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Abstract

A significant amount of the industrial energy consumption is related to process heat. Several industries use heat in ranges reachable by heat pumps, and temperatures from 100-200°C are especially needed in the paper and the food and tobacco industries. Drying, distillation, cooking, boiling and sterilization are the main processes in this temperature range.

Steam regeneration through MVR processes see high potential COP, and several research projects exist. The DryF project and the PACO project seem most promising, aiming at 150°C. The challenges of the steam processes are related to high temperatures in the equipment, and high specific volume of steam. Different approaches exist, but more research remains before these products are market-ready.

The economics of MVR processes are closely related to electricity/gas price ratio, and make the MVR process especially feasible in countries with low electricity prices.

Executive summary

In accordance with the Paris agreement, the greenhouse gas emissions need to be reduced to limit the global warming. One of the measures to reduce the emissions is to reduce the energy consumption, and hence, the specific energy consumption. The European energy strategy targets a reduction in energy consumption of at least 27% within 2030.

Approx. one third of the Norwegian energy demand is related to the industrial sectors, with a significant share related to process heat. In Germany and Netherlands, 66% and 80% of the final energy demand is estimated to be process heat-related. The knowledge in the industry regarding excess heat amounts and temperatures is generally low. 75 TWh is estimated to be reachable by high temperature heat pumps in Europe, with the paper industry and the food and tobacco segment as the most interesting areas. Especially within drying, but also within cooking, boiling, sterilization and distillation, there is a high need for temperatures in the range of 100-200℃.

Mechanical vapour recompression (MVR) is an open loop steam heat pump which is able to obtain high efficiencies due to thermodynamic properties and reduction of losses in equipment. The main process acts as the evaporator, reducing the heat exchanger needs. The MVR process uses steam as a working fluid, which is free, safe and represents no environmental hazard. The thermodynamic properties are also good, especially for high temperature applications. Above 100℃, steam is very attractive as a working fluid. The challenges of using steam are related to high temperatures at the compressor outlet and high specific volume.

Few MVR-processes are available at the market today at suitable capacities and costs, but several research projects exist. The PACO project and the DryF project are the two projects which seem most promising. They both aim at 150℃, with slightly different technology approaches regarding the compressor.

The compressor is the main challenge in MVR processes, caused by the high temperatures and the high specific volume. Turbo-compressors seem to be the most promising technology, and the difficulties are mainly related to temperatures and high rotational speeds. Further research is needed to solve these issues. Heat exchangers are also limited by the high temperatures, as well as possible fouling in an open loop and the huge change in specific volume.

A main barrier for implementation of high temperature heat pumps is the economics. In several European countries, the electricity price is far higher than gas prices, making it difficult to compete with traditional gas-fired boilers. High COP is needed to be competitive, another feature making steam advantageous compared to other working media. High overall efficiencies are crucial to be able to implement high temperature heat pumps in the market.

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1 Introduction

The greenhouse gas emissions must be reduced in order to reduce the global warming. The 166 nations which have ratified the convention from Paris 2015 have committed to taking action to keep the global temperature rise this century well below 2 degrees Celsius above pre-industrial levels.[1] To reach these goals it will be necessary for all industry sectors to utilize their energy more efficiently, and it is likely that stricter governmental demands will be introduced in the years to come. Reducing the specific energy consumption in production is one of the measures which in addition to reducing the greenhouse gas emissions can reduce operating costs.

The technology-driven transition to a low-emission future has already proven to be profitable within several fields. For the past three years, the worldwide CO_2-emissions from energy production have stayed flat, even though the world economy grew in 2016.[2] This is the first time during the last 40 years where the emissions have fallen without being associated with economic predicament.[3] Also DNV GL conclude in their *Energy Transition Outlook* that the global energy demand is about to plateau, and this will probably happen in the 2030s.[4] This indicates that the technological transition is initiated, but this is not yet enough to keep the global temperatures from rising above 2℃. In addition to the change in energy sources from fossil fuels to renewables, it is important to find more efficient ways for the industry to use energy, hence reducing the total energy demand. The European energy strategy targets a reduction in energy consumption of at least 27% within 2030, rising the need for reduction in specific energy consumption.[5]

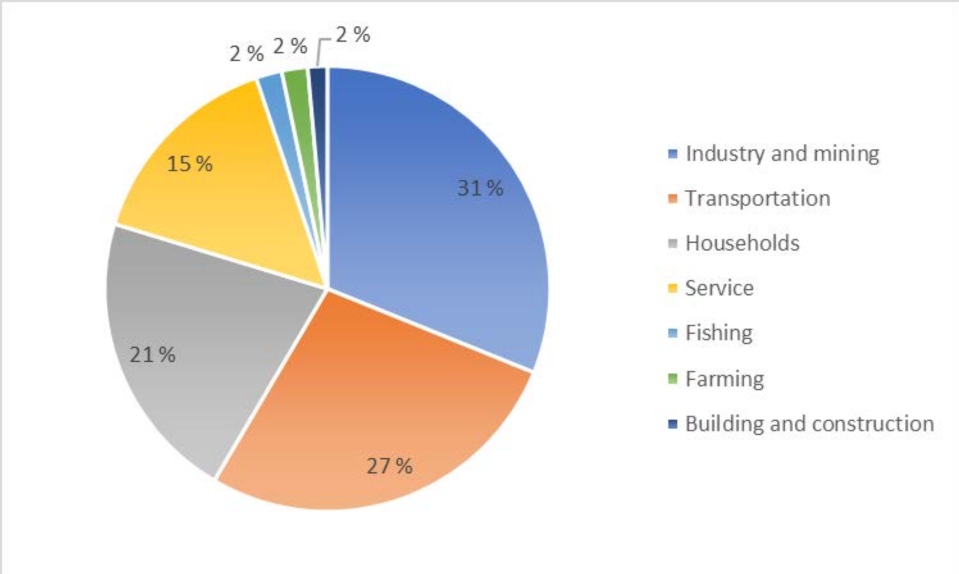

Figure 1 Norwegian distribution of energy consumption between sectors, 2015[6]

Approx 31% of the Norwegian energy demand in 2015 was consumed by the industrial sector,[7] with oil, gas and chemical and the metal industries as the two largest segments. As seen in Figure 1, the industrial sector is the largest consumer of energy in Norway. In total, the Norwegian industrial energy consumption was approx. 77 TWh in 2016. Of this, approx. 807 GWh of the energy used in the Industrial and mining-section was related to purchased steam produced off-site.[7] These numbers do not include the use of internally produced excess steam, and reliable numbers regarding on-site produced steam are difficult to find for the Norwegian industry. The largest share of steam for industry utilisation is generally produced directly on-site, through boiler systems or combined heat and power units.[8]

Excess steam in production processes is often vented to the atmosphere or condensed in a cooling tower and hence gives a potential for increased efficiency. The excess steam is normally at a lower pressure and temperature than what is required in the process. This report will review the possibility of re-compressing the steam, and deliver it back to the same, or another, process in the production. Such re-compression systems for steam are often referred to as Mechanical Vapor Recompression (MVR) systems.

Open loop MVR systems have the advantage of using the main process of the production as an evaporator for the working media (steam), and does not require a separate working fluid or evaporator. This makes it possible to reach a higher COP than for ordinary heat pump systems. Technically, the main challenge of MVR systems lies within the compressor, as a result of the high energy intensity of steam.

This report will focus on MVR-systems for steam processes up to 150℃. A lot of effort and achievements at high temperature heat pumps up to 80℃ have been carried out, but fewer at high temperatures up to 150℃. The focus will therefore be directed at the temperature levels between 80 and 150℃ for MVR systems using steam as working fluid, with the main focus of applications above 100℃, due to the atmospheric boiling point of water.

2 Steam utilization in Norway and Europe today

2.1 Amounts

In the industry, there are two ways to rely on steam in production, it can either be produced on-site, or be bought from external suppliers. The off-site supply is fairly well mapped by SSB in Norway, but the on-site production is not systematically reported. The excess heat in the Norwegian industry was mapped in a survey from 2009[9] where data was gathered from 72 Norwegian industries, accounting for approx. 63% of the Norwegian energy use. This revealed a reported excess heat of 19 TWh in 2008.

