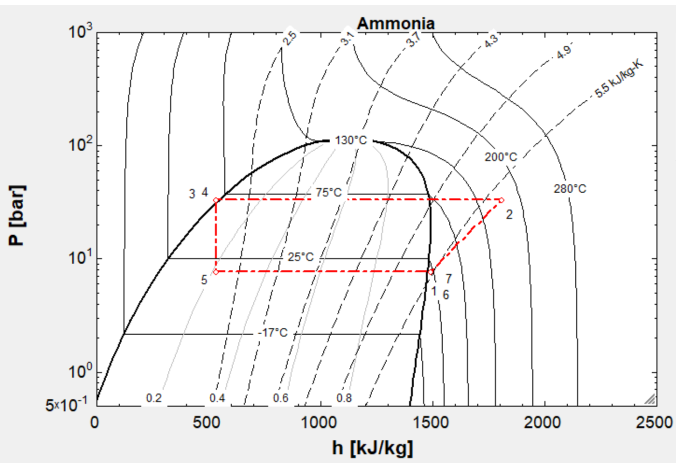
Results simulation with a unit water mass flow of 1 kg/s at the inlet.

Step (see figure)	Pressure ratio [-]	ΔTemperature [T]	ΔEnthalpy[kJ/kg]	Massflow [kg/s]	Q [kW]
0 → 1	1/4	-25	0	1	0
1 → 3	1	0	2240	1	2240
3 → 4	2.39	79	151	1	151
4 → 5	1	-58	-115	1.05	-121
5 → 6	2.39	83	159	1.05	167
6 → 7	1	-59	-121	1.11	-134.31
0 → 7	1	20	2314	1.11	2569

To calculate the COP, the total electrical power from each compression steps has to be divided by the power needed to heat the water from the initial state to the final state.
Electrical power = 151 + 167 = 318 kW
COP = 2569 kW / 318 kW = 8.08

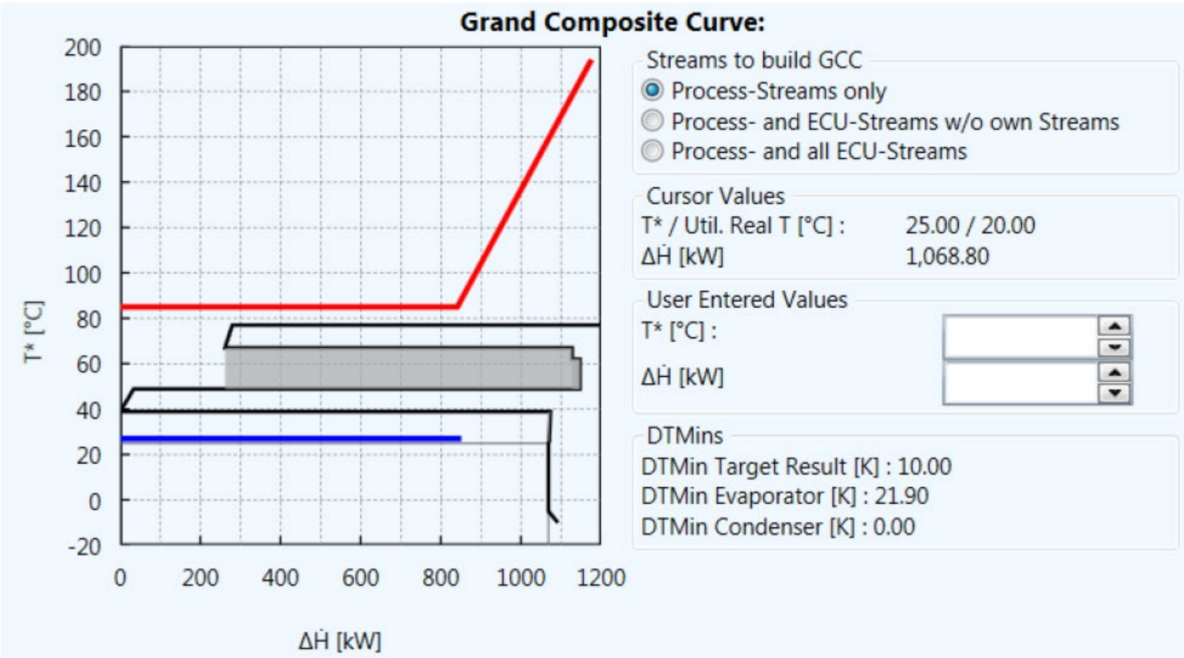
The evaporation power needed from the heat pump is:
$Q_{evap} = (h_3 - h_2) * m_{flow} = 2240$ kW
An ammonia heat pump with evaporation temperature 17°C and condensation temperature 70°C without subcooling and with 5°C overheating gives a COP of 4.02. That means that for a sink power of 2240 kW, the electrical power is 2240 / 4.02 = 557 kW. Thus, the COP of the combined cycle can be calculated: 2569 kW / (318 kW + 557 kW) = 2.94. This appendix is using rounded value, by using more precise values, the **COP is 2.922**. The more precise value was used in the report.





