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Report

Potential for steam regeneration in Norwegian industry

Within the framework of RCN-funded KPN project HeatUp

Authors

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"In short, I expect almost totally to prevent waste of steam"

James Watt, Letter to Dr. Lind, 1765

2017-12-18

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ABSTRACT

The goal of the report is to evaluate the general potential in Norwegian industry for industrial heat pumps using low-pressure and low-temperature excess steam to efficiently upgrade it to higher pressure and temperature and re-inject the steam into a local process. Significant savings on the local production of steam or purchase of steam would be achieved in the industry where such a solution is implemented, not to mention an increased competitiveness and reduced environmental impact. Implementing a dedicated heat pump would represent a relatively low investment cost compared to the operational savings. However, not all excess heat consists of usable steam with a significant flow rate. Therefore, a quantification is needed for the Norwegian case, regarding the different available processes.
The report focuses on investigating the current situation of steam utilisation in Norwegian industry. An extensive section investigates the available excess heat in Norwegian industry, as well as the opportunities for steam regeneration in the most relevant standard processes. The potential of such systems is also demonstrated by efficiency and coefficient of performance (COP) calculations.

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1 Introduction

1.1 Background

The EU Energy Strategy demands a 40 % reduction in greenhouse gas emissions and a 27 % increase in energy efficiency by 2030 [1]. These requirements are expected to become even stricter in the near future after the agreement on a 2-degree increase limit of global warming at the Paris Climate Conference in December 2015 [2]. Several countries with high political influence have already ratified the agreement (e.g. France, Germany and China). All industrial sectors are therefore expected to face stronger efforts to meet these climate goals, especially by dramatically reducing the reliance on fossil fuel and by optimising their specific energy consumption. Nevertheless, reducing specific energy consumption also results in an equivalent reduction of operating costs.

Steam is a common medium found in many industrial processes relying on high temperature and eventually high pressure. The success of steam in the industry is mainly due to the high availability of water all around the world. Nevertheless, due to the water's high specific heat capacity and latent heat of vaporization, producing steam remains extremely energy demanding, even with the most advanced steam production units which perform at close to the highest physically achievable efficiencies.

In parallel, large amounts of excess heat from industrial processes are estimated to reach up to 812 TWh/year in Europe (EU27) in 2010 [3]. Such figures are not systematically reported to international energy statistics, therefore they need to be estimated. In Norway, the last survey (from 2009 [4]) gathered data from 72 participating Norwegian industries, accounting for about 63 % (about 53 TWh/year) of the Norwegian industry energy use, revealed a reported excess heat of about 19 TWh in 2008. The reported excess heat corresponds to more than six times the net production of district heating in Norway in 2008 [5].

The excess heat is defined as the heat content of all streams, which are discharged from an industrial process at a given moment [6]. It generally takes the form of a stream of gas, liquid water, steam, air, etc. and ranges from above ambient temperature to a few hundred degrees Celsius. The purity of these streams usually depends of the standards and regulations in place. Utilisation of excess heat can become relatively complex and/or economical, depending on the nature of the stream, the type of industry and processes available, the distance to other industrial clusters or urban areas.

There exists various ways to make use of excess heat in the industry [6]:

- Internally, to realise primary energy savings
- At another industry site or other industries in an industrial cluster
- Between an industry / industrial cluster and a district heating system
- Between an industry/industrial cluster and e.g. greenhouses or for other low-temperature purposes
- As a heat source in refrigeration plants for industrial or district cooling

The present report focuses on internal use of excess heat, especially in the form of excess steam, to realise primary energy savings. A heat pump can be designed to feed from industrial excess steam as low as 100°C and ambient pressure, and to efficiently upgrade it to higher pressure and temperature to re-inject the steam into a local process.

Heat pump is a well-known technology in the residential heating and cooling sector, warming up houses to 25 °C or domestic hot water to 65 °C, while relying on a low-temperature heat source (e.g., ambient air, sea water, or the ground) and additional electrical input. It is therefore possible to produce a large amount of high quality heat by using a low amount of electrical energy (preferably from renewable energy sources). Heat pumps also have a high potential in the industry due to their design and operational flexibility. They may be used to produce hot water up to 80-120 °C or steam at up to 200 °C, relying on a low-temperature excess heat source at 30-50 °C. Due to the higher ranges of temperatures than with the typical residential-heating heat pumps, working fluids and components must be adapted to each application to reach the highest efficiency and durability.

This is the focus of the RCN-funded KPN project HeatUp, where system components and solutions for high-temperature heat pumps will be developed together with the industries willing to apply the technology, including major industrial actors such as Hydro Aluminium AS, Statoil ASA, Mars Petcare, Statkraft Varme AS, Tine SA and Vedde AS. Close collaboration with the industry will ensure fast commissioning of new industrial heat pump designs.

The aim of the current report is to evaluate the general potential in the Norwegian industry for industrial heat pumps taking in low-pressure and low-temperature excess steam to efficiently upgrade it to higher pressure and temperature and re-inject the steam into a local process.

Significant savings on the local production of steam or purchase of steam would be achieved in the industry where such a solution is implemented, not to mention an increased competitiveness and reduced environmental impact. **Implementing a dedicated heat pump would represent a relatively low investment cost compared to the operational savings**. However, not all excess heat consists of usable steam with a significant flow rate, therefore a quantification is needed for the Norwegian case, with regards to the different available processes.

The present report focuses on investigating the current situation of steam utilisation in Norwegian industry. An extensive section investigates the available excess heat in Norwegian industry as well the opportunities for steam regeneration in the most relevant standard processes. The potential of the described heat pump system is also demonstrated by efficiency and coefficient of performance (COP) calculations relying on some real cases in Norway.

1.2 General concept for steam regeneration

The concept of interest in the current report relies on:

(1) The availability of steam as an output stream from industrial processes,
(2) A demand for steam at a higher pressure and temperature in a nearby process.

Excess low-pressure steam from industrial processes is often vented to the atmosphere or condensed in a cooling tower. Instead, the unused low-value steam could be recycled mechanically through a compressor unit, while preserving its latent energy. Using an efficient steam electrical compressor, staged or not, to increase the steam pressure depending on the local demand, should enable achieving the sought task with a coefficient of performance (COP) higher than 4.

Such a process often refers to as an MVR (Mechanical Vapour Recompression). The compressor operates as an open heat pump, yielding energy to the steam through compression, without relying on a working fluid as in a closed loop system. The open system approach does not require any evaporator nor a condenser, as in a regular heat pump, and therefore can reach a relatively high COP.

The highest potential of such steam regeneration is connected to the avoidance of excess steam, which is energy-costly. Through the regeneration of steam, a significant amount of steam will recirculate in a process, enabling to lower the initial steam needs and, in turn, reduce the energy consumption to produce the steam on-site, or the amount of purchased off-site steam. When it comes to industry locally producing steam from fossil-fuel combustion, the corresponding abatement in related CO_2 emission may be significant.

Depending on the complexity of the industrial process, the utilisation of steam may already be fully optimised in the most recent installations, leaving little room for steam regeneration as proposed in the current report. However, it is assumed that many industries still rely on older technologies, not fully optimised, where a retrofit for a steam regeneration system would be of high interest, since it represents a relatively low investment cost in comparison with the purchase of new optimised process systems.

2 Status of steam utilisation in Norwegian industrial processes

2.1 Overall energy use and cost for Norwegian industry

The overall energy use per industry branch in Norway over the period 2003 to 2016 is shown in Figure 1. Data are provided by SSB [5] (Statistics Norway), which gathers energy data from each Norwegian industry. The associated energy cost is shown in Figure 2.

Firstly, it should be noted that the effects of the high price volatility of oil and gas in 2008-2009 can be seen in both figures. Remarkably, the overall energy use in Norway has been steadily decreasing over the last decade. In parallel, energy price has significantly increased in the same time period, leading to overall purchased energy costs much higher in 2016 than they were back in 2003. However, since 2011, this trend has changed slope, displaying the effort of the Norwegian industry to rely on more affordable sources of energy to keep competitive.

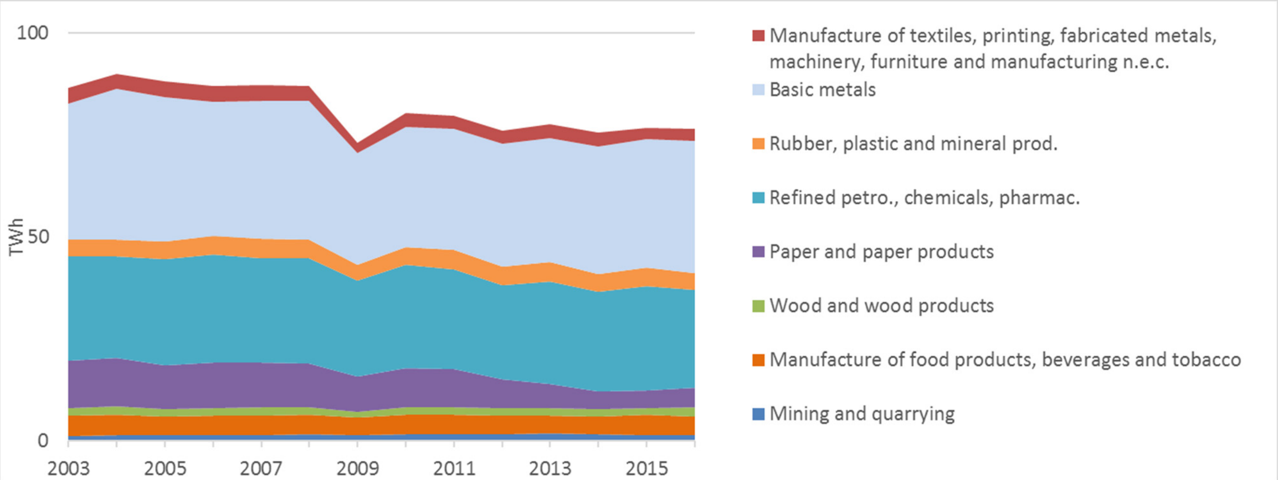


Figure 1: Energy use per industry branch in Norway [5].

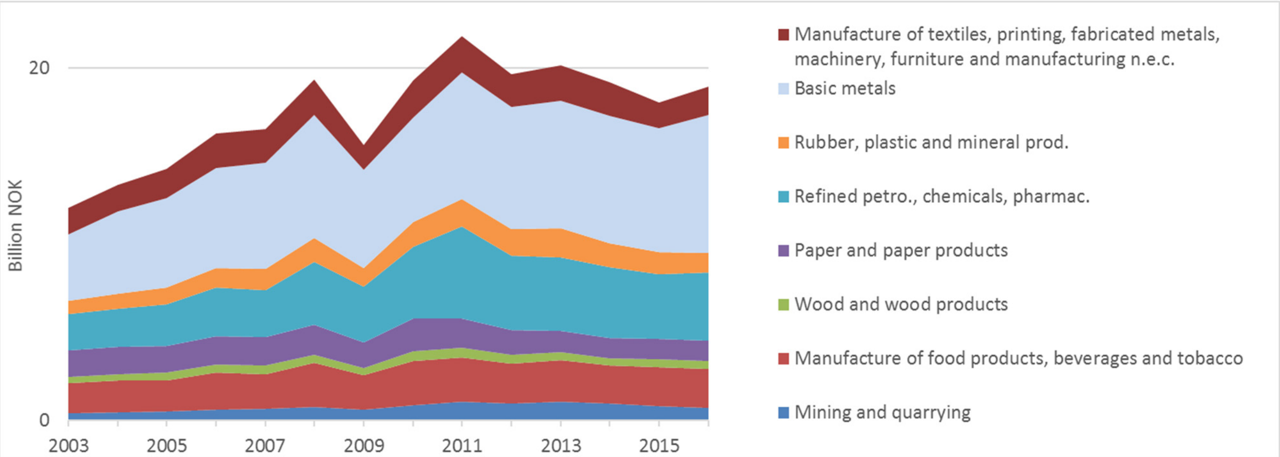


Figure 2: Energy cost per industry branch in Norway (includes only purchased fuels) [5].