The *International Energy Agency Heat Pump Centre*[1] performed an analysis of the Industrial Heat Pump market and applications in 2014, including a review of the energy and excess heat situation in several EU-countries.[10] Heat-related energy use is defined as a major consumption, and for the German industry, nearly 66% of the final energy demand is related to process heat, see Figure 2. According to the *Energy research Centre of the Netherlands*[2], 80% of the final industrial energy use in Netherland is used for heating purposes.[11]

[1] www.heatpumpingtechnologies.org

[2] www.ecn.nl

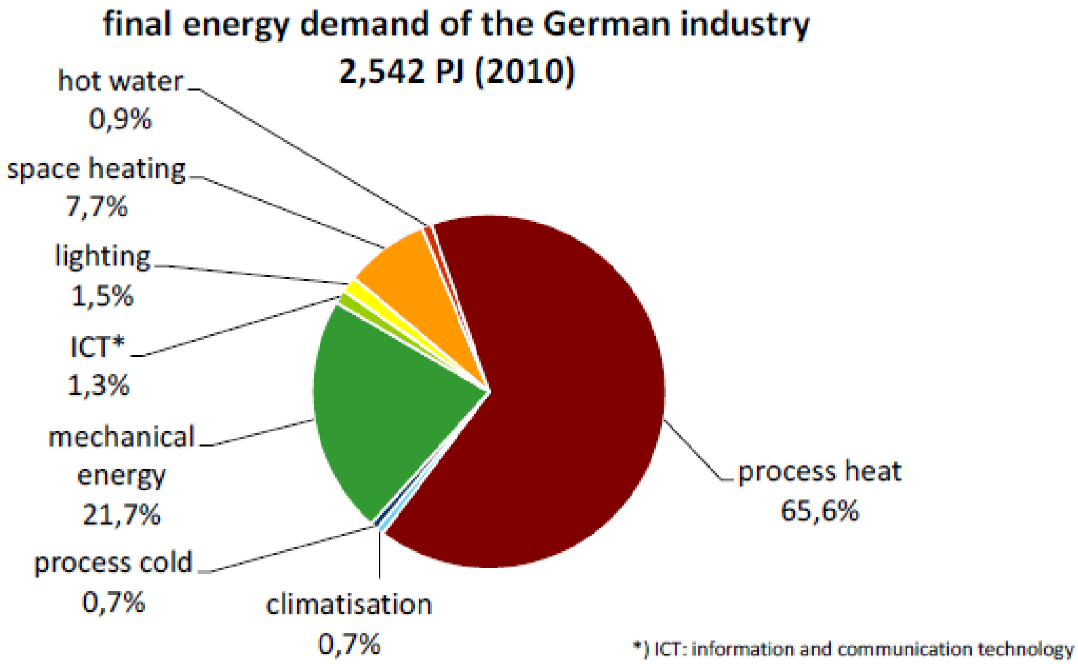

Figure 2 Final energy demand of the German industry in 2010[10]

Even though the energy used for heating purposes in the industry is generally high, the knowledge of the excess heat amounts and temperatures is low. Knowledge about the heating and cooling demands of their processes is quite rare in most companies, and mapping requires expensive and time consuming efforts.[10]

An analysis of the European markets shows a possible 2000 TWh of heat demand across different industries. About 174 TWh of this heat is reachable by industrial heat pumps and 74.8 TWh is high temperature (80– 150°C).[12] Figure 3 shows an overview of the distribution of industrial heat usage and the temperature across different European industries, including the temperature distribution.

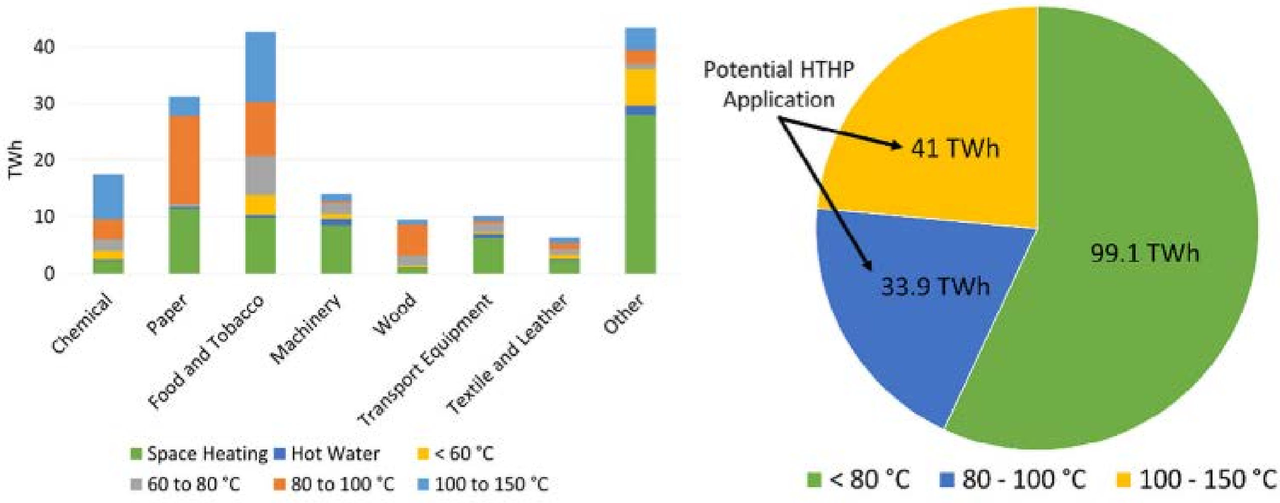

Figure 3 Heat demand amounts and temperatures in markets and industries in Europe[12]

2.2 Markets, market segments

As indicated in Figure 3, the main temperature distribution interesting for high temperature heat pumps is for heat demands at 80-150°C. The main markets and industries in which high temperature heat pumps may be applicable at these temperatures can be identified as the paper industry and the food and tobacco segment. These sectors can also be identified in an analysis of the German industrial heat pump potential from 2014, as seen in Figure 4.[13]

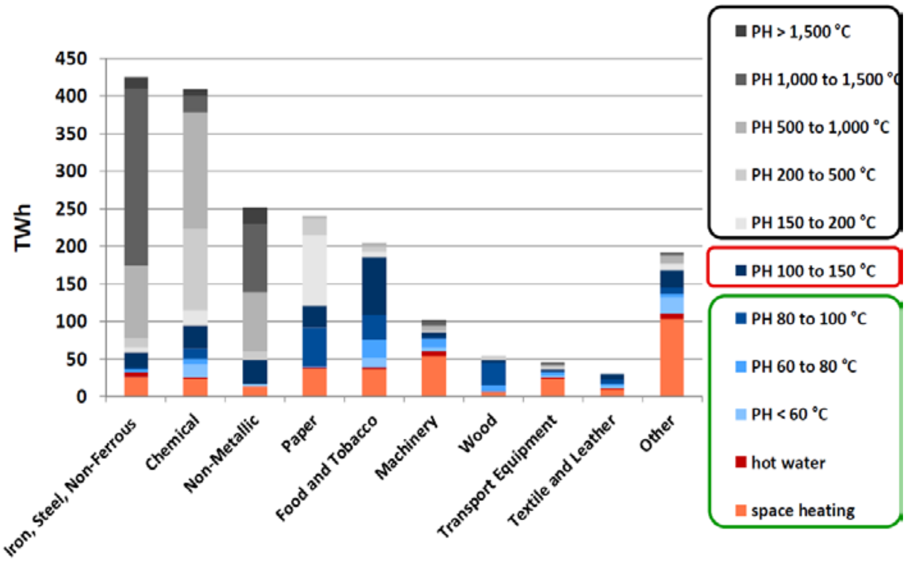

Figure 4: Estimates of industrial heat demand in Germany per sector and temperature range[13]

Exact numbers regarding heat demands for the Norwegian industry are not reported, but by reviewing the development in purchased district heating and steam per industry branch in Norway it is possible to find some indications (see Figure 5). The off-site steam supply to the "Manufacture of food products, beverages and tobacco" industry has seen a steady increase, doubling from 2003-2016.[8] This can be interpreted as an increasing demand in this market segment, also in Norway, for high temperature heat.

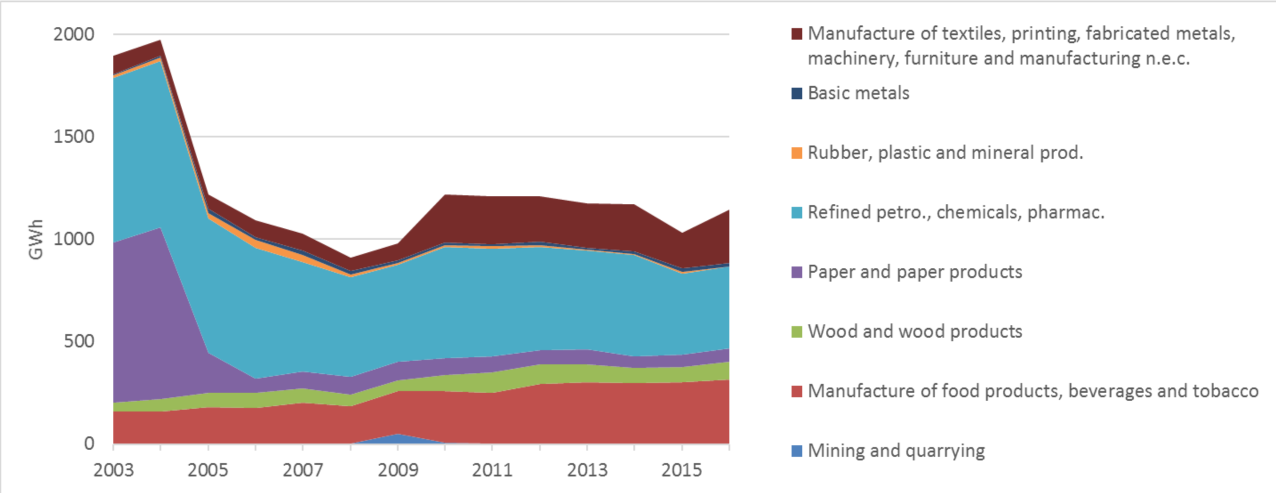

Figure 5: Purchased district heating and steam (energy) per industry branch in Norway[8]

There are several independent studies which have pointed to the food and beverages-industries as an interesting area of application for high temperature heat pumps. *Lauterbach et al.*[14] have in their study regarding the potential of solar heat in German industry in 2012 looked at the industrial heat demand in Germany in 2009 by investigating about 150 different energy customers. In Figure 6, the heat demand in the region 100-200°C is presented and distributed over different industrial sectors. This shows clearly that the Food products and beverages section dominates the demand in the region applicable for high temperature heat pumps.