11.3 Grand Composite Curve

Grand Composite Curve for USB Farchim CP2 distillation process from the 2015 studies. The red and blue lines are the heating and cooling supply. The proposition of this studies suggsests changing the heat exchangers of the distillation column to be able to reduce the heating fluid temperature.



11.4 Overview of development of supplier technologies

Table from the IES Annex 58 from https://heatpumpingtechnologies.org/annex58/task1/.

Supplier	Compressor type	Working fluid	Capacity	Tmax supply	TRL
Fuji Electric	Reciprocating	R-245fa	0.03 MW	120 °C	9
Emerson	Scroll and EVI Scroll	R-245fa, R410a, R-718	0.03 MW	120 °C	6
Mayekawa (EcoSirocco)	Reciproating	R-744	0.1 MW	120 °C	8-9
Mayekawa (EcoCircuit)	Reciprocating	R-1234ze(E)	0.1 MW	120 °C	8-9
Skala Fabrikk	Piston	R-290, R-600	0.3 MW	115 °C	7
Kobelco Compressors Corp. (SGH165)	Twin-screw	R-245fa/R-134a, R-718	0.4 MW	175 °C	9
Kobelco Compressors Corp. (SGH120)	Twin-screw	R-245fa	0.4 MW	120 °C	9
Mitsubishi Heavy Industries	Two-stage centifugal	R-134a	0.6 MW	130 °C	9
ecop	Centrifugal	ecop fluid 1	0.7 MW	150 °C	6-7
Mayekawa Europe (HS Comp)	Piston	R-600	0.8 MW	120 °C	7
Kobelco Compressors Corp. (MSRC160L)	Twin-screw	R-718	0.8 MW	175 °C	9
Mayekawa Europe (FC Comp)	Screw	R-601	1.0 MW	145 °C	5
GEA	Semi-hermetic piston	R-744	0.1-1.2 MW	130 °C	8
Fenagy	Reciprocating	R-744	0.3-1.8 MW	120 °C	5-6
Rank	Screw	R245fa, R-1336mzz(Z), R-1233zd(E)	0.12-2.0 MW	160 °C	7
SRM	Screw	R-718	0.25-2.0 MW	165 °C	5