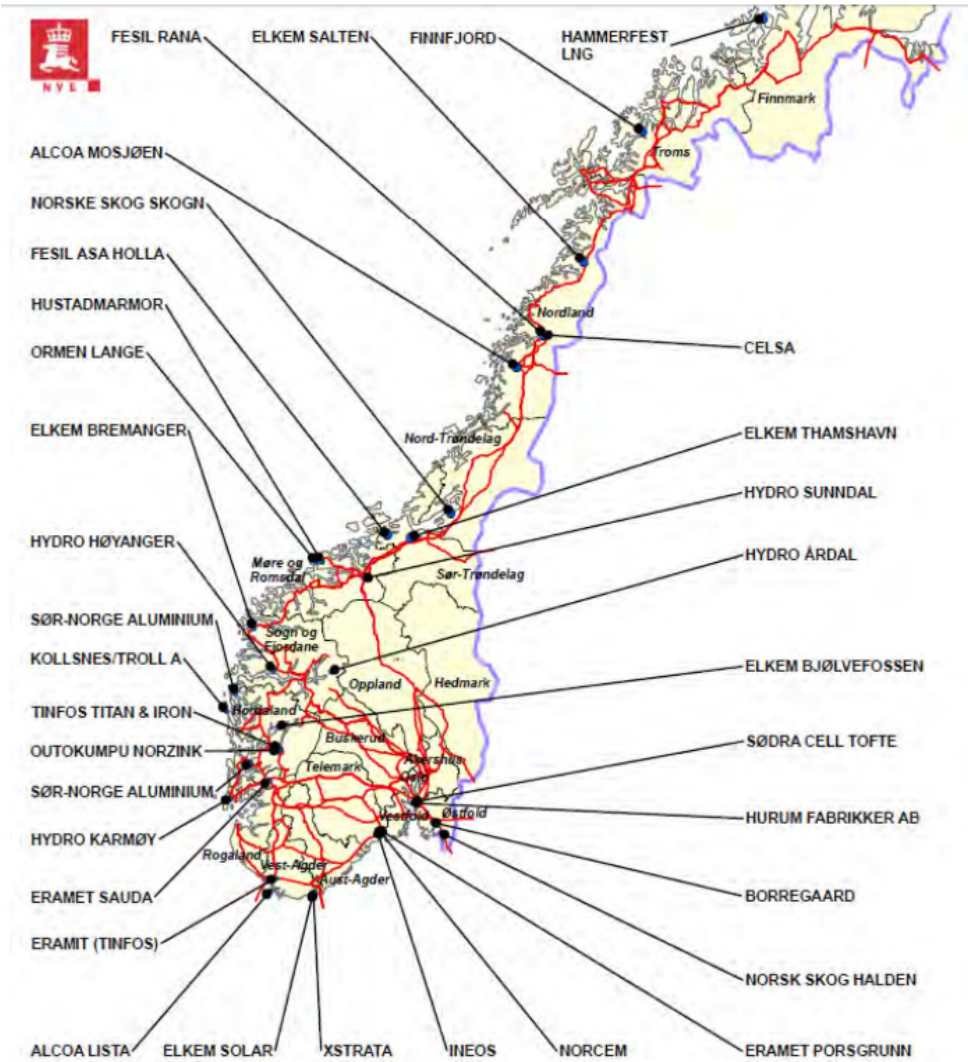


Figure 3: Location and name of the largest energy-intensive industries in Norway per 2012 [7].

The Norwegian industry is characterised by a number of energy-intensive industries which are geographically distributed all over the country. Figure 3 shows the location of the largest energy-intensive industries in Norway. This scattered distribution constitutes a challenge when it comes to local re-use of excess heat, whereas industry clusters would allow trading excess heat between industries. Such clusters now exist in Norway, e.g., Mo Industripark [8] in Mo i Rana, and their number is expected to grow in the near future. However, today's geographical distribution of energy-intensive industries is linked to the access of dedicated hydroelectric power plants and has enabled a high number of stable jobs in locations far away from the major Norwegian cities.

2.2 Steam utilisation and cost

2.2.1 Off-site production

There are two main ways to rely on steam in the industry: steam can be purchased or generated. Environment policies and environment taxes in Norway have driven some industries to rely on off-site production of steam. SSB [5] provides data on the purchased energy from district heating and steam. Note that for most energy-intensive industries, the share of district heating compared to steam is rather low, and for such industries, the numbers presented in Figure 4 and Figure 5 rather represent the purchased steam.

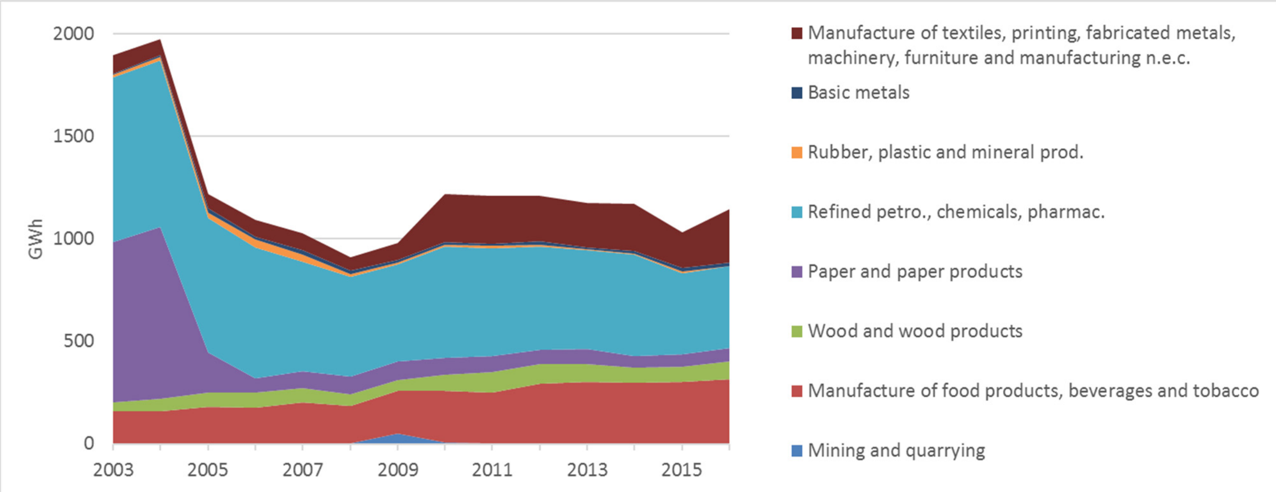


Figure 4: Purchased district heating and steam (energy) per industry branch in Norway [5].

Figure 4 displays large overall fluctuations in the amount of purchased district heating and steam in the Norwegian industry since 2003. Firstly, the large peak in the period 2003-2005 is linked to the large use of steam in the paper and paper products industries. The sudden fall starting from 2004 is strongly related to the closure of one major paper mill of the group Norske Skog in Norway, the Union Paper mill in Skien [9], producing newsprint and book paper. Cutbacks in its activity started in 2005 until it completely ceased operations by March 2006 due to Norske Skog suffering a mounting debt and the global oversupply in the paper industry due to the digitalisation of media.

Another feature of importance shown in Figure 4 is the steady increase of off-site steam supply to the "manufacture of food products, beverages and tobacco" industry, which doubled from 2003 to 2016. The costs of purchased district heating and steam shown in Figure 5 reveal a five-time increase in associated expenses for this sector. This highlights the importance of steam in current industrial processes and the significantly high costs associated to this commodity. Figure 5 also reflects the yearly volatility of the costs of purchased district heating and steam for the overall industrial sector.

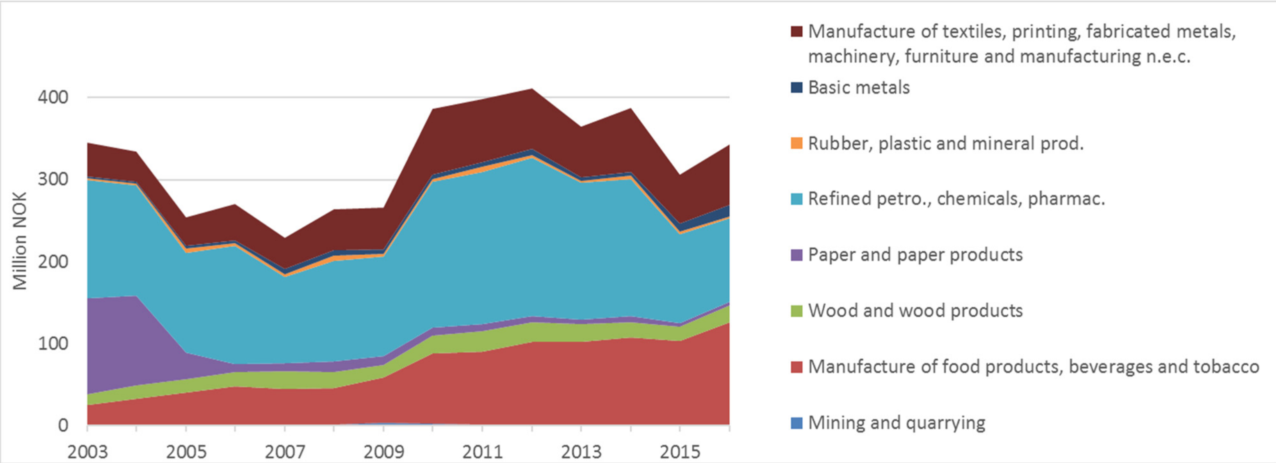


Figure 5: Purchased district heating and steam (costs) per industry branch in Norway [5].

2.2.2 On-site production

The largest share of steam for industry utilisation is generally produced directly on-site, either through conventional boiler systems or combined heat and power units. Exact reported data from on-site production of steam in the Norwegian industry are not part of the publicly accessible data. To keep competitive, industries often rely on relatively low-cost fuel to fire their boilers, such as petroleum or coal products. Gas may eventually be used, though its price (on energy basis) is in the same range as electricity or district heating and can be up to three times higher per kWh compared to petroleum or coal products [5].

For more information, Figure 6 shows the total amount of steam generated on-site for industry in the US, as well as the share of production between Combined Heat and Power (CHP) and conventional boiler systems. Not all industrial sectors have moved on to rely upon CHP yet, due to their higher inherent implementation costs.

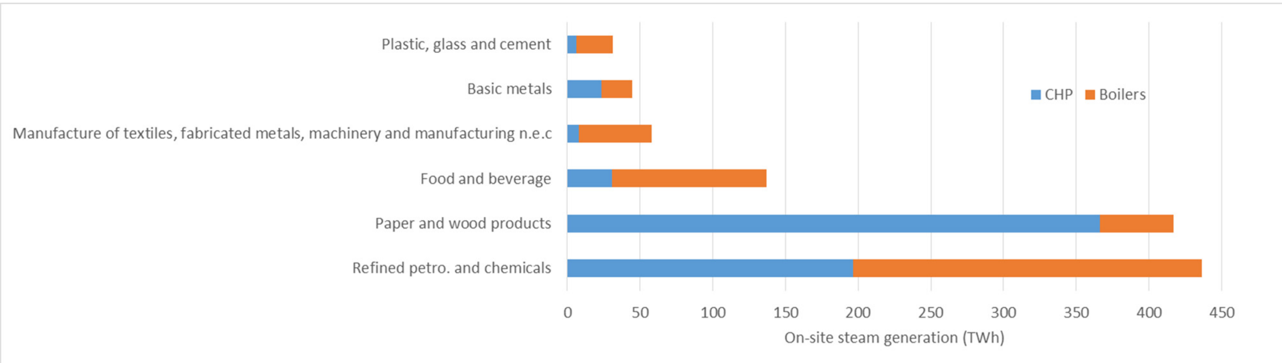


Figure 6: On-site steam generation from the manufacturing sectors in the USA [10].

Another view to bring on the on-site steam production is the relative importance of associated losses. Sathaye et al. [11] assessed the energy use and energy savings potential in selected industrial sectors in India. Resulting from this study, a breakdown of typical thermal energy use in a composite textile plant is shown in Figure 7. In this case, up to 35 % thermal use is associated to heat losses through the boiler plant (25 %) and (10 %) through steam distribution. This gives an idea of the amount of potential savings to be achieved on the steam supply. Though the textile industry is not considered as an energy-intensive industry, a recent study [12] showed that this sector ranks as the sixth largest steam consumer among the fifteen major industrial sectors in the USA. This gives an idea of the amount of potential savings to be achieve on the steam supply.

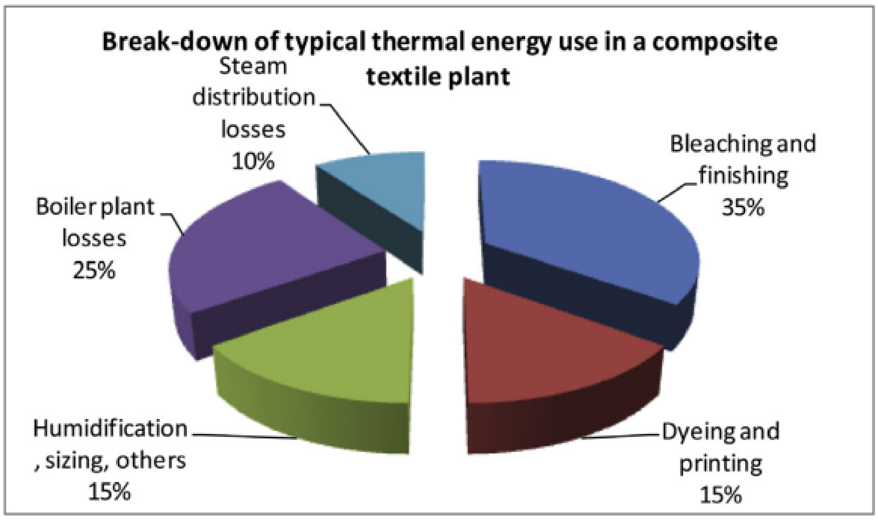


Figure 7: Breakdown of typical electricity and thermal energy use in a composite textile plant [11].