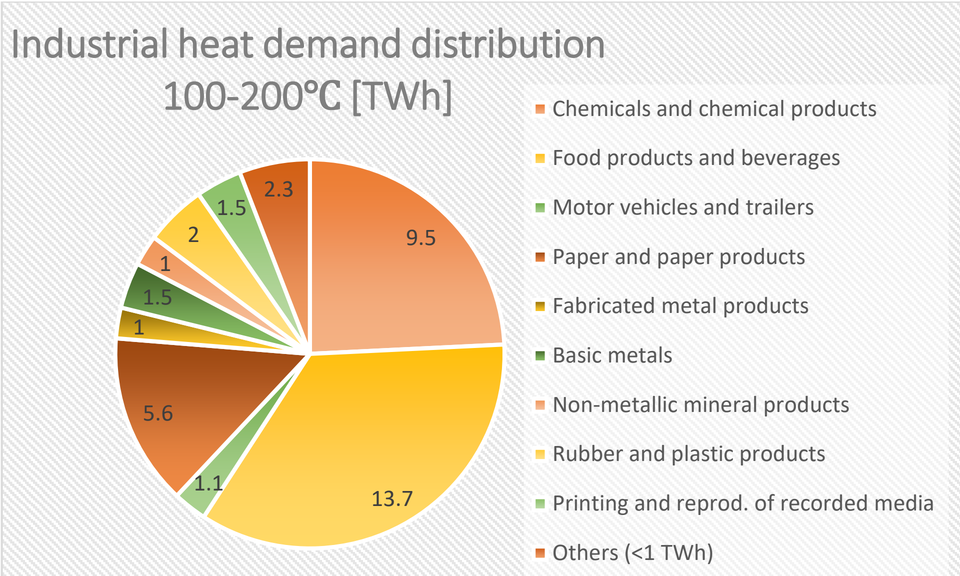

Figure 6 Industrial heat demand between 100-200℃ in German industry, 2009

These reviews indicate that the food and beverages sector are interesting as entry-points for high temperature heat pump technology. This was also identified in the SINTEF project CREATIV[3], where temperatures from 100 to 180°C were identified as suitable for drying processes.

In Figure 7 an overview of the heat consuming processes of several German industries requiring heat up to 160℃ is shown. As seen, the temperature range up to approx. 100℃ is covered by existing technologies and available HTHP. This covers several of the processes in the metal industry, as well as some of the other industries. At above 125℃, Drying processes dominate, and is relevant within most industrial sectors. There are several other processes within the paper and food industries which are relevant in this temperature domain as well, including cooking, evaporation, sterilisation and pasteurisation.

[3] https://www.sintef.no/projectweb/creativ/objective/

High temperature heat pumps up to 150°C can be regarded as having a huge potential, especially within the processes and industries mentioned. The next chapter will further discuss the technology selection, and the specific characteristics of open loop heat pumps.

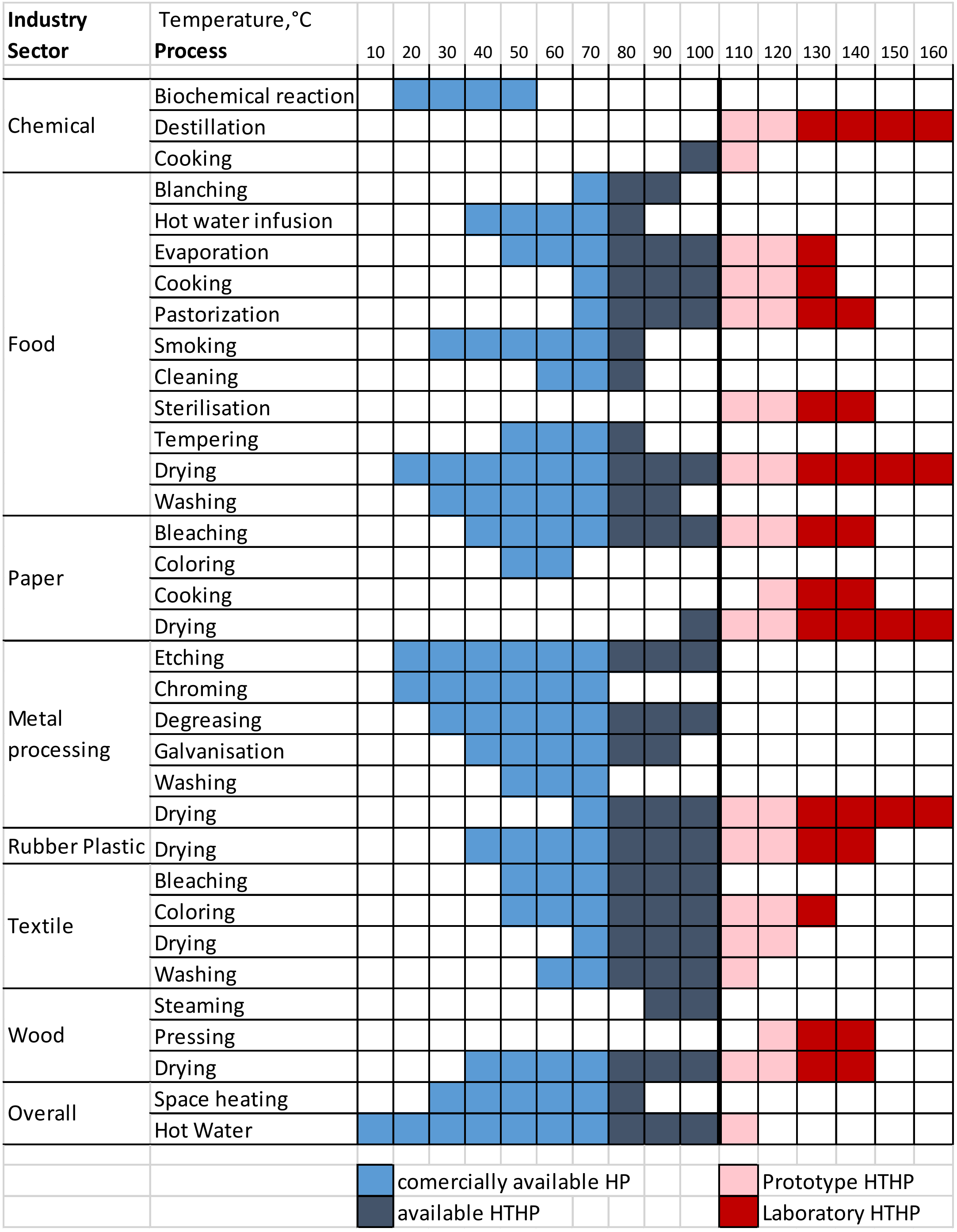

Figure 7 Temperatures of heat consumption in industrial processes, with related TRL levels[13]

3 Mechanical vapor recompression

3.1 System description

Mechanical vapor recompression (MVR) is a variation of the vapor compression cycle. It involves circulation in vapor phase of a fluid (usually water vapor) from a low pressure to higher pressure and temperature using a compressor. MVR applications and researches are common in industrial processes for drying, evaporation and distillation.[12]

The most attractive feature of the MVR process is that it is highly energy-efficient. Excess steam from the main thermal process can be applied directly in a heat pump, and elevated temperature steam is used to heat the mail thermal process. This way, the main thermal process acts as the evaporator of the heat pump, reducing the need for components, and hence reducing the losses compared to a closed loop system. In the process of mechanical vapor recompression, the steam generated by the evaporation of the solution is compressed by the vapor compressor to increase the pressure and temperature, so that it can be used to heat the incoming solution to evaporate.[15]

In processes where a heated process produces steam as a product or by-product, MVR is a relevant technology and should be considered. In general, a MVR heat pump consists of a main process producing steam, a compressor, a heat exchanger and a valve. Unlike a regular heat pump, where there is a need for two heat exchangers, the main process acts as the evaporator itself in the MVR system. Figure 8 shows a possible open loop setup where some of the excess steam from the main process is directed through the compressor to heat the rest of the steam used for heating. The heat pump set up in the open loop case can be arranged in several ways, specific to the necessary temperature and pressure lift and working fluid. Common for all systems are the three main components:

- Vapor compressor
- Heat exchanger
- Evaporator, normally the main process

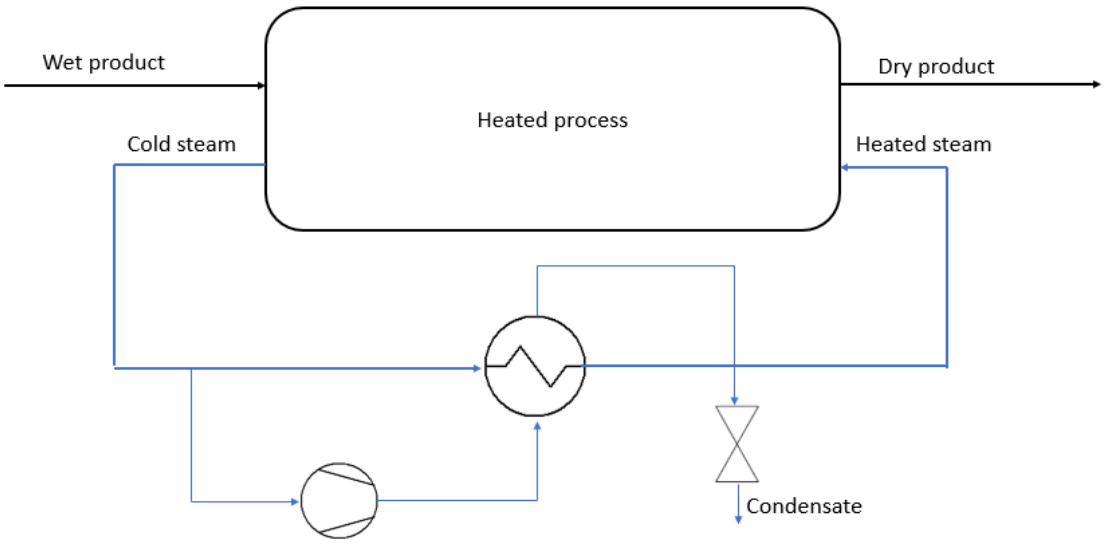

Figure 8 Example of MVR process for steam regeneration

The three main components will be further introduced in chapter 4, with the technological challenges affiliated to using them in an open loop steam application.

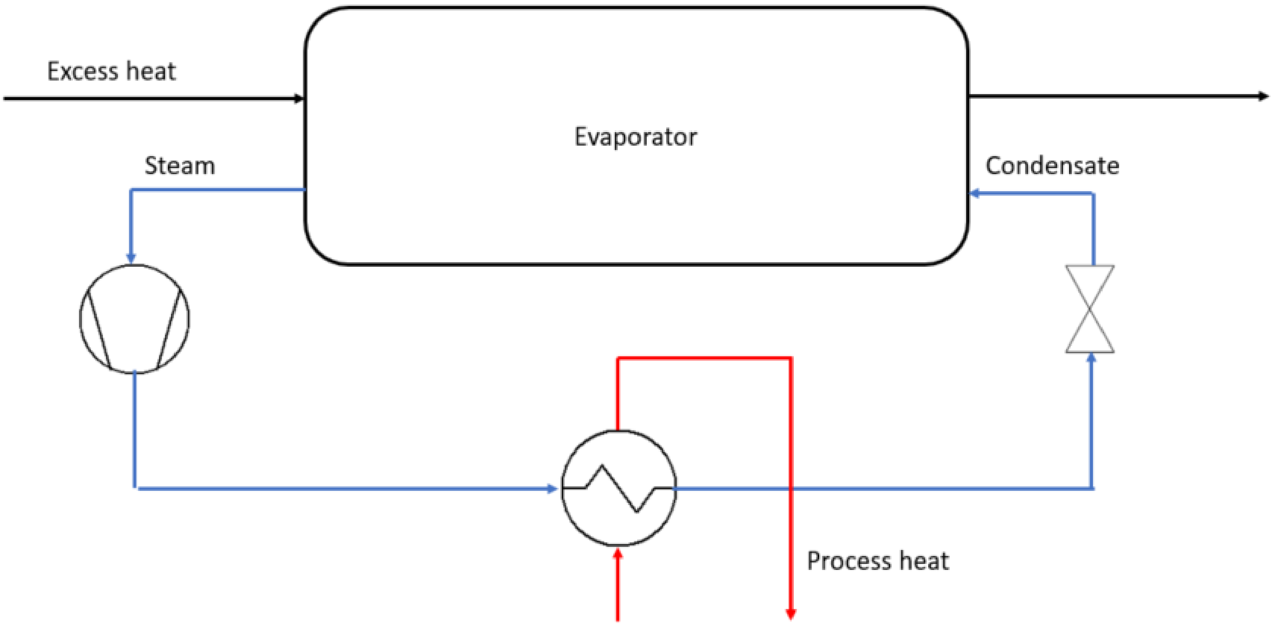

Figure 9 Example of closed loop steam compression with an evaporator at atmospheric pressure

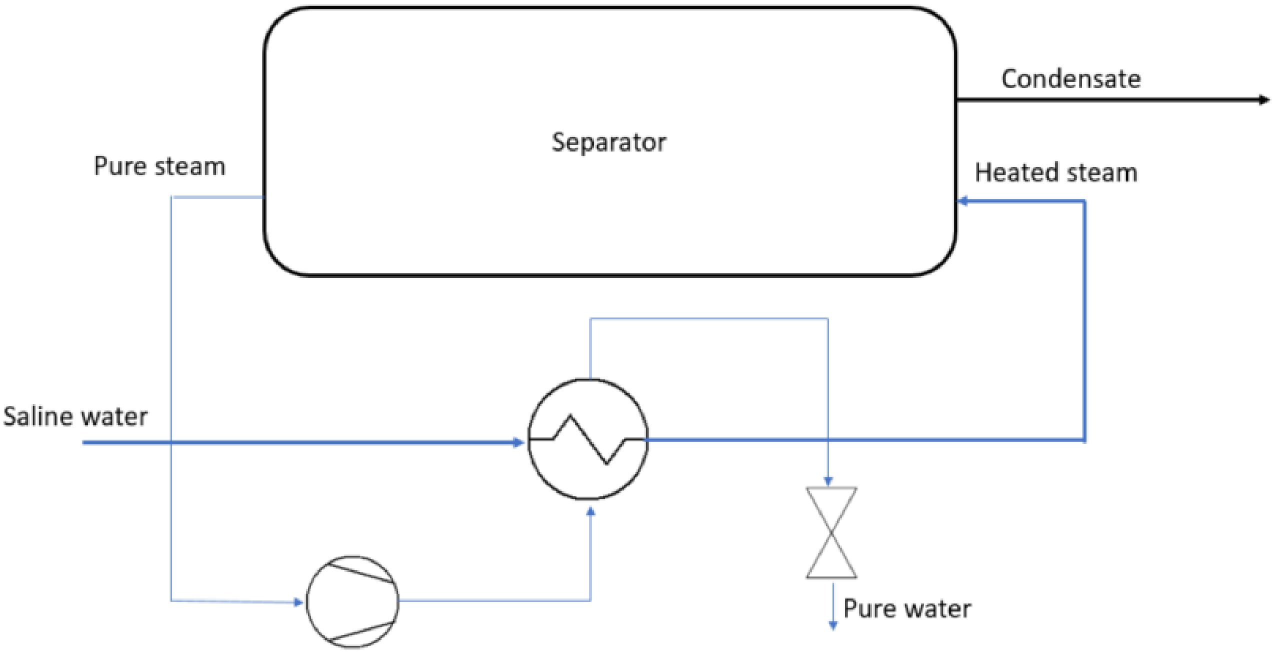

Figure 10 Example of a desalination process

3.2 Steam as a working fluid

Several studies have investigated different options for working media for high temperature heat pumps. Ammonia, Carbon dioxide, Helium, Butane and water are a few examples of the options. Water is both free and safe, with a GWP value of zero. It also shows good thermodynamic properties for use in high temperature heat pumps, including high critical temperature and pressure, see Table 1. Water has good thermal conductivity, and a relatively high enthalpy, also making it suitable for heat pump applications.

Table 1 Common natural working fluids and their properties[12]

Ashrae number	IUPAC name	ODP	Net GWP 100-yr	Molar mass (g mol^{-1})	Normal boiling point(s) (°C)	Critical temp. (°C)	Critical pressure (absolute) (kPa)
R-290	Propane	0	3.3	44.1	–42.1	96.7	4,248
R-600	Butane	0	4.0	58.1	0.0	152.0	3,796
R-600a	Isobutane	0	3.0	58.1	–11.7	134.7	3,640
R-601	Pentane	0	4.0	72.1	36.1	196.6	3,358
R-601a	Isopentane	0	4.0	72.1	27.7	187.8	3,378
R-717	Ammonia	0	0.0	17.0	–33.3	132.4	11,280
R-718	Water/Steam	0	0.2	18.0	100.0	373.9	22,060
R-744	Carbon dioxide	0	1.0	44.0	–78.0	31.0	7,380

Water is especially well suited if the heat source is at a temperature above water boiling point at atmospheric pressure. For operations below 100℃, the system will need to have a cascade set up, or be at sub-atmospheric pressures. Water also has a high heat of vaporization, giving it a high theoretical COP. Larminat, et al. [16] reviewed the potential coefficient of performance for several different fluids for a high temperature heat pump with a temperature lift of 45K, and concluded that above 100℃, water is by far the most efficient. Ammonia is also mentioned as interesting, but is limited by high pressure at high temperatures.