IntSGHP

Sustainable Process Heat	Piston	HFOs	0.3-5.0 MW	165 °C	6-8
Hybrid Energy	Piston, Screw	R-717, R-718	0.5-5.0 MW	120 °C	9
Johnson Controls	Reciprocating	R-717, R-600 (cascade)	0.5-5.0 MW	120 °C	7-8
ToCircle	Rotary vane	R-717, R-718	1.0-5.0 MW	188 °C	6-7
Weel & Sandvig	Turbo	R-718	1.0-5.0 MW	160 °C	4-9
Olvondo	Piston (double acting)	R-704	5.0 MW	200 °C	9
Heaten	Reciprocating, custom design	HFOs	1.0-6.0 MW	165 °C	7-9
Enerin	Piston	R-704	0.3-10.0 MW	250 °C	6
Ohmia Industry	Centrifugal / Piston	R-717, R-718	1.2-10.0 MW	150 °C	7-8
Enertime	Centrifugal	R-1336mzz(Z), R-1224yd(Z), R-1233zd(E)	2.0-10.0 MW	160 °C	4-8
Spilling	Piston	R-718	1.0-15.0 MW	280 °C	9
Epcon	HP centrifugal fan	R-718	0.5-30.0 MW	150 °C	9
Turboden	Turbon	Application specific	3.0-30.0 MW	200 °C	7-9
MAN Energy Solutions	Centrifugal turbo with expander	R-744	10.0-50.0 MW	150 °C	7-8
Piller	Turbo	R-718	1.0-70.0 MW	212 °C	8-9
Siemens Energy	Turbo (Geared / single-shaft)	R-1233zd(E) / R-1234ze(E)	8.0-70.0 MW	160 °C	9 (to 90 °C)
Qpinch	Chemical adsorption heat transformer	R-718, H3PO4 and derivatives	>2.0 MW	230 °C	9

11.5 Overview of demonstration cases

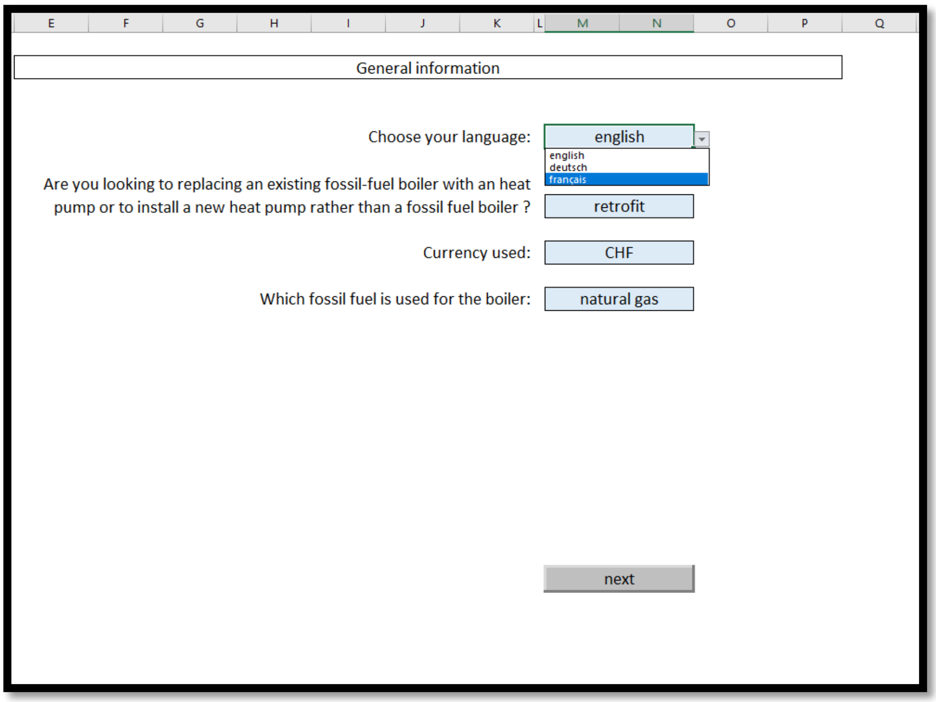
Table from the IES Annex 58 from https://heatpumpingtechnologies.org/annex58/task1/.