The whole amount of heat-energy losses identified in industrial processes is not equal to the recoverable energy; only a fraction is. Non-recoverable energy losses can take several forms [10], such as:

- Heat storage in a batch furnace where losses are not economically recoverable
- Transmission losses where low-quality energy loss is impractical to recover over a long distance
- Frictional losses

Among all factors affecting the recovery of excess heat, the most significant ones are excess heat temperature, quantity, accessibility, cleanliness, corrosiveness and the intended use.

3 Excess heat and opportunities for steam regeneration in Norwegian industry

3.1 Excess heat in Norwegian industry

3.1.1 Definitions and potential

In the present report we refer to excess heat as defined in the IEA Industrial Energy-Related Technologies and Systems Annex 15 [6], differentiating "excess heat" and "waste heat":
***"Excess heat** is the heat content of all streams (gas, water, air, etc.) which are discharged from an industrial process at a given moment. A part of that can be internally or externally **usable heat**, technically and economically. [...] **Non-usable excess heat** is the remaining part of the excess heat, when the internally and externally parts have been deducted. This part can be called **waste heat.** The often-used term true excess heat can be defined as white or green excess heat, depending on fossil or biomass origin."*

The potential for steam regeneration mainly depends on two parameters: the availability of steam out of an existing process, and the heat demand for steam at higher pressure and higher temperature in the same or close-by process. Generally, the operating conditions of a steam distribution system in the industry are selected according to the highest operating temperature and pressure in the process of interest. Depending on the complexity of possible combinations between processes and the amount of steam needed for a given process, several steam distribution systems can be operated in parallel at different temperature and/or pressure levels. Getting a more detailed knowledge of the thermodynamic state of the available exhaust steam and the heat demand for processes in the Norwegian industry will ultimately help to estimate the potential investment costs and operational savings using industrial heat pumps for steam regeneration.

3.1.2 Inventory of excess heat in Norway

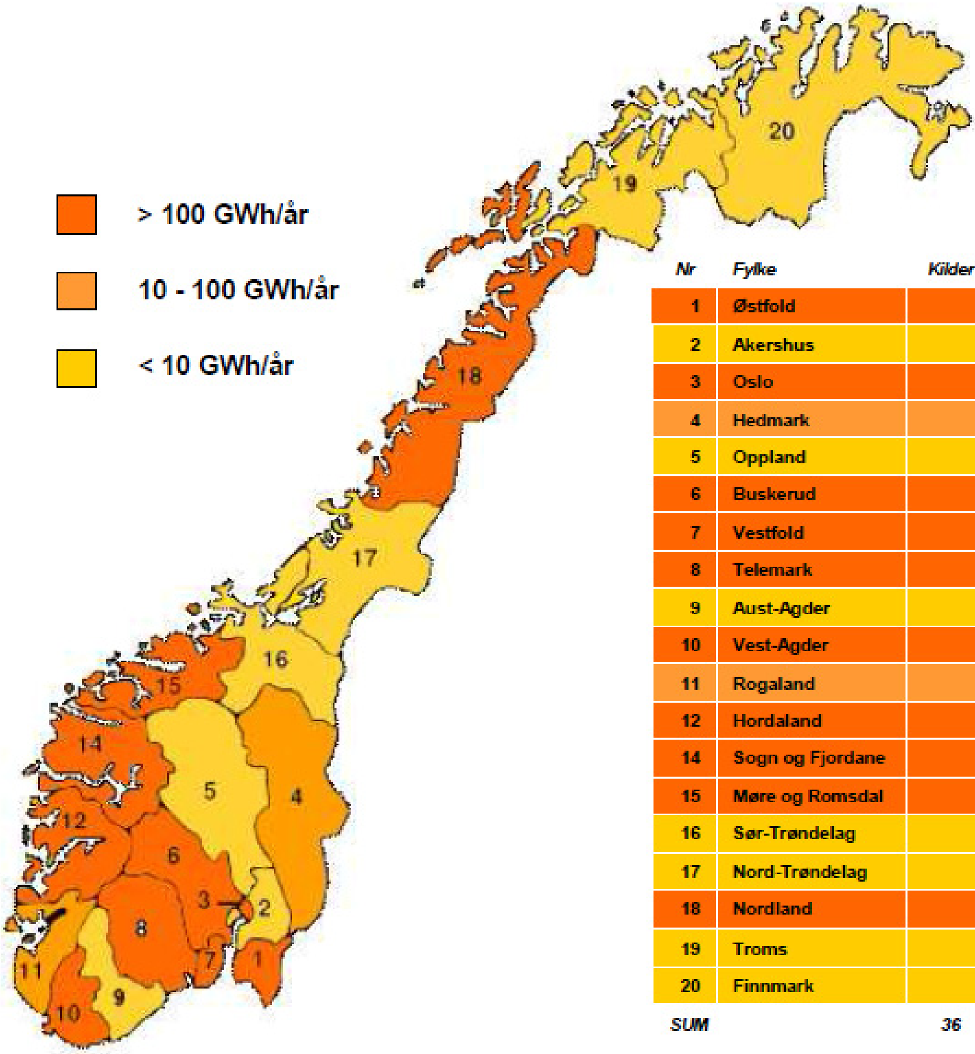
The Norwegian agency ENOVA [13], owned by and operating for the Norwegian Ministry of Petroleum and Energy, commissioned an evaluation of the potential for excess heat utilisation within the Norwegian industry. The investigation performed by Norsk Energi and NEPAS was published in 2009 [4] and presents data averaged from 72 participating Norwegian industries, accounting for about 63 % (ca. 53 TWh/year) of the Norwegian industry energy use. As a side note, an updated version of the report is expected in the coming years. The total reported excess heat resources not utilised in 2008 have been accounted for into two different ways:

- By nature, within three categories: water/waste water, steam and exhaust gas
- By temperature range: 25-40 °C, 40-60 °C, 60-140 °C and > 140 °C

Regarding the classification by temperature, the last two categories are of interest for the present report since they represent the temperature ranges where steam is present and where heat pumps effectively can operate to regenerate steam. Figure 8 and Figure 9 show the geographical distribution of reported excess heat in Norway for the two different categories of interest.

Steam as an excess heat resource, however, represents only a small fraction of the reported excess heat for the participating industries, as shown in Table 1. 9.5 % of the energy use for the participating chemistry industries ends up as excess heat in the form of steam. with corresponding figures of 2.6 % for the manufacture of food products and beverages, 1.8 % for wood and wood products, paper and paper products, and 1.7 % for basic metal industries. It is very encouraging that these numbers are low, since they imply that steam is properly used almost to its fullest potential in most industrial processes in Norway. It also means that there is still a fraction of non-optimised processes where steam may be efficiently regenerated locally to reduce the overall energy use. In fact, looking at the absolute reported values of excess heat as steam, they are in the same range as the purchased district heating and steam shown in Figure 4 for the corresponding industries. Yet, only a part of the Norwegian industry was represented through the cited study.

Based on an average steam price of 0.29 NOK/kWh evaluated for 2008 from Figure 4 and Figure 5, and the total reported excess heat as steam in Table 1 (545 GWh in 2008), the reported excess heat as steam represents a loss of about 158 MNOK for the 72 participating Norwegian industries. To put this figure in perspective, 158 MNOK is about 10 % of the whole district heating sales incomes in Norway in 2008, while the 72 participating industries roughly account for about 50 % of the energy use in the Norwegian industry in 2008 (cf. Figure 1).



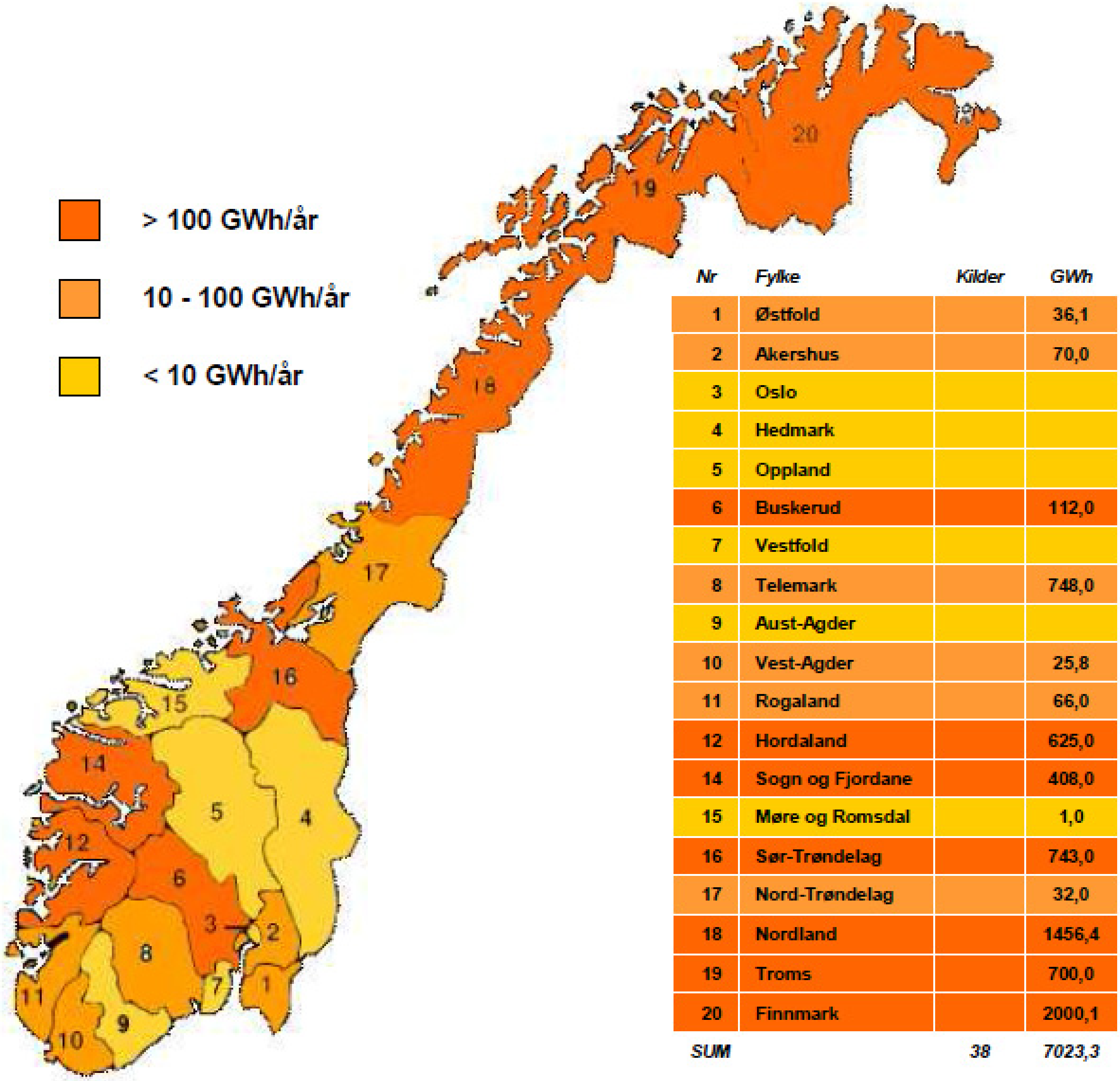
Nr	Fylke	Kilder	GWh
1	Østfold		399,4
2	Akershus		7,5
3	Oslo		130,0
4	Hedmark		11,0
5	Oppland		8,0
6	Buskerud		510,0
7	Vestfold		175,0
8	Telemark		262,0
9	Aust-Agder		
10	Vest-Agder		153,4
11	Rogaland		11,5
12	Hordaland		600,0
14	Sogn og Fjordane		243,0
15	Møre og Romsdal		205,0
16	Sør-Trøndelag		7,0
17	Nord-Trøndelag		
18	Nordland		418,4
19	Troms		
20	Finnmark		
SUM		36	3141,2

Figure 8: Geographical distribution of reported excess heat for Norway in 2008 in the temperature range 60-140°C [4].

Table 1: Examples of excess heat as steam reported for the Norwegian industry for 2008 [4].