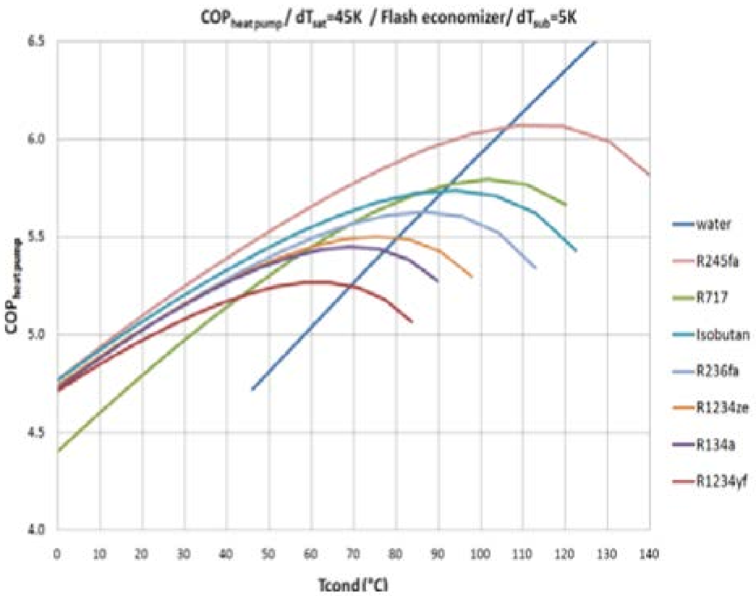

Figure 11 Heating COP of various fluids[16]

The challenges of using water as a refrigerant are mainly related to the relatively low density of water vapour and to the high temperature increase for a given temperature lift.[12] These factors result in a need for a higher volume flow for a given energy transfer compared to other working media, as well as high temperature rise when superheating in the compressor. This limits the compressor operation, causing a special need for research on materials, operation, compressor type and lubrication. In a study regarding refrigeration using water cycles, the specific volume of water is 2400 times higher than for the same cooling capacity using refrigerant R-134a.[17] Superheat losses, high requirement for volumetric capacities and a high necessary compression ratio are mentioned as key challenges using water as a refrigerant. The same study concludes that significant technological advances within compressor technology are necessary to make water an economically competitive refrigerant.

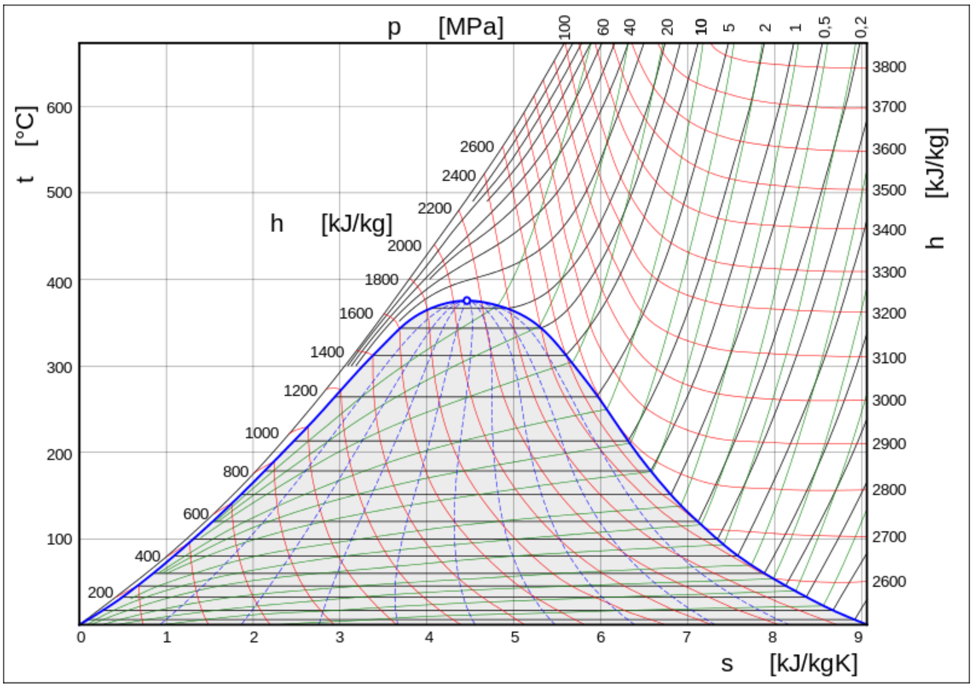

Figure 12 Temperature-entropy chart for water

3.3 Technology status

High temperature heat pumps are subject to a large number of R&D projects and high interest from the industry. Ammonia, CO_2 and Butane are commonly used as refrigerants, but less research has been carried out for steam based processes. Figure 13 shows an overview of state of the art of high temperature heat pump research for all working media. The existing technologies using steam as a working media are mainly closed loop, and are in general based on expensive and large screw compressors with high capacities.[18] Industrial demands typically range from 500 kW to 3-4 MW, and are in a range where conventional compressor technology is difficult to apply.

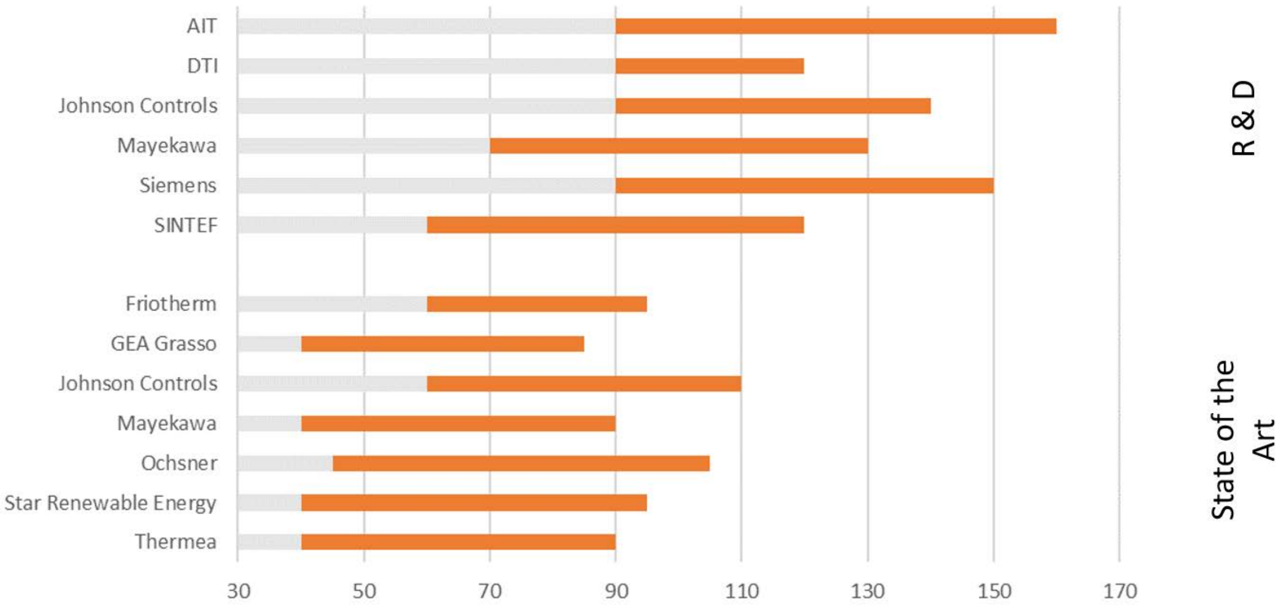

Figure 13 State of the art & ongoing research – useful temperature above 80℃ [11]

MVR systems are today commonly found in desalination systems where the main process is a separator concentrating saline solutions and delivering pure steam to the compressor before going through a distillation process. For industrial energy recovery, MVR systems are not in a commercial phase yet, and few pilot projects exist. The only known projects in a pilot phase today are the PACO project by Johnson-Control and the DryF project by AIT and SINTEF.

Johnson Controls have developed a high temperature heat pump using water as refrigerant for industrial heat recovery through the PACO project. They identified a significant market need for heat above 130℃ with a temperature lift of 30-40K, and decided to use water as refrigerant. The choice of using water was mainly based on thermodynamic properties, but also the potential of using the heat pump in an open cycle. They first developed a heat pump using a screw compressor showing promising results in laboratory testing. The PACO project using screw compressors was further developed by aiming at exchanging the screw compressors with two-stage centrifugal compressors with magnetic bearings. They built and tested a prototype for 700 kW heating capacity operating within 90 and 130 °C heat sink outlet temperature.[16,19] Johnson Controls are currently working on the PACO2 project, aiming to reach condensation temperatures up to 150℃ and capacities of 1-3 MW.[11] The challenge is to lower the costs of the engine and compressor setup in order to make it economically feasible.