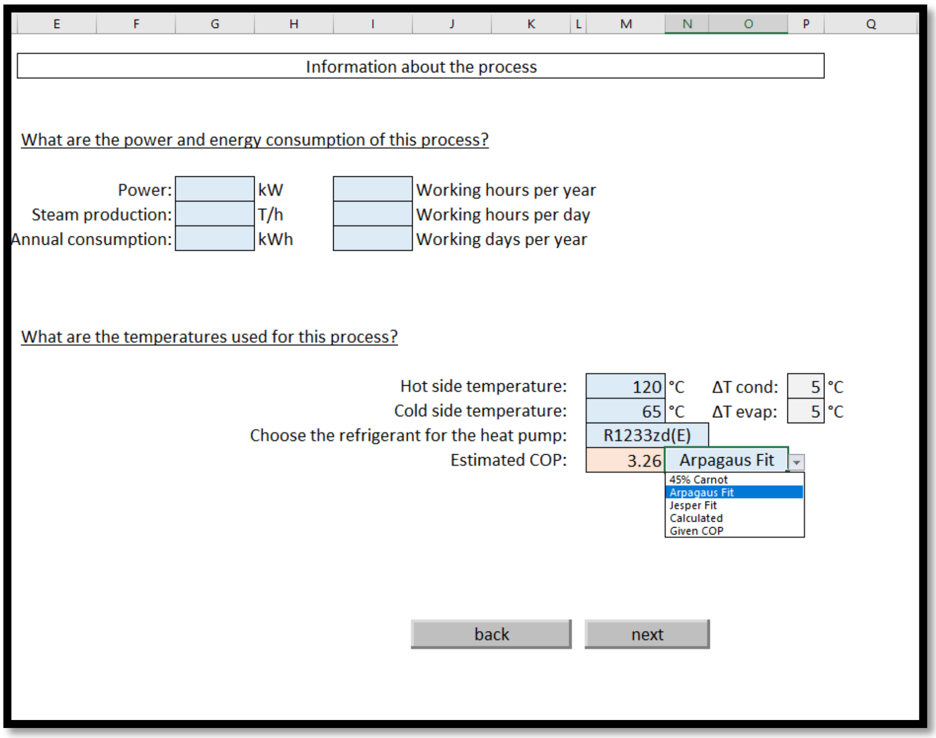
Supplier	Industry / Process	Source in → out	Sink in → **out**	Refrigerant	Compressor	Capacity	COP
Mayekawa*	Electronic / Coil drying	30 °C → 25 °C	20 °C → 120 °C	R-744	Piston	0.1 MW	3.1
AMT/AIT	Minerals / Brick drying	88 °C → 84 °C	96 °C → 121 °C	R-1336mzz(Z)	Piston (8 compr.)	0.3 MW	5
SkaleUP	Dairy / Process water	20 °C → 12 °C	95 °C → 115 °C	LT-C: R-290 HT-C: R-600	Piston	0.3 MW	2.5
n. a.*	Beverage / Alcoholic distillation	78 °C → 75 °C	n. a. → 140 °C	n. a.	n. a.	0.4 MW	5.2
AMT/AIT	Food / Starch drying	76 °C → 72 °C	96 °C → 138 °C	R-1336mzz(Z)	Screw	0.4 MW	3.2
Rotrex, Epcon	Sewage / Sludge drying	n. a. → 100 °C	n. a. → 146 °C	R-718	Turbo (2 stages)	0.5 MW	4.5
MHI	Electronic / Coil drying	55 °C → 50 °C	70 °C → 130 °C	R-134a	Centrifugal	0.6 MW	3
Kobelco	Sewage / Sludge drying	93 °C → 93 °C	160 °C →160 °C	R-718	Twin-screw, Roots blower	0.7 MW	2.9
Olvondo	Pharma / Recooling	36 °C → 34 °C	178 °C →183 °C	R-704	Piston	1.5 MW	1.7
Kobelco	Refinery / Bioethanol distillation	65 °C → 60 °C	20 °C →120 °C	R-245fa	Twin-screw	1.9 MW	3.5
QPinch	Chemical /			H2PO4	Heat-driven	2.9 MW	