From reporting industries only	Reported energy use (TWh/year)	Reported excess heat	Excess heat as steam	Excess heat as steam (GWh/year)	Excess heat as steam vs. energy use
Manufacture of food products, beverages	0.5	14.4%	18%	13	2.6%
Wood, wood products and paper products	11.2	44.2%	4%	198	1.8%
Cement and building block processing	1.9	45.4%	0%	0	0.0%
Chemistry*	2	158.1%	6%	190	9.5%
Aluminium	18.5	12.0%	0%	0	0.0%
Basic metals	8.3	57.8%	3%	144	1.7%

** Exothermic processes yield excess heat higher than energy use.*



Nr	Fylke	Kilder	GWh
1	Østfold		36,1
2	Akershus		70,0
3	Oslo		
4	Hedmark		
5	Oppland		
6	Buskerud		112,0
7	Vestfold		
8	Telemark		748,0
9	Aust-Agder		
10	Vest-Agder		25,8
11	Rogaland		66,0
12	Hordaland		625,0
14	Sogn og Fjordane		408,0
15	Møre og Romsdal		1,0
16	Sør-Trøndelag		743,0
17	Nord-Trøndelag		32,0
18	Nordland		1456,4
19	Troms		700,0
20	Finnmark		2000,1
SUM		*38*	*7023,3*

Figure 9: Geographical distribution of reported excess heat for Norway in 2008 in the temperature range > 140°C [4].

Similar inventories are available in Europe, though not always as detailed as the above-mentioned Norwegian inventory. For example, the results presented in Figure 10 are based on estimates deduced from declared equivalent CO_2 emissions, which are available for most European industries. Note that Norway was not part of this study. The aim of such studies, beyond providing a range of total excess heat available, is to locate the excess heat sources and matching them with locations of high heat demand, e.g., medium-large cities.

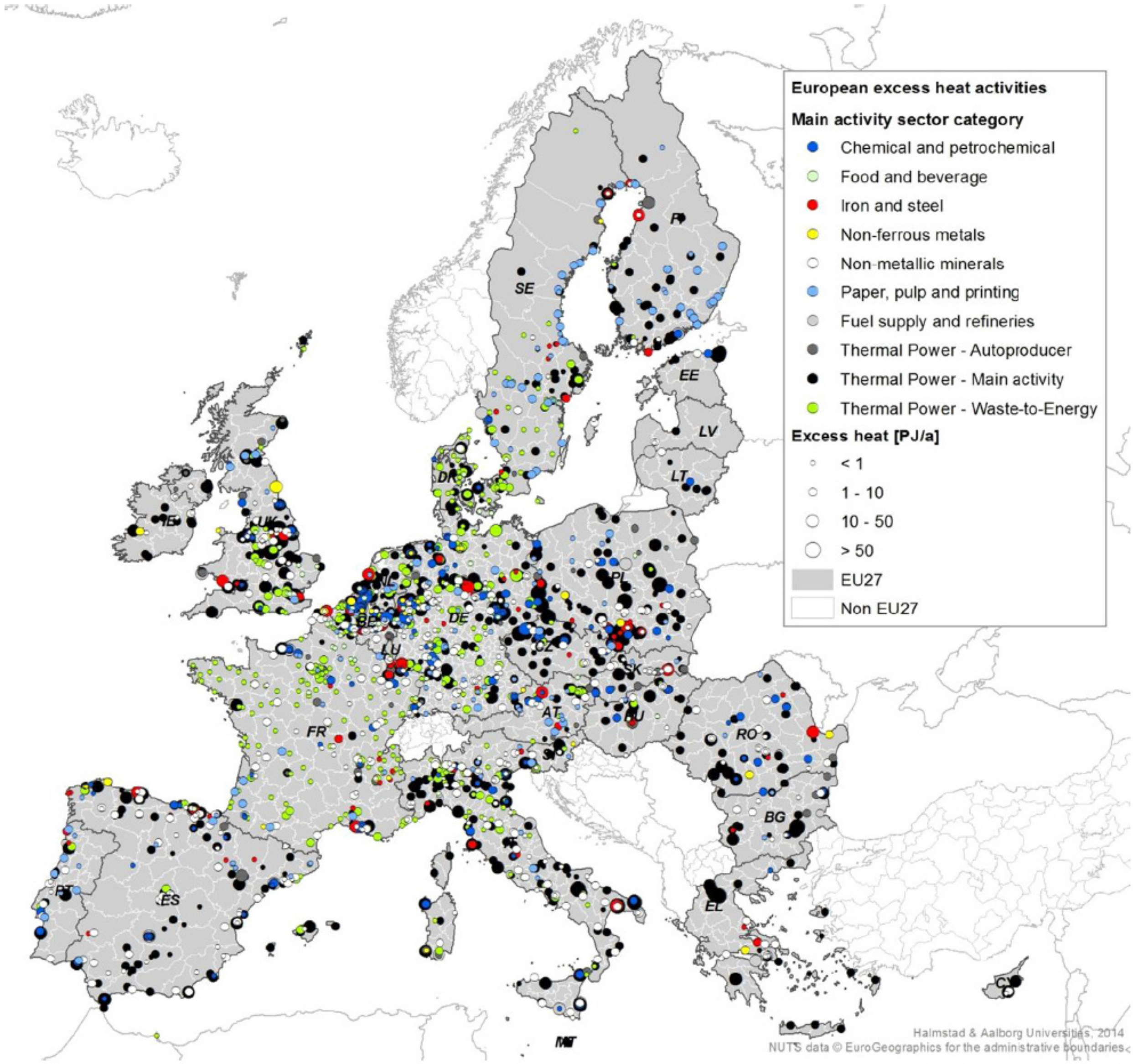


Figure 10: Study of EU27 excess heat facilities by main activity sectors and assessed annual excess heat volumes. Thermal power generation activities > 50 MW. 1 PJ/a equivalent to 278 GWh/year. Source: Persson [3], CEWEP (2014) [14], EEA (2013) [15], IndustryAbout (2014) [16], ISWA (2012) [17], Heat Roadmap Europe [18].

3.2 Applicable processes for steam regeneration in Norwegian industry

3.2.1 Background on steam on-site production

Large and high chimneys releasing steam are common sights on industry sites. Examples are found in the literature [19] of combined steam boilers of capacities between 80 to 240 tons steam/hour, using respectively Boiler 1 only or Boiler 1 and Boiler 2, as illustrated in Figure 11. Considering the high volumes of produced steam, it is not unusual to see such systems equipped with a heat recovery system (shown as "Recuperator" in Figure 11), cooling down the exhaust gas from 130 °C to about 45 °C and, in turn, warming up the recovered water from the processes from 20 °C to about 60 °C. On a basis of 80 tons steam/hour, about 3.8 MW can be recovered this way.

The previous example illustrates the efforts of the industry to recover excess heat from the largest local heat sources. However, as shown in Table 1, excess heat as steam in the Norwegian industry was reported as high as 545 GWh in 2008 for the 72 participating industries. Therefore, there is still a long way to go to utilise the process steam to its full potential.

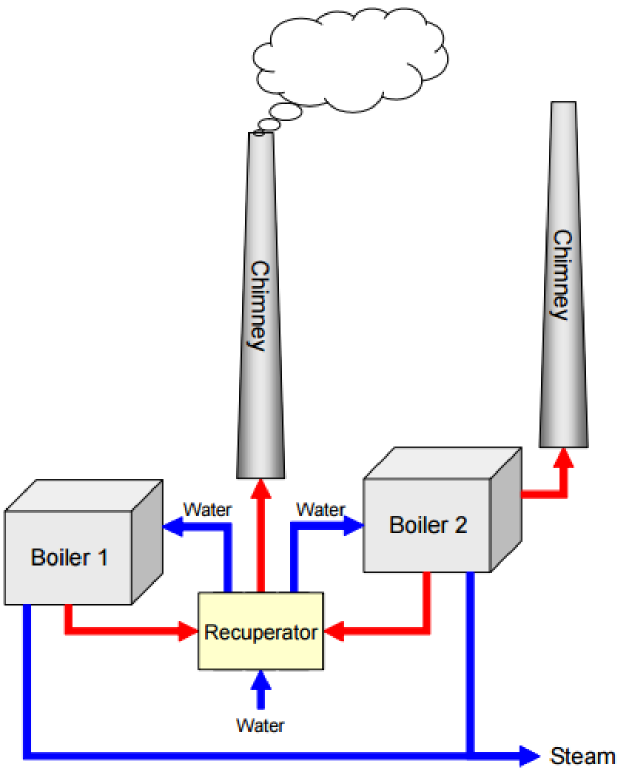


Figure 11: Schematic example of combined boilers with a heat recuperator [19].

3.2.2 Equipment and processes relying on process steam

Table 2 provides an overview of typical equipment and associated processes and industry branches related to steam end use. With regard to the focus of the present report on steam regeneration, of all the listed equipment the condenser may be discarded since by definition it will not be of interest for recovery of steam as an output stream. On the same basis, the reboiler may also be discarded since there should not be any possibility for direct steam recovery from the reboiler if it is properly designed.

Regarding the remaining listed equipment, the potential for steam regeneration will depend on the typical operating temperature range. If the process demands steam at a temperature higher than about 200 °C, a concept of steam regeneration based on heat pumps may not be applicable, at least not with the current state-of-the-art technology.

Table 2: Steam end-use equipment and general processes in energy-intensive industries [10, 20].

Equipment	Process application	Industry
Condenser	Steam turbine operation	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Distillation tower	Distillation, fractionation	Chemicals, petroleum refining
Dryer	Drying	Forest products
Evaporator	Evaporation/concentration	Chemicals, forest products, petroleum refining
Process heat exchanger	Alkylation, process air heating, process water heating, gas recovery/light ends distillation, isomerization, storage tank heating, visbreaking/coking	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Reboiler	Fractionation	Petroleum refining
Reformer	Hydrogen generation	Chemicals, petroleum refining
Separator	Component separation	Chemicals, forest products, petroleum refining
Steam ejector	Condenser operation, vacuum distillation	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Steam injector	Agitation/blending, heating	Chemicals, forest products, petroleum refining
Steam turbine	Power generation, compressor mechanical drive, hydrocracking, naphtha reforming, pump mechanical drive, feed pump mechanical drive	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Stripper	Distillation (crude and vacuum units), catalytic cracking, asphalt processing, catalytic reforming, component removal, component separation, fractionation, hydrogen treatment lube oil processing	Chemicals, petroleum refining
Thermo-compressor	Drying, steam pressure amplification	Forest products

3.2.3 Identification of relevant industrial processes by temperature range

Several studies [21, 22] have analysed the potential for industrial heat pumps in the European market. Results for the German industry shown in Figure 12 reveal a large demand for thermal energy in the temperature range from 100 °C to 200 °C in various industry sectors, which is the ideal targeted range for steam regenerated by efficient industrial heat pumps.

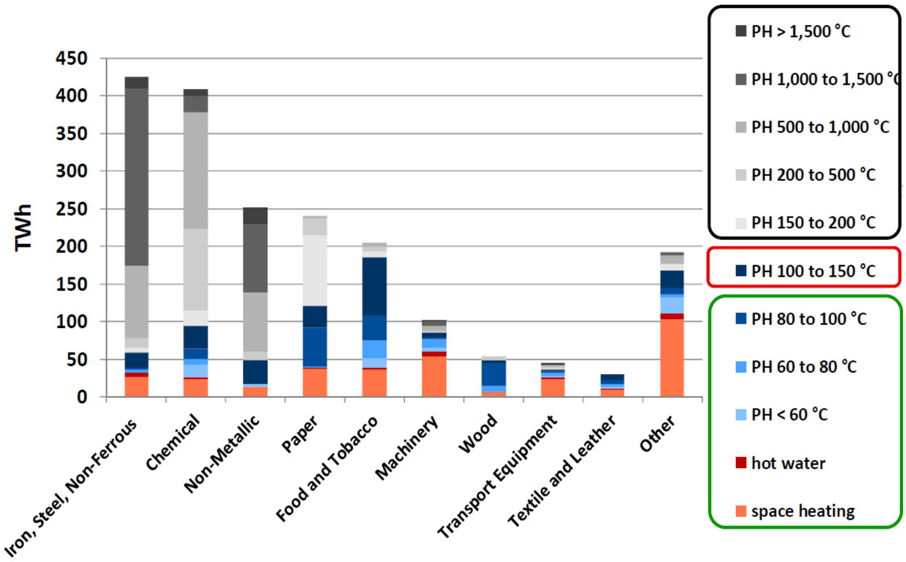


Figure 12: Estimates of industrial heat demand in Germany per sector and temperature range [21].