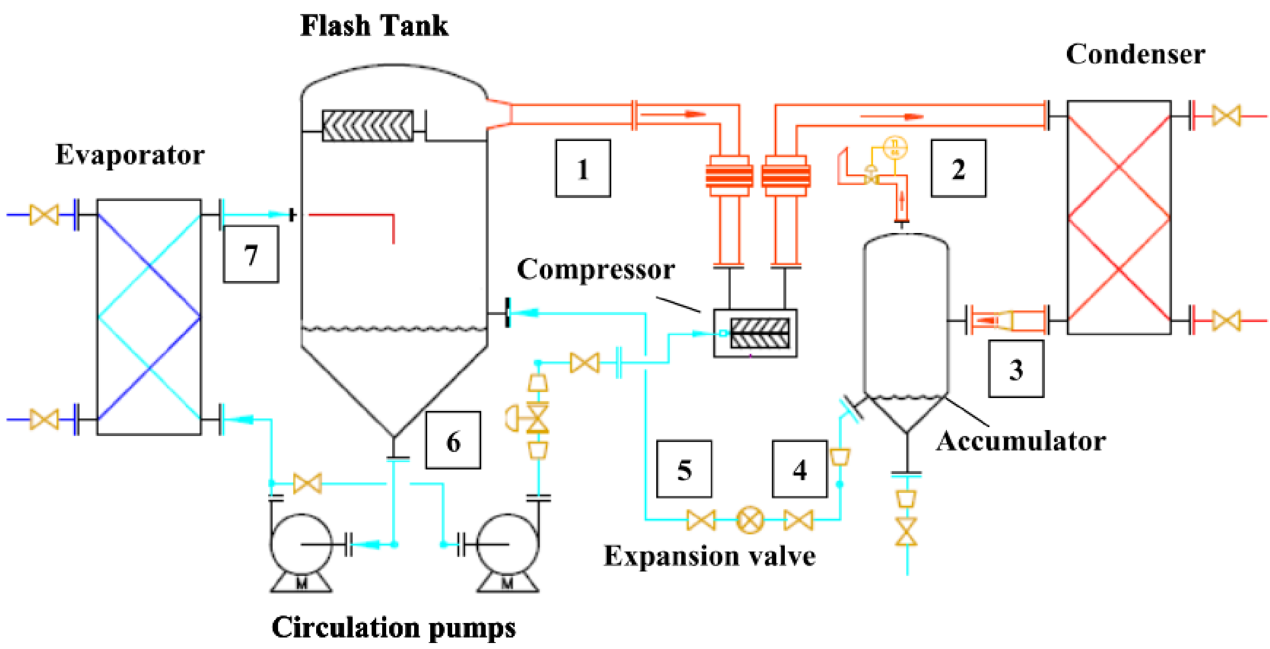

Figure 14 PACO Screw compressor heat pump[19]

Figure 15 PACO heat pump with centrifugal compressors[16]

The DryF project currently being executed by AIT and SINTEF aims at reaching a condenser temperature of 150℃ using centrifugal compressors in an open loop heat pump. The technology consists of a two stage compression using turbo-compressors running at high speeds. In cooperation with Rotrex, a planetary gear has been developed to enable the use of an engine running at much lower speeds. The challenge also here is the high temperatures of the steam in the compressor, causing the lubrication in the gear box to degrade. Testing is currently being performed at the SINTEF Energy Laboratory, and results are expected within the first half of 2018.

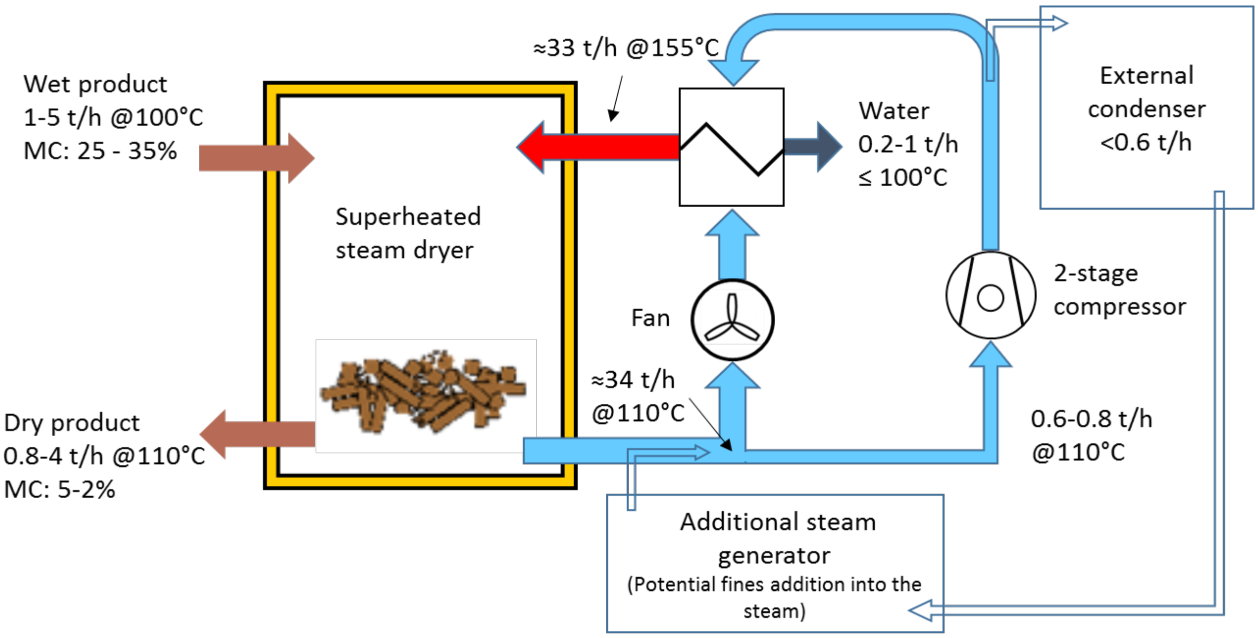

Figure 16 Schematic of the DryF case

4 Technological feasibility

Defining the right type of equipment, sizing and operating parameters is perhaps the most difficult aspect of HTHP development. Using water vapor as the working fluid, the high temperature rise related to pressure increase, as well as the high specific volume are the main challenges. Especially within the compressor, these characteristics are challenging. The high temperature of superheated steam challenges the material choices and characteristics of the lubrication, while the high specific volume limits the possible technologies suitable for delivering a sufficient capacity and temperature lift.

A theoretical analysis of HTHP cycles shows that the highest amount of irreversible losses occurs for the two main components; the compressor and the heat exchangers, with the compressor having the highest irreversible loss. [12]

4.1 Compressor

As mentioned earlier, the compressor technology is the key element to succeed in developing a high temperature heat pump for steam. Providing sufficient volumetric capacity, at the same time as being efficient, affordable and reliable at high temperatures seems to be difficult to achieve even with today's technology. However, EDF R&D shows that water vapor compression at high temperatures can be performed today, but with several limitations: [19]

- Blowers allow compression of high mass flow rates but under low compression ratios (corresponding to saturated temperature difference ΔT of 5 to 7 K).
- Multi-stages blowers allow an increase of ΔT to 10 to 12 K.
- Lobe compressors are adapted to low flow rates but with higher ΔT to 20 K. These compressors have a poor isentropic efficiency.
- Classical centrifugal compressors (mechanical bearings) can be used in double stage compression process to attain a maximum ΔT of 40 K. These machines are relatively expensive and work at high rotational speeds at high compression ratio. At these conditions, high level of maintenance is required. In addition, reduced reliability of these compressors is due to the use of mechanical bearings and imperfect sealing at these conditions.

Larminat, et al. [16] identifies the existing state of the art for direct vapor recompression and their project target as shown in Figure 17, showing the limitations of the existing technologies. Screw compressors and centrifugal- or turbo-compressors are the two technologies able to deliver sufficient compression ratio at a reasonable mass flow, and for both these technologies, the lubrication is a challenged, due to the high temperatures. Screw compressors exist in both dry and lubricated versions. The dry versions suffer from low efficiencies, while the lubrication introduces difficulties related to the mentioned high temperatures. Turbo compressors seem promising due to their high volumetric capacity, but are challenged by high rotational speeds, bringing into action the before mentioned lubrication problems. Despite this, both the PACO project and the HeatUP[4] project identified turbo-compressors as the most promising technology for high temperature steam compression. Turbo compressors are also generally associated with lower investment costs than screw compressors, reducing the cost by a factor of 10.