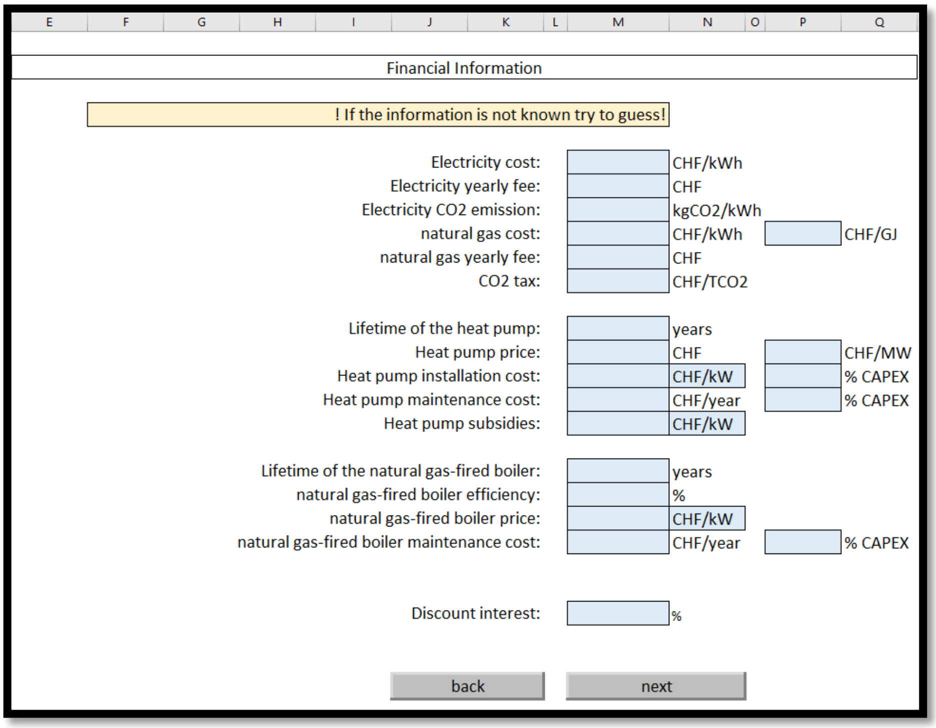
	Steam prod.	120 °C →145 °C	140 °C→185 °C				0.45 (COP_{heat}, trans.)
Piller	Plastics / Thermal sep.	60 °C → 60 °C	126 °C →131 °C	R-718	Turbo (8 blowers)	10.0 MW	4.4
Spilling	Pulp and paper / Pulp drying	133 °C →105 °C	n. a. → 201 °C	R-718	Piston (4 LT-, 2 HT-cyl.)	11.2 MW	4.2
Spilling	Chemical / Chemical	152 °C →105 °C	n. a. → 211 °C	R-718	Piston (4 LT-, 2 HT-cyl.)	12.0 MW	5.3

11.6 Excel Document

Excel file on calculation of HP amortisation: HeatPump_IntegrationCalculation.xlsx