The studies also provided some insight into the typical operating temperatures of industrial heat demands in Europe per sector and type of process (see Figure 13). Only temperature ranges are shown since the exact operating temperatures depend on each particular method used to achieve the given process. Note that not all existing processes are shown and that temperature ranges above 200 °C may be reached, which is beyond the scope of the present report. The temperature domains are coloured according to the status of corresponding heat pump technologies. The technology readiness level (TRL) decreases with the temperature in this case, especially with heat pump technologies for temperature ranges above 120 °C.

The temperature range of interest for the present report is between 100 °C and 200 °C. This reduces the industry sectors and processes of interest to:

- Chemical industry: distillation, compression and thickening
- Food industry: evaporation, cooking, pasteurisation, sterilisation and drying
- Paper industry: bleaching, cooking and drying
- Fabricated metal: drying
- Rubber and plastic industry: drying
- Textile industry: colouring and drying
- Wood industry: compression and drying

Drying is an example of an industrial process with a large potential for steam regeneration using industrial heat pumps, also due to the extra steam generated from the water content of the products to dry (when applicable). This is the focus of the ongoing research project DRYficiency, funded by EU's Horizon 2020 programme [23].

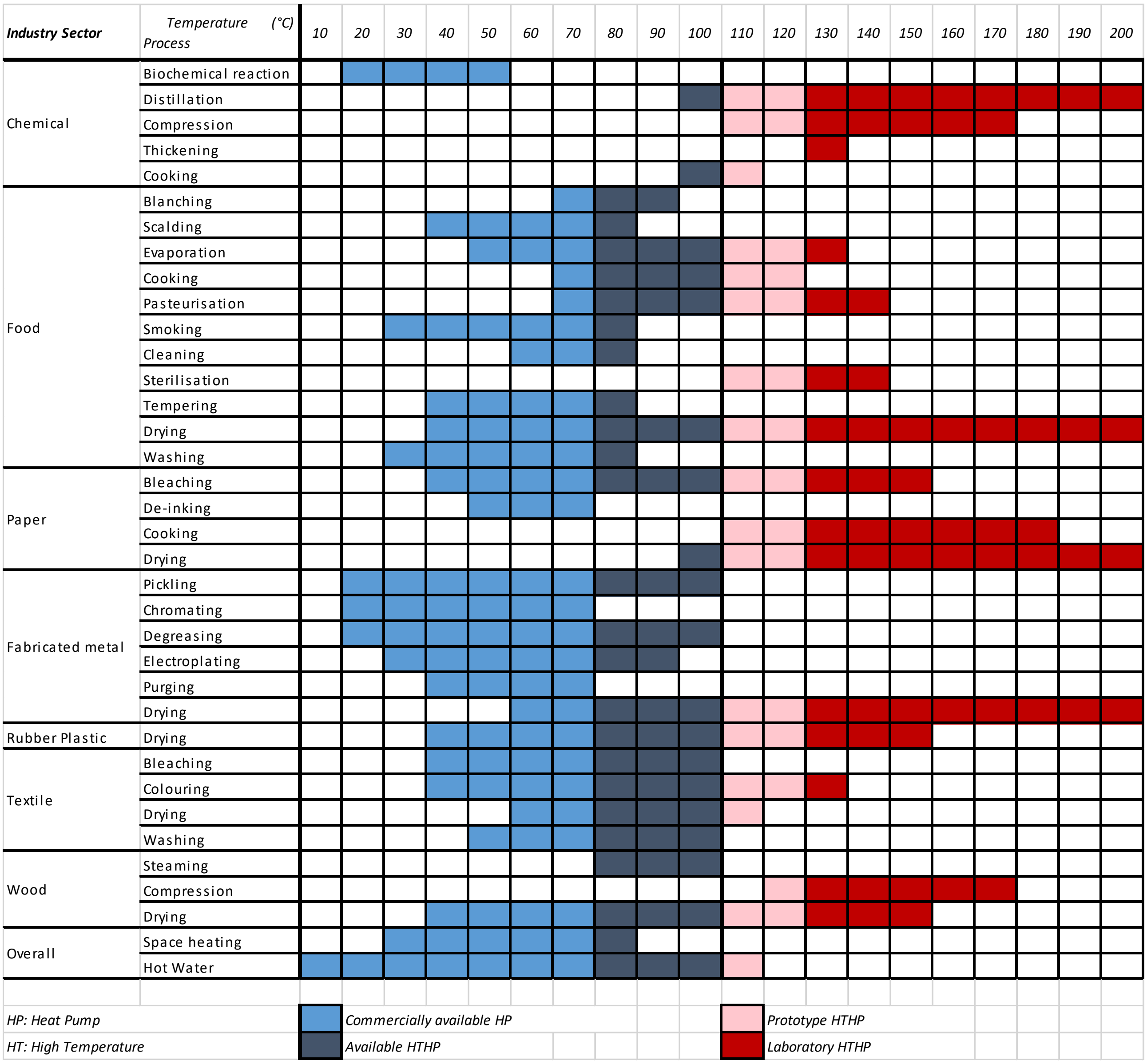


Figure 13: Estimates of industrial heat demand in Europe per sector and type of process [21, 22].

Based on data extracted from Figure 12, relative values of the heat demand per temperature domains have been estimated for various industry branches, as shown in Figure 14. Some sectors display a high heat demand in relative values for the temperature range 100 °C to 200 °C, e.g., "Paper and Paper Products" with 51 % of heat demand and "Food, Beverages and Tobacco" with 42 % of heat demand in this temperature range. These estimates can be used to obtain an overview of the potential overall heat demand for the Norwegian industry.

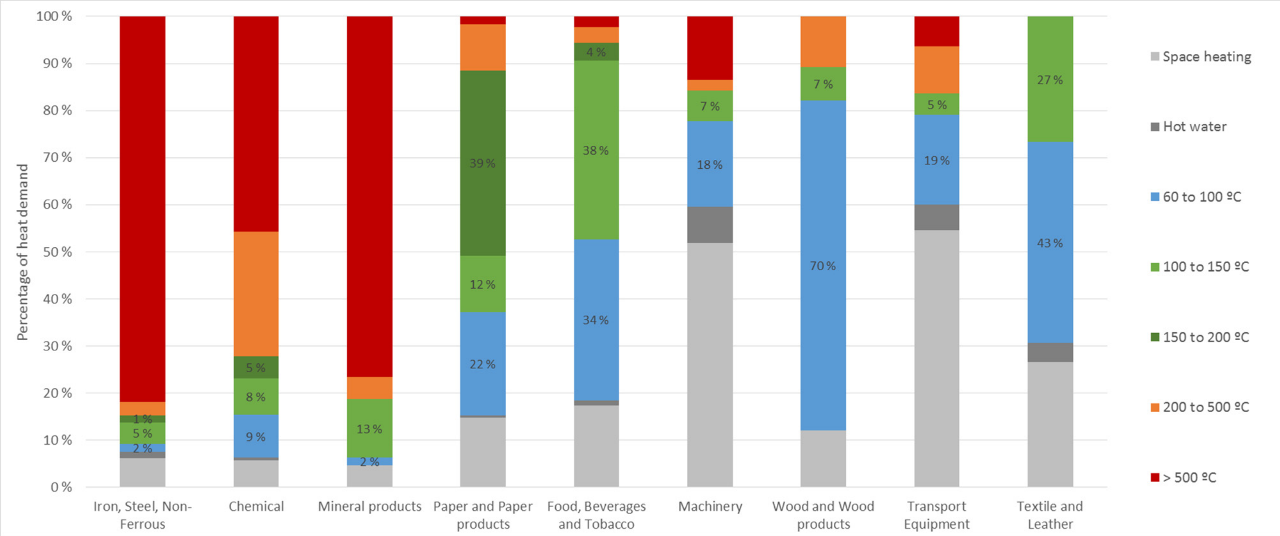


Figure 14: Estimates of relative values of the heat demand per temperature domains for different industry branches.

Combining the estimates shown in Figure 14 and the total energy consumption for each of the mentioned industry branches in 2015 [5], a rough estimate of the heat demand for each temperature range has been determined, as shown in Figure 15. It is worth noticing that these estimates should have been based on the actual total heat demand for each industry branch rather than the total energy use since energy has not been fully used to generate the heat. Hence, these estimates are overestimated but may be used to highlight the sectors where certain temperature ranges can be expected to be in high demand.

On this basis, we can identify four main sectors of special interest in Norway for the temperature range 100-200 °C for which the corresponding absolute heat appears significant:

- Food, Beverages and Tobacco industry
- Chemical industry
- Paper and Paper Products industry
- Iron, Steel, Non-Ferrous industry

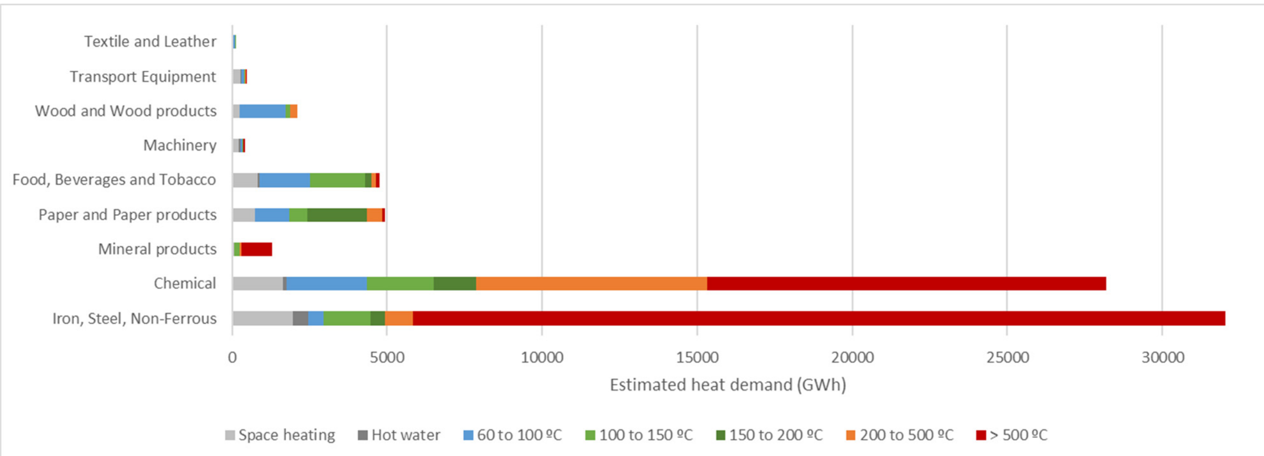


Figure 15: Estimates of the heat demand for the Norwegian industry per sector for 2016.

A more detailed view of the estimates for the selected industry sectors for the temperature range 100-200 °C is shown in Figure 16. The corresponding costs are indicated for each sector as if it were purchased steam with the industrial cost in 2016 (ca. 0.299 NOK/kWh) [5].

Returning to the selected processes at the start of this section, the selection may now be narrowed down to:

- Chemical industry: distillation, compression and thickening
- Food, Beverages and Tobacco: evaporation, cooking, pasteurisation, sterilisation and drying
- Paper and Paper Products industry: bleaching, cooking and drying
- Iron, Steel, Non-Ferrous / Fabricated metal: drying

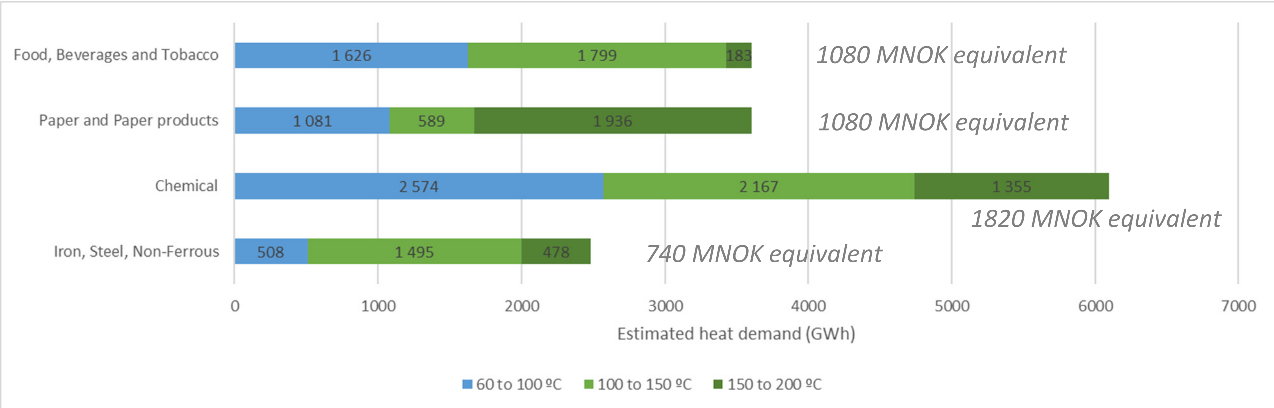


Figure 16: Estimates of the heat demand (GWh) for the Norwegian industry per industry branch for 2016.