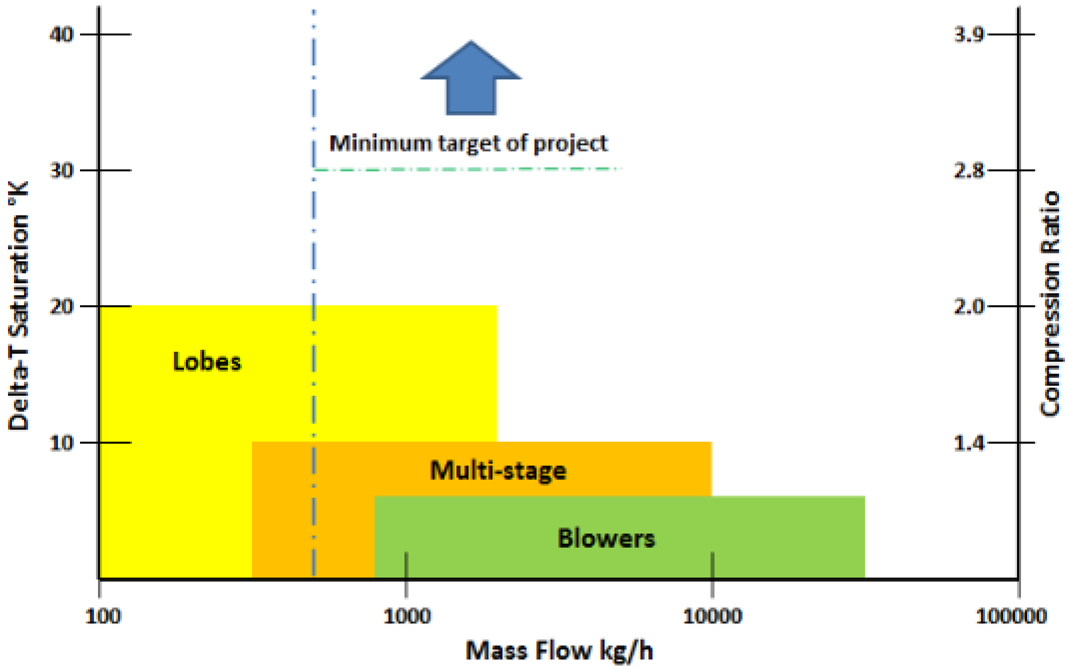

Figure 17 State of the art for direct vapor recompression and PACO project target

[4] http://www.sintef.no/heatup

Hence, the main focus of ongoing and future development within steam compressors lies within the lubrication and bearing system of the engine, gearbox and compressor. The PACO project is experimenting with magnetic bearings on a direct-driven shaft for two centrifugal compressors in a 100% oil-free system. This requires a high speed electrical engine running at up to 40000 rpm, introducing significant costs. The DryF-project is experimenting using a more traditional set up, where a low-speed engine at approx. 9000 rpm is geared up to the necessary rotational speed of the impeller. The challenge here is related to the before mentioned temperature rise of the lubrication and materials.

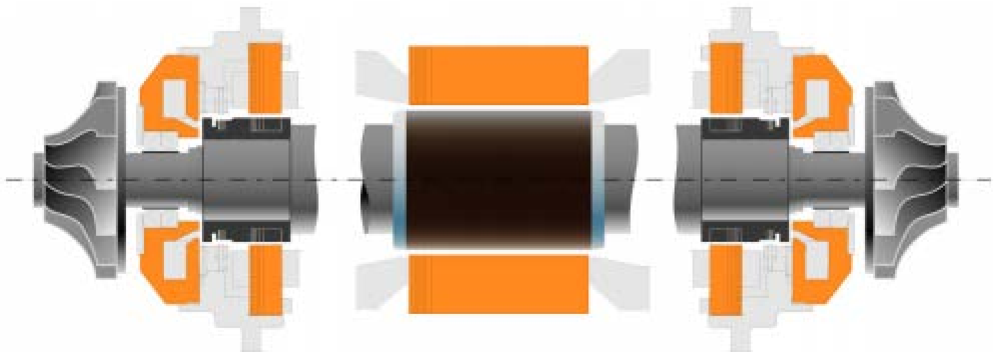

Figure 18 PACO direct driven twin compressors

4.2 Heat exchanger

The main advantage of the MVR heat pump compared to a regular closed loop heat pump is the need for only one heat exchanger. The heat exchanger will act as a condenser after the compressor, delivering heat from the working fluid to the process. Bamigbetan, et al. [12] identified the compressor and heat exchanger as the main source of losses in a high temperature heat pump. Heat exchangers are in general a lot cheaper and simpler than the compressor, and the technology is well developed. However, some characteristics must be taken into consideration for steam heat exchangers at these temperature levels. Steam in general has high heat transfer coefficient compared to other relevant working media, estimated to 5000-15000 W/m^{2}K for film heat transfer. In comparison, ammonia has a heat transfer coefficient of approx. 3000-6000 W/m^{2}K. [20] Another important thermodynamic feature is the evaporation enthalpy, as a high heat of evaporation leads to less fluid needed in the cycle to transfer a given amount of heat. Water also has a low saturation pressure as a function of temperature, which makes the system operate at lower pressures than what is realistic for other working fluids. This is an advantage both when it comes to safety and operation, as well as the cost of equipment.

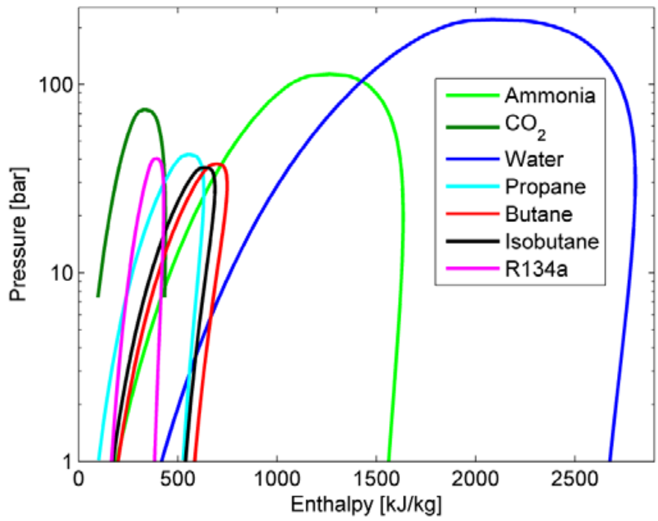

Figure 19 Log(p) - h diagrams for different working fluids [21]

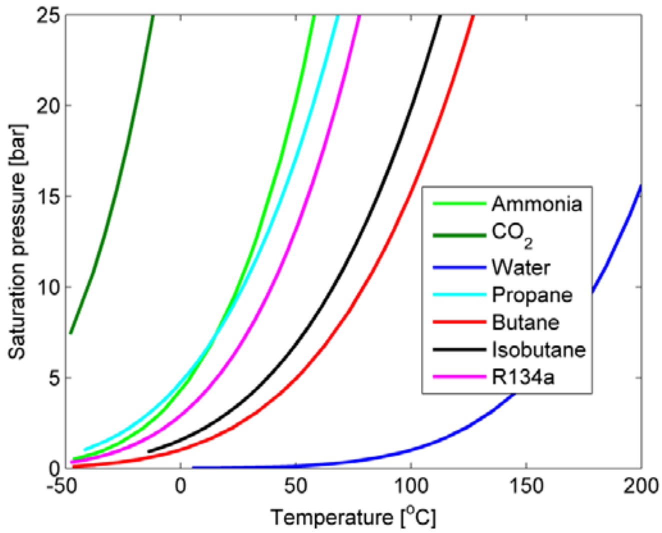

Figure 20 Saturation temperature as a function of pressure [21]

The challenges related to steam heat exchanger are mainly related to the same properties as the compressor technology, namely the high temperature and the high specific volume. Water contracts at a ratio of approx. 1:200 when condensed at 150℃, while e.g. butane contracts at a ratio of nearly 1:2 when condensed at the same temperature. The huge change in specific volume is a challenge in sizing the heat exchanger, especially when it comes to pressure drop considerations.

At the inlet of the heat exchanger, the temperature will typically be in the range of approx. 300℃ caused by the superheating in the compressor. This applies requirements in design and material choices in the heat exchanger which must be considered. Plate heat exchangers are typically not designed for these temperatures, making it necessary to use more expensive shell and tube heat exchangers.

Fouling is another important aspect within heat exchanger which needs to be considered. In an open loop setup, the purity of the steam is a characteristic which will highly influence the fouling of the heat exchanger, and hence the heat transfer coefficient. While good quality steam will reduce the heat transfer coefficient by 20-30% over time, contaminated steam can reduce the heat transfer coefficient by 60-70%. [20] This is of course depending on the contamination level, and what kind of contaminants, but is nonetheless a key factor to consider.

4.3 Evaporator

A main characteristic in the MVR heat pump is the fact that the evaporator is a part of the main process. I drying or boiling applications, the drier or boiler itself is the evaporator, while in separation processes, a separator is the evaporator. Which products are being treated in the process is a crucial factor in the performance characteristics of the heat pump. With a turbo compressor running at 60-90 000 rpm, it is of high importance to avoid any particles or droplets going into the system, and the heat exchanger fouling is as described relying strongly on the steam purity. Purification measures, filters, separators or other ways to ensure a high-quality steam should be considered in the design phase.