E F G H I J K L M N O P Q
Financial Information
! If the information is not known try to guess!
Electricity cost: CHF/kWh
Electricity yearly fee: CHF
Electricity CO2 emission: kgCO2/kWh
natural gas cost: CHF/kWh CHF/GJ
natural gas yearly fee: CHF
CO2 tax: CHF/TCO2
Lifetime of the heat pump: years
Heat pump price: CHF CHF/MW
Heat pump installation cost: CHF/kW % CAPEX
Heat pump maintenance cost: CHF/year % CAPEX
Heat pump subsidies: CHF/kW
Lifetime of the natural gas-fired boiler: years
natural gas-fired boiler efficiency: %
natural gas-fired boiler price: CHF/kW
natural gas-fired boiler maintenance cost: CHF/year % CAPEX
Discount interest: %
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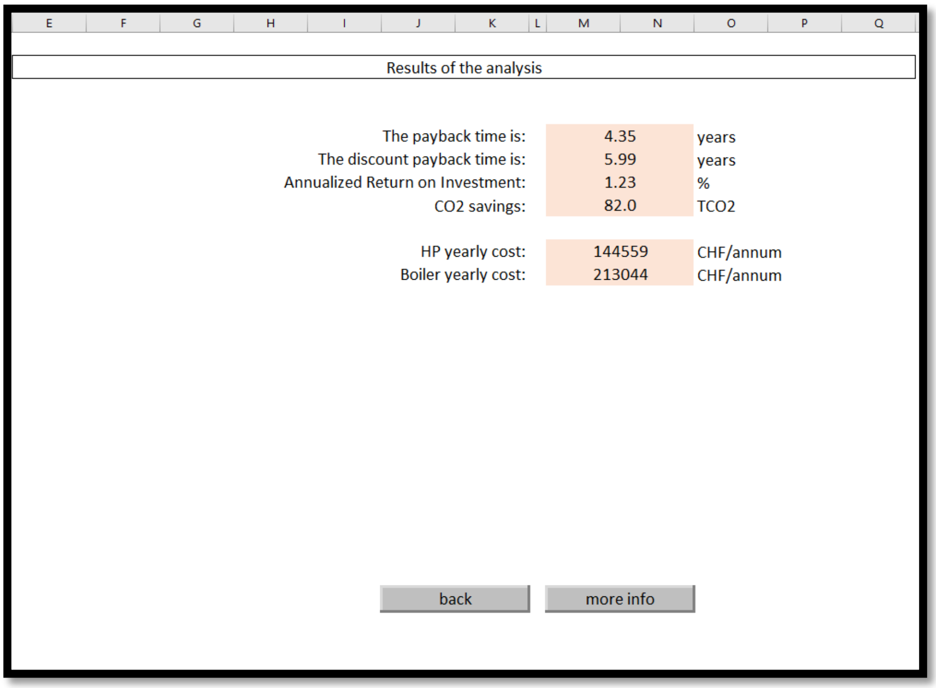
E F G H I J K L M N O P Q
Results of the analysis
The payback time is: 4.35 years
The discount payback time is: 5.99 years
Annualized Return on Investment: 1.23 %
CO2 savings: 82.0 TCO2
HP yearly cost: 144559 CHF/annum
Boiler yearly cost: 213044 CHF/annum
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Information on replacing a boiler by a heat pump

The payback time is 4.3 years. The discount payback time is 6 years.
The annualized return on investment is 1.23 %.
The CO_2 savings are 82 tons per year.

Heat pump information:		
Heat pump price:	230000	CHF
Heat pump installation:	115000	CHF
Heat pump subsidies:	47380	CHF
Heat pump CAPEX:	392380	CHF
Heat pump electricity cost:	137659	CHF/annum
Heat pump maintenance:	6900	CHF/annum
Heat pump yearly cost:	144559	CHF/annum
Boiler information:		
Boiler price:	27600	CHF
Boiler installation:	15000	CHF
Boiler CAPEX:	42600	CHF
Natural Gas cost:	209683	CHF/annum
Boiler maintenance:	828	CHF/annum
CO2 Tax:	2533	CHF/annum
Boiler yearly cost:	213044	CHF/annum

The values in this page is only a rough estimation and a more details analysis should be made in order to verify the technical and economical feasibility of this case. Please contact stefan.bertsch@ost.ch to discuss this case further.

16.10.2022

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11.7 Guideline

Guidelines for integrating industrial heat pump

Short summary

This short guideline is intended to help planners and end-customers to prepare when starting a project involving the integration of steam-generating heat pumps in their industrial processes.

Before implementing a steam-generating heat pump

Installing a steam-generating heat pump in a running industrial plant is not trivial. It requires a lot of preparation and information about the whole plant, not only where the heat pump will be installed.

There are two possible locations to install an industrial heat pump:

1. **Centralized heating** and cooling of the whole plant
2. Installation for one or a few **specific processes**

For the centralized heating and cooling, it is usually a bit easier to determine the requirement for the heat pump, since fuel data is available in most cases. However, since central supply temperatures are usually higher than the temperature range of the processes, this solution can lead to poor efficiency. In most cases simply replacing a fossil-fuel based steam generator with a heat pump is not successful.