3.2.4 Chemical industry

Concerning steam recovery for the chemical industry, it is assumed that the largest share of the process steam is utilised to a high degree in processes until condensation. However, as shown in Table 1, the responding chemical industry in Norway reported as high as 190 GWh in 2008 of excess heat in the form of steam. Based on an average steam price of 0.29 NOK/kWh evaluated for 2008 from Figure 4 and Figure 5, this represents about 55.1 MNOK in commercial steam.

As for the chemical industry, the following industrial processes have been identified through Figure 13 to be of particular interest for steam regeneration: distillation, compression and thickening. Thickening processes might take many forms depending on the type of chemical and equipment used and should be considered on a case-by-case basis. However, distillation and compression can be detailed further.

3.2.4.1 Distillation

Among the identified processes in this industry branch, distillation is assumed to be the most steam-consuming process. There exists various main methods for distillation in the chemical industry, of which a few is cited here [24]:

- **Distillation without reflux:** Vapour is produced by boiling the liquid mixture to be separated and condensing the vapours without allowing any liquid to return to the still.
    - **Flash distillation:** a defined fraction of the liquid is vaporized in a manner that the vapour is in thermodynamic equilibrium with the residual liquid. The vapour is then separated from the liquid and condensed.

    - **Batch distillation:** volatile products may be recovered from the liquid solution by batch distillation. The mixture is charged to a still or reboiler, heated to the boiling point so that part of the batch vaporizes.

- **Distillation with reflux:** Part of the condensate returns to the still and it encounters the vapour as the vapour flows to the condenser.
    - **Continuous distillation with reflux (rectification):** In a distillation column, the produced vapour produced is condensed in a condenser and the liquid is vaporized in a reboiler. Part of these streams is recycled in the distillation column (reflux). By using plates inside the distillation column, the gas and liquid mixtures are brought into contact and their concentrations tend to move toward an equilibrium state. Some of the more volatile components are vaporized from the liquid, decreasing the liquid concentration, while some of the less volatile components are condensed from the vapour, increasing the vapour concentration. If no azeotropes are encountered, both overhead and bottom products may be obtained in any desired purity if enough plates and adequate reflux are provided.

As an advanced example of distillation process, Figure 17 shows an energetically coupled distillation process. Distillation is carried out in two steps (two columns) to produce DMF (Dimethylformamide). The steam from the top of the first column (left) goes through a heat exchanger before entering the second column. This type of combination enables 50 % lower steam usage than decoupled processes, though the two columns are now intrinsically dependent.

Though already optimised, Figure 17 shows an inlet of steam on the left side, and a cooling water unit on the right side, cooling the steam exiting the second column. If such a process is implemented in the industry as shown **here, there is clear potential for steam regeneration through MVR.**

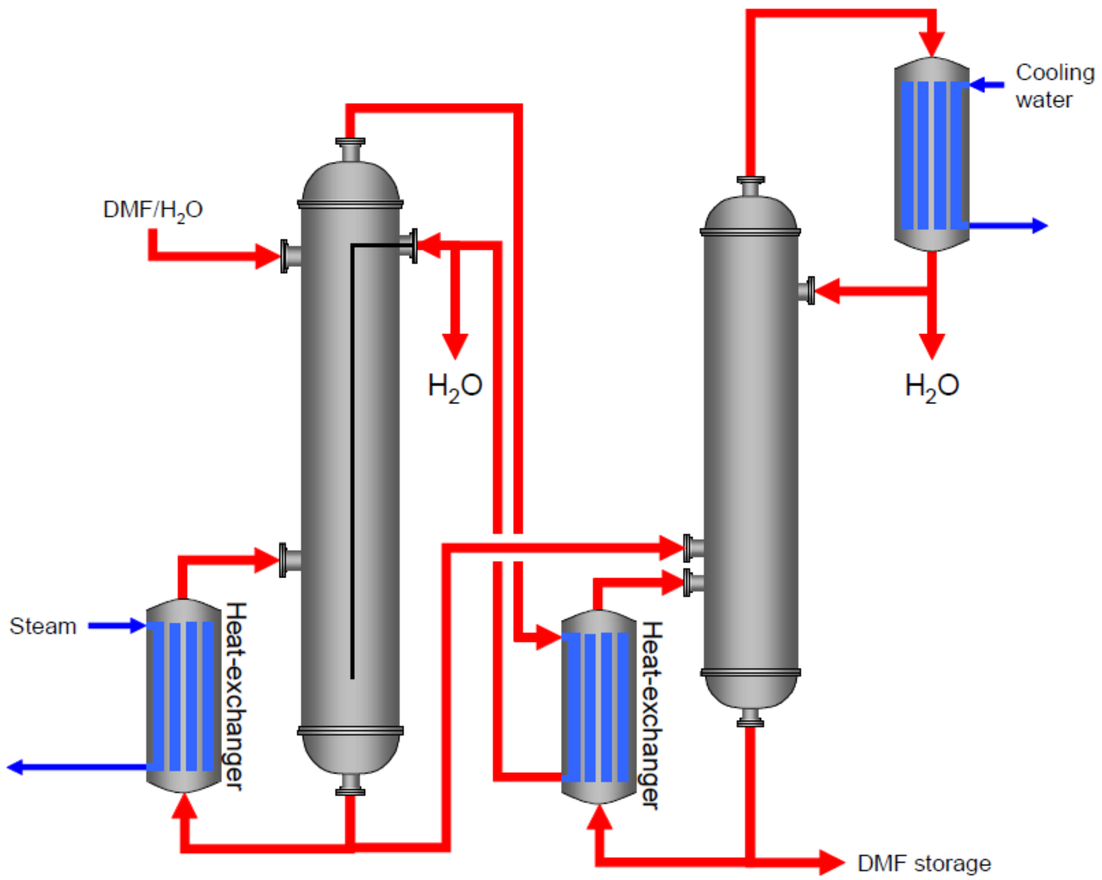


Figure 17: Energetically coupled distillation of DMF [19, 25].

3.2.4.2 Compression

Compression processes operated between 100 °C and 200 °C and based on steam are often referred to as thermo-compression, relying on an electrical or steam-driven thermo-compressor. The electrical thermo-compressor is the focus of the present report to regenerate steam and will not be detailed further in this section. The steam driven thermo-compressor, also referred to as a steam jet ejector or thermal vapour compressor, is often found in solar thermal plants [26] and desalination processes [27]. Figure 18 shows an example of a steam driven thermo-compressor. As illustrated in Figure 18, the entrained vapour is often low-value steam exiting a process, to be regenerated into higher pressure and higher temperature steam through the thermo-compressor.

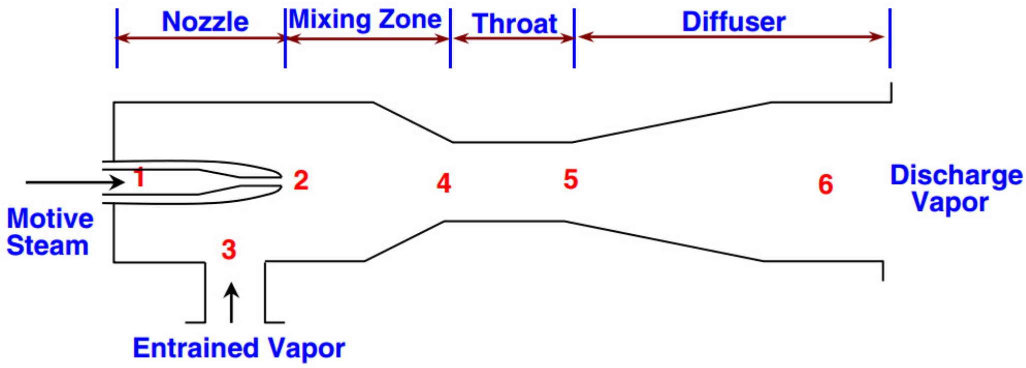


Figure 18: Schematic of a steam jet ejector, or thermal vapour compression unit [27].

Such systems are already optimised to avoid any excess steam and will therefore not be of further interest in the current report to identify potential industrial processes. **It could, however, be of interest to compare their performance to MVR units in further work**.

3.2.5 Manufacture of food products, beverages

As shown in Table 1, the responding food products and beverages manufacturers in Norway reported about 13 GWh in 2008 of excess heat in the form of steam. Based on an average steam price of 0.29 NOK/kWh evaluated for 2008 from Figure 4 and Figure 5, 13 GWh represents about 3.77 MNOK in commercial steam.

Regarding the food and beverage industry, the following industrial processes have been identified through Figure 13 to be of particular interest for steam regeneration: evaporation, cooking, pasteurisation, sterilisation and drying.

By definition, evaporation and cooking will generate steam as an output stream whose level of purity varies. Processes dedicated to these two processes may take a large variety of configurations, and hence, an evaluation of their potential for steam regeneration shall be taken on a case-by-case basis and will not be detailed further in this section.

3.2.5.1 Pasteurisation

Pasteurisation is a controlled heating process used to eliminate viable forms of any pathogen or spoilage causing microorganisms that may be present in milk, fruit-based drinks, some meat products, and other foods. It is also used to extend shelf-life as is the case with beer [28].

Examples of operating conditions for pasteurisation processes are summarised in Table 3. As far as the literature shows [28, 29], processes are running at temperatures below 100 °C, meaning that if steam is in demand for such process, it is assumed to be condensed at the outlet in most cases. Therefore, pasteurisation will not be of high focus for the present report.

Table 3: Examples of operating conditions used in food industry for pasteurisation [29, 30].

Food product	***Heating temperature and residence time***	***Details***
Bulk liquid	63 °C, 30 min	*Vat pasteurisation of milk*
Milk	72 °C, 15-30 s	*Continuous short-time pasteurisation of milk for safety*
	93-100 °C, 10-25 min	*Condensed milk production*
	85-90 °C, several seconds	*Production of sweetened condensed milk*
Butter	>95 °C	*Milk pasteurisation*
Cheese	72 °C, 16 s	*High-temperature short-time milk pasteurisation*
	60 °C, 16 s	*Alternative milk pasteurisation*
Yogurt	80-90 °C, 30 min	*Milk pasteurisation*
	90-95 °C, 5 min	*Milk pasteurisation*
Meat	65-75 °C internal temperature	*Cooking ready-to-eat products (ham, meat loafs, frankfurters, etc)*
Vegetables	Variable (e.g. 75 °C for 5 min)	*Blanching: for enzyme deactivation, tissue softening*
In-bottle beer	60 °C for 10 min	*Shelf-life extension of beer*

3.2.5.2 Sterilisation

Sterilisation is exhaustively described in the Best Available Techniques in the Food, Drink and Milk Industries [28], where most of the explanations and examples in this section were taken.

While pasteurisation relies on operating temperatures below 100 °C, a heat treatment of at temperatures **above 100 °C** is required for a given period in the case of sterilisation. Sterilisation is a controlled heating process used to eliminate viable forms and spores of any pathogen or spoilage causing microorganism that may be present in preserved food. The food industry does not necessarily require to eliminate all microorganisms in the sterilisation process, as long as those who survive are unlikely to grow during storage and cause product spoilage [30]. This can be achieved by moist heat, dry heat, filtration, irradiation, or by chemical methods.

Steam or hot water is generally used for sterilisation of canned or bottled products. Sterilisation may be batch or continuous processes. In sterilisation with moist heat, temperatures generally range from 110 °C to 130 °C with sterilisation periods from 20 to 40 minutes. For example, canned foods are sterilised in an autoclave at about 121 °C for 20 min. Higher temperatures and shorter time periods may have similar effects, e.g., 134 °C for 3 min may be equivalent to the 121 °C/20 min sterilisation. However, if conditions do not allow the germination of spores, lower temperatures and shorter times may also be applied. For example, with acid fruit juices, jam, or desserts, heating up to 80 to 100 °C for 10 minutes is normally sufficient.

To achieve the purpose of sterilisation with dry heat (e.g. killing bacterial endospores), longer exposure times and higher temperatures are required than with moist heat, e.g. up to 2 hours at 160 °C to 180 °C. Therefore, steam is often the process fluid of interest for sterilisation in the food industry.

A more specific heat treatment heavily used in the food industry is the **UHT treatment** (Ultra-High Temperature processing). UHT processing consists of applying a very short heat treatment at temperatures of 135 °C to 150 °C for only a few seconds to a food product. This results in a sterilised product with minimal heat damage to the product properties. UHT treatment is only possible in flow-through equipment.

For UHT treatment, either indirect heating (e.g., in plate and frame or tubular heat exchangers) or direct heating (e.g., steam injection or steam infusion) may be applied [30]. Direct heating is often preferred to indirect heating because the product is exposed at elevated temperature for a shorter period of time. Considering heat-sensitive products such as milk, this leads to less heat and, thus, to lower product quality loss, as illustrated in Figure 19.