5 Economic feasibility

The main feature to be able to implement high temperature heat pumps in the industry for energy revocery is to be competitive on price, compared to existing solutions. The International Energy Agency has also identified the economics as one of the main barriers against industrial implementation of high temperature heat pumps.[11] By exchanging the existing gas driven steam boilers with electric heat pumps, the environmental benefit will be significant, but in several countries the electricity price is already higher than gas and rising.

Country	Electricity/Gas Price Ratio Households	Electricity/Gas Price Ratio Small Enterprises	Electricity/Gas Price Ratio Large Enterprises	Indicator
Sweden	1,2	1,3	1,0	↑
Finland		1,8	1,2	↑
Bulgaria	1,9	2,6	2,0	↑
Netherlands	1,5	2,6	2,6	↑
France	1,4	2,7	2,5	↑
Slovenia	2,5	2,1		↑
Portugal	2,1	2,5	2,4	↑
Estonia	2,5	2,6	2,2	↑
Austria	2,8	2,7	2,0	↑
Poland	2,4	2,8	2,4	→
Lithuania	1,7	3,4		→
Croatia	2,6	2,6		→
Hungary	3,1	2,4	2,8	→
Latvia	2,2	3,5	2,7	→
Luxembourg	3,2	2,3		→
Slovakia	1,7	3,5	3,2	→
Denmark	4,2	1,9	2,7	→
Czech Republic	2,2	3,7	2,9	→
Spain	2,9	3,5	2,5	→
Greece	2,3	4,0		→
Italy	2,2	3,9	3,7	→
Romania	4,2	3,0	2,8	→
Belgium	2,8	4,0	3,2	→
Germany	3,0	4,0	3,5	→
Ireland	4,1	3,9		↓
United Kingdom	2,8	4,2	5,1	↓
EU-28	2,4	3,3	3,0	→

Figure 21 Comparison of electricity and gas prices for selected European countries. [11]

Comparing gas fired boilers with electricity driven heat pumps, the numbers from Figure 21 can simplified give an indication of the necessary heat pump COP to be competitive on operating costs. The coefficient of performance is a quantification of how much heat is delivered per work input, and therefore gives an indication of how much gas is replaced per electricity input. There are great differences in the electricity prices across Europe, and the required COP to give a competitive operating cost is therefore far higher in Belgium, Germany and UK, than in Sweden, Finland and Norway. Looking at Figure 11, it is obvious that water is the only working fluid capable at being competitive at such high temperatures.

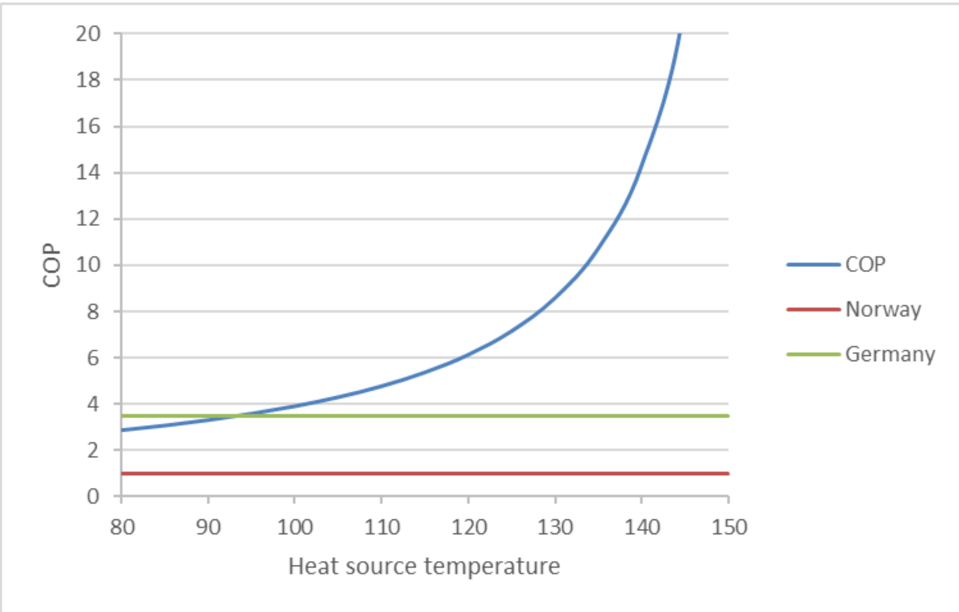

Figure 22 Maximum obtainable COP for a heat sink of 150℃, a deltaT of 5K in the condenser and a Carnot efficiency of 50% of the heat pump cycle, along with Electricity/gas price ratio for Sweden and Germany.

Comparing the data from Figure 21 and Figure 22, a high temperature heat pump delivering heat to a sink at 150℃ should be economically competitive from an operating cost point of view for most European countries for heat sources of above 90-100℃. The data in Figure 22 correlates well with the results of Larminat, et al. [16] where the test results gave a carnot efficiency of 55% and a COP of 5.5 at a 40K temperature lift to 130℃.

As the operating costs seem to be competitive, or even advantageous for the high temperature heat pumps, the investment cost should be the main focus of investigation. The payback period requirement of such investments in the industry typically lies within 2-3 years, limiting the maximum heat pump investment depending on the energy savings. In Figure 23 a calculation of maximum investment costs for different sizes and energy prices is shown, to give an indication of the impact of the energy price on the investment options.

	Norway			Germany		
	1MW	5MW	10MW	1MW	5MW	10MW
Capacity [kW]	1000	5000	10000	1000	5000	10000
Annual working hours [h]	6500	6500	6500	6500	6500	6500
Annual heat demand [GWh]	6.5	32.5	65	6.5	32.5	65
COP	3.89	3.89	3.89	3.89	3.89	3.89
Energy input [kW]	257	1285	2569	257	1285	2569
Electricity price [EUR/kWh]	0.07	0.07	0.07	0.15	0.15	0.15
Gas price [EUR/kWh]	0.06	0.06	0.06	0.04	0.04	0.04
Net savings [EUR]	273102	1365509	2731017	9504	47518	95037
Payback period	2.5	2.5	2.5	2.5	2.5	2.5
Maximum investment [EUR]	682754	3413771	6827543	23759	118796	237592
Investment per kW	682.8	682.8	682.8	23.8	23.8	23.8

Figure 23 Calculated maximum investment for a high temperature heat pump with a heat source of 100°C and a heat sink at 150°C and a carnot efficiency of 50%

The maximum investment cost for a high temperature heat pump in Germany of 24 €/kW is unrealistic, so the carnot efficiency of the heat pump needs to be higher than 50%. The savings is very sensitive to the efficiency, and by adjusting to 60%, the numbers are quite different, as seen in Figure 24. Optimum design of the heat pump is clearly an important factor of these evaluations.

	Norway			Germany		
	1MW	5MW	10MW	1MW	5MW	10MW
Capacity [kW]	1000	5000	10000	1000	5000	10000
Annual working hours [h]	6500	6500	6500	6500	6500	6500
Annual heat demand [GWh]	6.5	32.5	65	6.5	32.5	65
COP	4.67	4.67	4.67	4.67	4.67	4.67
Energy input [kW]	214	1070	2141	214	1070	2141
Electricity price [EUR/kWh]	0.07	0.07	0.07	0.15	0.15	0.15
Gas price [EUR/kWh]	0.06	0.06	0.06	0.04	0.04	0.04
Net savings [EUR]	292585	1462924	2925848	51253	256265	512531
Payback period	2.5	2.5	2.5	2.5	2.5	2.5
Maximum investment [EUR]	731462	3657310	7314619	128133	640663	1281327
Investment per kW	731.5	731.5	731.5	128.1	128.1	128.1

Figure 24 Calculated maximum investment for a high temperature heat pump with a heat source of 100°C and a heat sink at 150°C and a carnot efficiency of 60%

6 Conclusion/further work

It is clear that high temperature heat pumps have a huge potential in Europe and Norway, as the steam demand in the industry is significant. The biggest potential within the temperature range of 100-200℃ is in the food, paper and textile industries, with drying, boiling and distillation as some of the main processes. The existing technology does not yet cover the demand, but several research projects are aiming at developing heat pumps for higher temperatures, as several independent sources have identified high temperature heat pumps as a topic with significant potential.

The main challenge when it comes to cycle technology lies within the compressor. The existing technology does not sufficiently cover the desired temperature range for steam, and both high temperatures and high specific volume is challenging. Further developments in these areas is crucial to enable implementation of high temperature steam heat pumps in the industry. Special attention should be paid to issues regarding lubrication and materials for high temperatures. Independent sources have identified turbo compressors as the most interesting technology to evaluate further, as the other technologies are either too expensive, or limited in pressure increase.

Economics is today one of the main barriers of implementation in the industry, and cheaper technologies need to be developed. Lachner, et al. [17] estimates the compressor cost in a steam refrigeration cycle currently to represent nearly 90% of the total cost, so it is clear that the main focus should be on developing cost efficient compressor technology. It can also be seen that the economics is highly related to the system efficiency, and a high overall efficiency is crucial to make a system economically feasible. In one project, the carnot efficiency of the test unit was 55%, lying at the lower limit necessary, so further research is also needed here to improve it.

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