For a heat pump installation on a specific process, a **Pinch Analysis** of the process and the knowledge of **any potential modification planned on the process** are necessary before going forward with the project.

To have a good overview of the heating and cooling demand and to be ready to ascertain if a heat pump is the best technology for a centralized heating and cooling solution, it is highly encouraged to perform a **Pinch Analysis** of the whole plant. This analysis generates a grand composite curve of the plant for different periods of the year. Using this graphical summary of all the flows, it is convenient to determine the temperatures and capacities where a simple heat recovery via a heat exchanger is possible and where heat could be upgraded via a heat pump. The temperature lift between the cold and hot demand and the capacity are visible, clearly showing if and where a heat pump is the right solution. Results of a Pinch Analysis also help planners choose the right type of heat pump for the application. However, for simple processes, a full Pinch analysis may not be necessary. The list of process streams (with mass flow and temperatures) may be enough to design the best heat pump system.

It is also very important to have a **plan of future modifications to the plant** that are foreseeable. Heat pumps are designed to work at particular temperatures and capacity. Modifying the temperatures or the capacity can greatly reduce a heat pump's efficiency or even make it impossible to deliver new heating and cooling demands. While they can be very efficient, they are not as flexible as current steam boilers.

If the process does not match its cooling and heating demand well, looking for nearby process demands with similar running profiles is recommended.

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Furthermore, a heat pump can only run if adequate cooling and heating demands are available at the same time. It is important not to neglect the **temporality of the processes**. If discrepancies exist or processes are not steady in power and temperature, adding heat storage is necessary.

It is also important to know that an electric-driven heat pump needs a heat source, unlike a fuel-burning system. Therefore, if the heat pump is linked to the process that will produce this heat source, **another provider of heat may be needed to start up**. It can be an electrical, fuel-fired, or heat storage system. For example, if a proposed heat pump supplying heat to a plant uses the waste heat from the plant, another heat source is needed to start the process.

Finally, before looking more into heat pump design, it is important to ensure the **heat flows delivered to the process are optimal in terms of temperatures**. To have a more efficient system, heat flows need to be at the lowest possible temperature, and cold flows need to be at the highest possible temperature to reduce the heat pump's temperature lift and increase its coefficient of performance (COP). If steam is used as a heating medium, an analysis should be made to confirm that it cannot be replaced by hot water (even pressurized hot water). Heat pump efficiency typically drops for 2-3% per Kelvin increase in temperature lift.

Before going into detail

After having analyzed the desired processes or those of the whole plant, it is important to collect the following information concerning some aspects of steam-generating heat pumps:

1. What is the temperature lift between the hot (heat sink) and the cold temperature (heat source)?
2. Heat pumps use refrigerants to work. It is important to seek out internal regulations concerning the use of chemicals in the company, as some refrigerants are toxic or flammable (e.g., ammonia and propane, respectively). The newest heat pump refrigerants are hydrofluoroolefins (HFO), which are being regulated, especially in Europe, and may be phased out. The trend and the current most future-proof refrigerants are natural refrigerants (e.g., water, ammonia, and hydrocarbons), which might require additional safety measures.
3. High temperature heat pumps are a family of different cycles, each cycles have different advantages and disadvantages; therefore it is difficult to compare heat pumps.
4. If steam is required and the heat source has a high temperature (i.e. in excess of 80-90°C), vapor recompression using water as refrigerant should be investigated as it brings the best efficiency.
5. To know the size of the heat pump, rough capacities of the cold or hot side are needed. Furthermore, estimating the operating hours per year is useful in determining the duty cycle of the heat pump.
6. The potential installation location for the heat pump needs to be investigated, as a heat pump can require larger space than an electrical heater of the same capacity. It is hard to quantify the size of such system, heat pump of around 1MW are estimated to be around from 45 to 75m3 for a compact one or two stages heat pump. However, place around the heat pump and place for the electrical cabinet needs also to be taken into account.
7. Noise pollution should be considered when choosing their location.
8. Heat pumps need to be maintained at room temperature to start. High-temperature heat pumps (HTHP) with a bottom and a top cycle may need to be heated before starting. Furthermore, due to heat loss, a heat pump also heats its direct environment and may thus need to be in a ventilated area or even cooled down while running.