For **UHT treatment by direct heating,** two main methods are used [30]:

- **Injection:** High pressure steam is injected into pre-heated liquid by a steam injector leading to a rapid rise in temperature. The product is then flash-cooled in vacuum to remove water equivalent to the amount of condensed steam used. This method allows fast heating and cooling, and volatile removal, but is only suitable for some products. It is energy-intensive and since the product is in contact with hot equipment, there is a risk for flavour damage.

- **Infusion:** A liquid product stream is pumped through a distributing nozzle into a chamber of high pressure steam. This system is characterized by a large steam volume and a small product volume, distributed in a large surface area of the product. The product temperature is accurately controlled through the pressure. Additional holding time may be accomplished through the use of plate or tubular heat exchangers, followed by flash cooling in vacuum chamber. This method has several advantages:
  - Instantaneous heating and rapid cooling
  - No localized overheating or burn-on
  - Suitable for low and higher viscosity products.

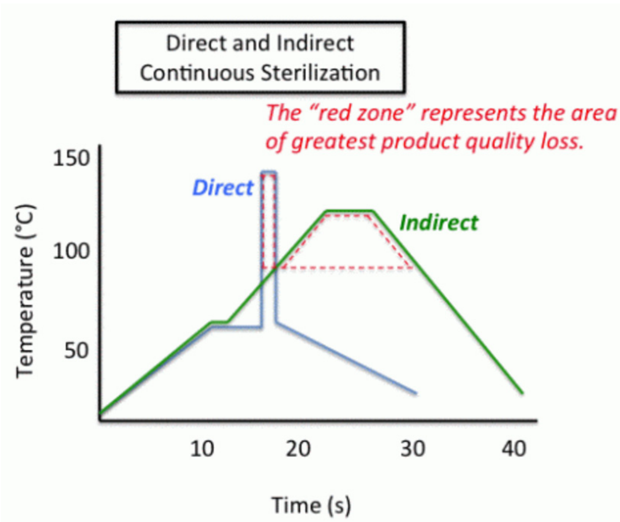


Figure 19: Schematic of the direct and indirect sterilisation processes [30].

3.2.5.3 Drying

Drying processes can take many forms. Those relying on steam often operate similarly to the superheated steam drying process illustrated in Figure 20. Steam enters the process at 1 bar and 170 °C and quickly brings the food product to a higher temperature to evaporate its water content. A higher quantity of steam exits the process at the same pressure but lower temperature (e.g. ≥ 110 °C in Figure 20).

This type of processes has a high potential for steam regeneration. The topic constitutes the main focus of the current EU Commission-funded H2020 project DRYficiency [23], led by AIT – Austrian Institute of Technology and involving SINTEF Energy Research.

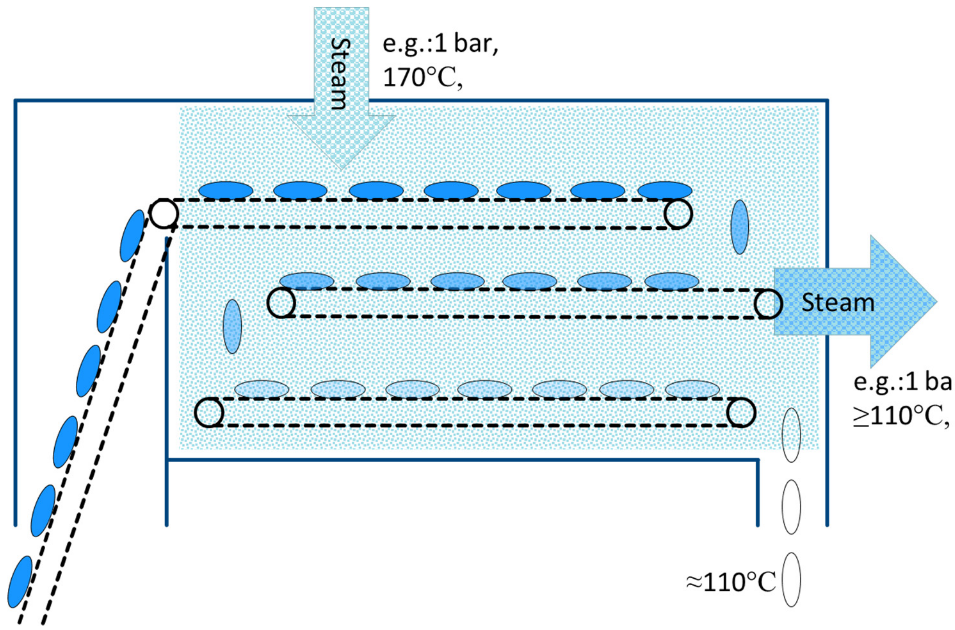


Figure 20: Example of superheated steam drying processes for the food industry [31].

3.2.6 Manufacture of wood, wood products and paper products

As shown in Table 1, the responding manufacturers of wood, wood products and paper products in Norway reported about 198 GWh in 2008 of excess heat in the form of steam. Based on an average steam price of 0.29 NOK/kWh evaluated for 2008 from Figure 4 and Figure 5, 198 GWh represents about 57.4 MNOK in commercial steam.

Regarding the manufacturers of wood, wood products and paper products, the following industrial processes have been identified through Figure 13 to be of particular interest for steam regeneration: bleaching, cooking, compression and drying.

Note that compression has already been covered in Section 3.2.4.2 and drying in Section 3.2.5.3.

3.2.6.1 Bleaching

The purpose of the bleaching process applied to wood pulp is to obtain certain pulp quality criteria with respect to brightness, brightness stability, cleanliness and strength. Unbleached wood pulp is rather low (below 30 % ISO), whereas fully bleached pulp may reach a brightness level of 88 % ISO or higher [32].

Bleaching can be performed in various configurations and operating conditions, generally in combination with chemicals, such as chlorine dioxide (ClO_2), oxygen (O_2), hydrogen peroxide (H_2O_2), sodium hydroxide (NaOH), and sometimes ozone (O_3) [32]. Bleaching generally occurs along several subsequent stages, with temperatures ranging from 50°C to 90°C and residence times from 30 to 120 min per stage, depending on the material and the type of chemical the product is exposed to [33].

Due to the range of operating temperatures below 100 °C, it is expected that if steam is on demand, it is condensed throughout the process. Therefore, bleaching will not be of high interest for the current report.

3.2.6.2 Cooking

Cooking affects both the amount of effluent and the quality of the pulp. The process can be performed through direct or indirect heat treatment, as shown in Figure 21.

The **direct steam injection** is performed by introducing medium-pressure steam (e.g. 4 bar) into the circulation line [34]. The digester shown below is heated up to cooking temperatures of 155 °C to 180 °C.

The **indirect heat transfer** is performed through shell and tube heat exchangers, until steam condensation, where the condensate is recycled.

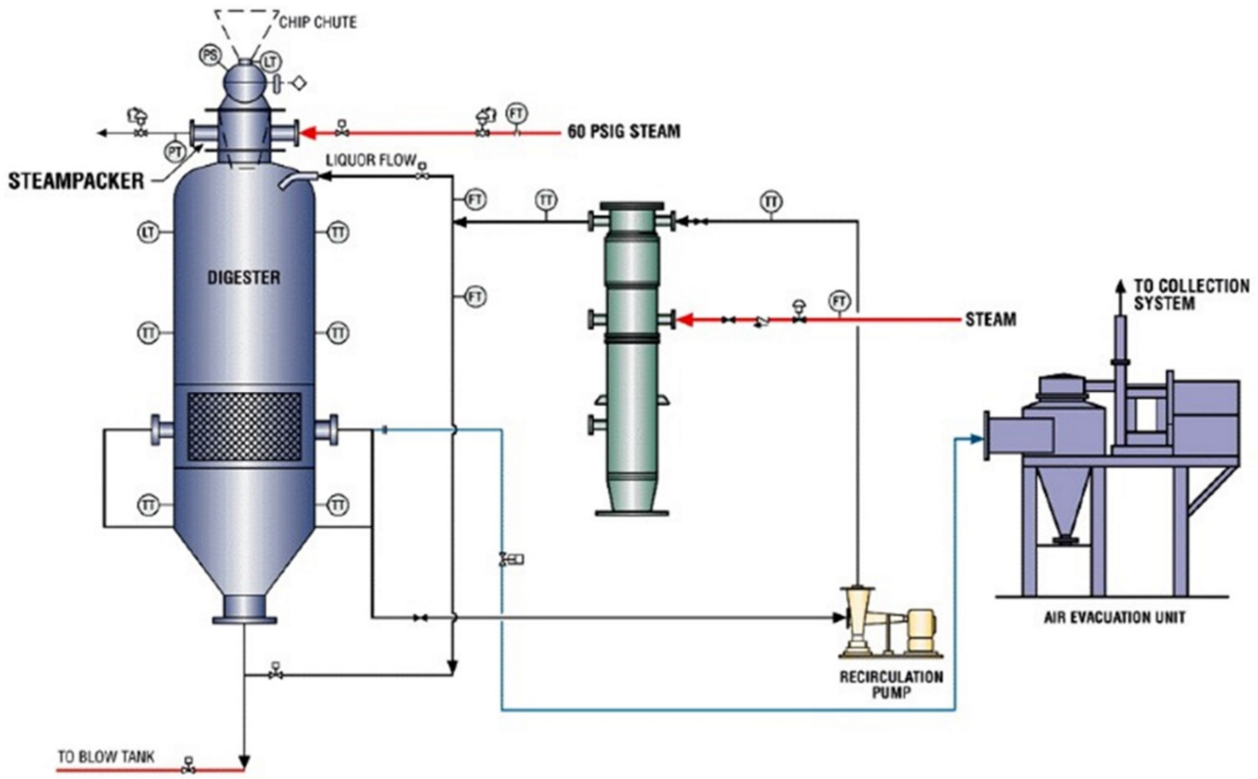


Figure 21: Example of conventional batch cooking unit [34].

3.3 Examples of operating conditions for relevant industrial processes

Data found in the literature for some of the described processes of interest for the current work are shown in Table 4. The steam operating temperature and pressure can be slightly higher depending on the type of process involved, and whether steam is in direct contact with the products or not. The listed data form the basis for a theoretical evaluation of the potential of steam regeneration detailed in Section 4.

Note that the data shown in Table 4 apply to the aforementioned industrial processes in general, not specifically to Norway where recent and relevant information is not available.

For additional data on superheated steam drying, a list of operating temperature and pressure ranges for a wide variety of food products and wood products and specific drying technologies has been inventoried by Romdhana et al. [35].

Table 4: Examples of steam operating conditions for a selection of industrial processes relevant to the current work.

Process	***Technology***	***Treated products***	***T (°C)***		***Pressure (bar)***	***Remarks***	***Reference***
			Min	***Max***			
Superheated steam drying	Fluidized bed drying	*Paddy (1kg) (unmilled rice)*	120	170	1.06		*Taechapairoj et al. [36]*
	Kiln drying chamber	*Asian noodles*	110	150	1.3		*Pronyk et al. [37]*
	Tunnel drying	*Sapwood and hardwood*	160	160	1		*Perre et al. [38]*
	Tunnel drying	*Fish*	110	170	1		*Bantle et al. [31]*
Aluminium production	Digestion	*Bauxite slurry and caustic soda*	145	145	4.5	*Injection of 1500 t/h steam*	*Hydro Alunorte [39]*
Sterilisation	Autoclave	*Canned foods*	121	121	1	*Residence time: 20min*	*BAT 2006 [28]*
	Autoclave	*Canned foods*	134	134	1	*Residence time: 3min*	*BAT 2006 [28]*
UHT	Steam infusion	*Milk*	135	150	1	*Temperature accurately controlled by pressure*	*BAT 2006 [28]*
Conventional batch cooking	Digester w/ direct steam injection	*Wood/paper pulp*	155	180	4.1		*GL&V Pulp and Paper [34]*

4 Applicable technology for steam regeneration

4.1 Technology concept overview

The concept of interest in the current report relies on the availability of steam as an output stream from an industrial process and the demand for steam at higher pressure and temperature in a nearby process. The unused low-value steam could be recycled mechanically through a compressor unit, while preserving its latent energy. With the use of an efficient steam electrical compressor, staged or not, to increase the steam pressure depending on the local demand, the sought task should be enabled with a coefficient of performance (COP) higher than 4.

This technology is often referred to as MVR. The compressor operates as an open heat pump, yielding energy to the steam through compression, without relying on a working fluid as in a closed loop system. The open system approach does not require any evaporator nor condenser, as in a regular heat pump, and therefore can reach a relatively high COP.