9. The most common heat pump technology is the vapor compression cycle. However, for some cases, absorption heat pumps (incl. absorption heat transformers) may be an appropriate solution.
10. Current and future energy prices are necessary to estimate the payback time: electricity and gas rate (eventually annual fee), CO_2 levy, etc. A financial tool is available online[1].
11. Information on the possibilities of financial help such as KLIK, EnergieSchweiz, SFOE, Canton, Commune or Government funding needs to be collected.
12. Any specificity of the process or plant, such as pipe material, chemical usage (for the refrigerant choice), and the importance of not having oil or other substances in the heating medium, should be collected before making a heat pump feasibility study to speed up the process. In Some cases it might be necessary to include intermediate circuit to avoid refrigerant or oil leaking into the process in case of heat exchanger failure.

Once the information is collected, consultation with a research institute or an engineering bureau is recommended. An Excel file to **estimate the payback time** of a heat pump is available online[1].

Details of industrial heat pump pre-study

It is important to precisely evaluate the temperatures needed on the heating and cooling sides. As written earlier, ensuring that the hot temperature is the lowest and the cold temperature is the highest possible will increase the heat pump's efficiency.

Large industrial heat pumps need high voltage and electrical power to run. That means that an electrical power cable able to deliver the correct voltage and current will have to be pulled up to the potential location of the heat pump. That may constrain the potential location of the heat pump.

Large industrial heat pumps are also heavy. Thus, the heat pump's potential location should be stable and strong enough to support a heavy machine that vibrates. The ease of access to bring the heat pump to the potential location may also restrict the potential location.

Depending on the heat pump design, the heat pump may need to be kept at room temperature before starting or even being heated up thus the location of the heat pump should be hot enough before it starts. That means an additional heating system for the heat pump may be needed for startup.

When running, the heat pump suffers from heat loss through its electrical drive & control, hulls, pipes, and heat exchangers, which may lead to overheating of the location. Therefore, ventilation of the heat pump space may be needed.

Safety measures are well-defined and standardized. Some refrigerants, such as ammonia, can be toxic, while others, such as butane or pentane, can be flammable. Hence, it is important to include the personnel in charge of the project's security and safety at the plant site.

Once the heat pump is in operation, the process engineers must monitor its performance. Thus, it is important to include them from the beginning of the project to learn from their knowledge and explain and prepare them for the change the heat pump will have on their work.

As mentioned above, start-ups of heat pumps are more complex than fuel boilers; thus, a start-up concept should be clearly defined.

[1] https://www.sweet-decarb.ch/decarbonization-tools

Particularity of a steam-generating heat pump

Water vapor suffers from heat and pressure loss. Therefore, the pipes must be adapted to **minimize these losses**.

If the process using the steam delivered from the heat pump starts with a separate system, then the steam valves between the start-up steam (or network steam) and heat pump steam must be very well designed to **avoid any backflow** or similar problems.

As steam is a corrosive material, the pipe material should be adapted. Each plant has a different standard in terms of its piping material; please check the plant standard to ensure the plan does not have to be modified later.

Similarly, **the heat pump heat exchanger and piping material should be defined and discussed with the** manufacturer.

In terms of storage, steam storage is available on the market (for example like the "Dampfspeicher CoPES" from Jaske & Wolf Verfahrenstechnik GmbH) even though it is much less common than water storage or other thermal storage[2].

[2] Many information can be found on www.sweet-decarb.ch and https://heatpumpingtechnologies.org/annex58/