The highest potential of such a system is the avoidance of excess steam, which is energy costly. Through the regeneration of the steam, a significant amount of steam will recirculate in a process, enabling to lower the initial steam needs and, in turn, reduce energy consumption to produce the steam on-site or the amount of purchased off-site steam. For industry locally producing steam from fossil fuel combustion, the corresponding abatement in related CO_2 emission may be significant.

Depending on the complexity of the industrial process, the utilisation of steam may already be fully optimised in the most recent installations, leaving little room for steam regeneration as proposed here. However, it is assumed that several industries still rely on older technologies, not fully optimised, where a retrofit for a steam regeneration system would be of high interest. This possibility represents a relatively low investment cost in comparison with the purchase of new optimised process systems.

The idea for steam regeneration is to utilize surplus steam from an existing process by increasing the temperature of the steam using a turbo-compressor. A sketch of the concept is shown in Figure 22. The upgraded steam can either be used directly by another process, or be used to deliver heat to a process by means of a heat exchanger.

An existing turbo-compressor, which has been used in the automotive industry, has been further developed and adjusted so that it can be used with superheated steam in a MVR-system. Testing has shown that this turbo-compressor can achieve a pressure ratio of at least 2.4, and an isentropic efficiency of up to 75 % [31].

Since the excess steam from the process is used directly in the compressor, there will be no temperature drop between the heat source and the inlet of the compressor. However, it is important to make sure that there are no particles in the steam, which can damage the compressor.

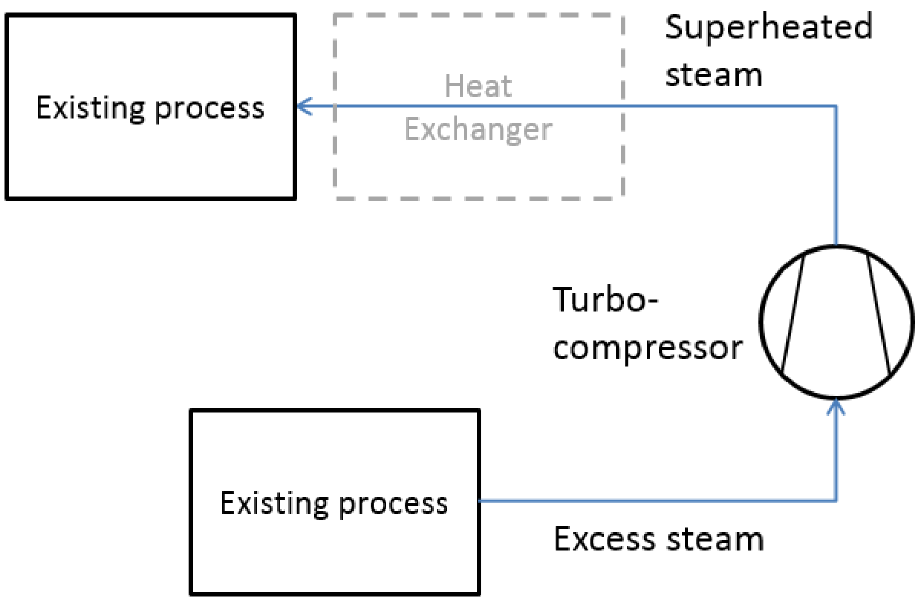


Figure 22: Sketch of the steam regeneration concept.

4.2 Theoretical case study

The highest possible coefficient of performance (*COP*) value for a heat pump is given by the ideal Carnot heat pump cycle. For constant temperature reservoirs, the *COP* value can be expressed from the temperature of the heat source, T_c, and the heat sink, T_h, as expressed in the equation below:

$$COP_{\text{Carnot}} = \frac{T_h}{T_h - T_c} \quad (1)$$

However, real heat pumps are not able to give as high *COP* values as the Carnot heat pump cycle due to various component losses and temperature differences in heat exchangers. Typically, real heat pumps will have a *COP* of about 60 % of the theoretical maximum. The *COP* for a real heat pump is given by the following formula:

$$COP = \frac{Q}{E} \approx \eta_{\text{Carnot}} \frac{T_h}{T_h - T_c} \quad (2)$$

where *Q* is the heat delivered by the condenser, *E* is the electrical energy provided to the compressor, and η_{Carnot} is the Carnot cycle efficiency.

For an open heat pump, there will be no heat loss between the heat source and the inlet of the compressor as there is no evaporator. This is beneficial compared to a closed loop system where there is a temperature drop between the heat source and the evaporating temperature.

The efficiency of the compressor is also important when considering the real *COP* of the heat pump, and tests have shown that an isentropic efficiency of up to 75 % can be achieved.

4.2.1 Efficiency calculation

The efficiency of the heat pump is mostly dependent on the temperature difference between the heat source and the heat sink and the pressure ratio. As long as the excess steam has atmospheric pressure, the temperature is not affecting the *COP* significantly, but a certain amount of superheat is needed to ensure that droplets does not enter the compressor.

In the following calculations, it is assumed that the heat source is excess steam at 1 bar and 110 °C and the isentropic efficiency of the compressor is set to 70 %. For a multi-staged system, the steam has to be cooled between each stage. In a closed system, this heat could have been used to evaporate water from an intermediate pressure vessel and thereby increase the mass flow in the following step. But since we are considering an open system, it is assumed that the heat is lost from the system. However, the heat can be delivered to another process through a heat exchanger.

The pressure ratio for the compressor limits the temperature lift per stage as shown in Figure 23. Two stages are needed if the condensing temperature is above 130 °C, and three stages are needed above 160 °C.

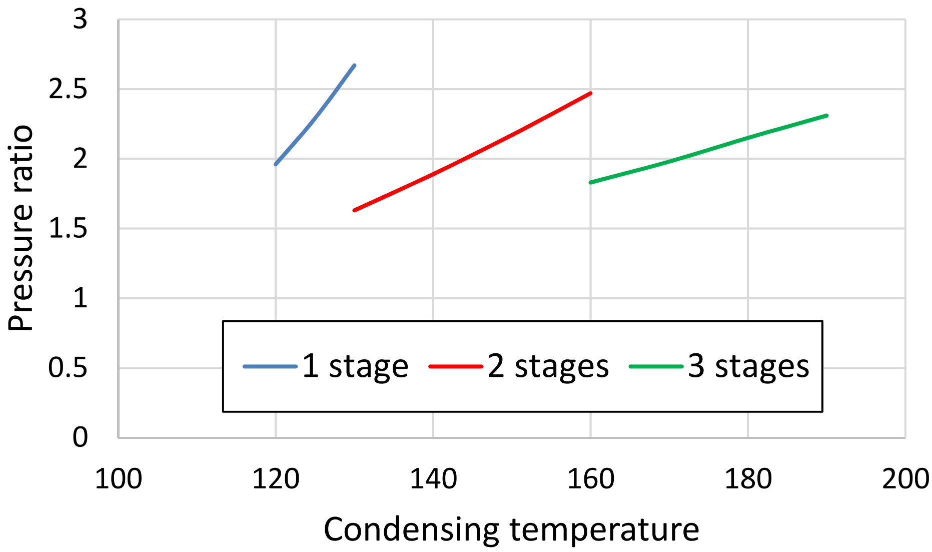


Figure 23: Pressure ratio for the compressor at different condensing temperatures and stages.

Figure 24 shows the *COP* at different condensing temperatures. As shown by the graph, the *COP* decreases when the condensing temperature increases, but a *COP* of above 4 could be achieved for condensing temperatures up to 160 °C.

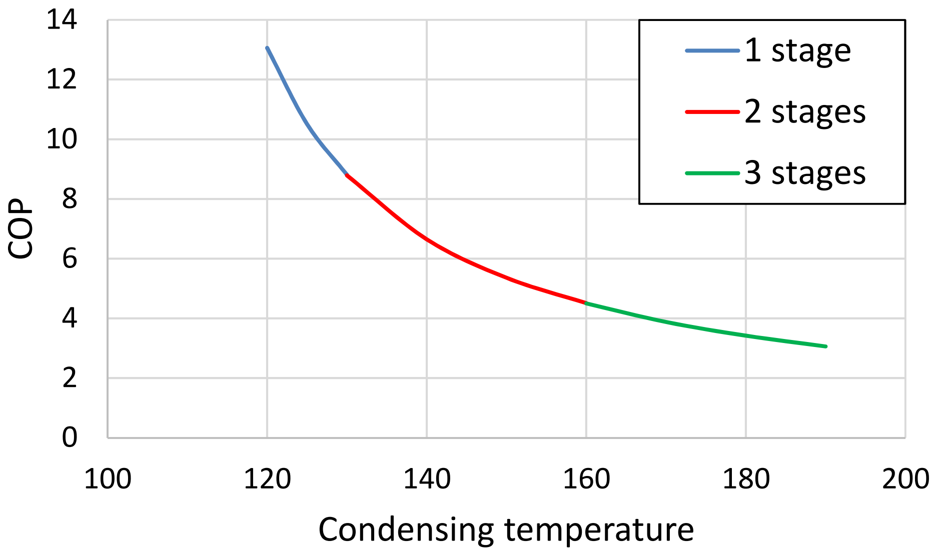


Figure 24: COP at different condensing temperatures.

4.3 Turbo-compressor test

Radial turbo-compressors are evaluated to be an efficient and reasonably priced compression technology for steam-based thermal processes (such as steam drying, pasteurisation (UHT), distillation or cookers/evaporators), especially for processes with thermal capacities in the range of 500-2000 kW.

A test-rig for a prototype radial turbo-compressor has recently been built on-site in the laboratories of Mars in Verden/Germany, with the purpose to evaluate and demonstrate the potential of the prototype technology on a pre-industrial technological readiness level (TRL5-TRL6). At full-load operating with a pressure ratio of 2.4 at 90 000 rpm and a mass flow of 450 kg/h of superheated steam the achieved performance was an isentropic efficiency of 73.5 %. This result was in accordance with the expected performance based on the predicted compressor map.

If the prototype of the turbo-compressor at this condition is to be used in an MVR-system, it would be possible to achieve a *COP* of approximately 11.5. Compared to other heat pump systems this seems quite high but it should be taken into account that the temperature lift will be only 24 K between the evaporating and condensing temperatures.

5 Conclusions and recommendations

5.1 Conclusions

In this report, the potential for steam regeneration in the Norwegian industry has been evaluated, i.e., the potential utilisation of existing excess steam within temperatures of 100-200 °C by re-injecting it at higher temperature and pressure in the on-site or nearby processes.

The report shows that process steam is heavily used in the Norwegian industry. The ENOVA 2008 report concludes that the corresponding amount of unused excess steam is the equivalent of more than 150 MNOK. Not all industries responded to this inventory (only about half of the total energy consumption in industry) and used steam may have been condensed for convenience in some industries and then reported as excess stream at a lower temperature. Therefore, based on this underestimation, one may assume that the true figure is rather close to about 300 MNOK as per 2008, and potentially even higher today with the increasing energy prices and the limited number of infrastructure investments to make use of the excess steam.

Provided that the investment cost of the steam regeneration system remains low, there is a fair potential for energy- and cost-saving in the Norwegian industry. The benefits of such systems may also be enhanced by reducing the CO_2 emissions associated to the targeted process through higher overall efficiency.

The report identifies and describes the most relevant industry branches and corresponding processes that will gain the most from steam regeneration:

- Chemical industry: distillation, compression and thickening
- Food industry: evaporation, cooking, pasteurisation, sterilisation and drying
- Paper industry: bleaching, cooking and drying
- Fabricated metal: drying
- Rubber and plastic industry: drying
- Textile industry: colouring and drying
- Wood industry: compression and drying

Theoretical efficiency calculations, as well as practical pilot tests, show very promising results favouring the approach of steam regeneration from excess steam in Norway.

5.2 Recommendations for further work

The Norwegian excess heat inventory has been a key component to point out the potential for utilisation of excess heat in Norway. The update of this inventory with more recent figures and especially a larger number of responding industries would be of great help for more realistic data. Among the potential improvements to the inventory methods, all sources of excess heat, e.g., including hot surfaces, should be included, as well the relative pressures of those streams as long as no recovery of the expansion work is in place. The access to such improved data would enable researchers and the industry to elaborate more accurately to find more effective solutions to the challenge of utilisation of excess heat in the industry.

The issue linked to non-pure excess steam should also be addressed, both in the inventory and in the development of the steam regeneration concept. In the food and beverage industry for example, excess steam often contains other species than water, which to some extent might prevent their direct injection into a compressor. Establishing some realistic data of the type and concentration of species and, in parallel, the potential concentrations limits for direct regeneration, would be of great value.

Steam regeneration as described in this report is based on systems with MVR. Benchmarking the performance and relative techno-economics for various competing technologies for thermo-compression, e.g., a steam jet ejector, would also be of high interest.

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