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New Perspectives for the Application of large-scale Heat Pumps

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Abstract

Large-scale heat pumps are an efficient and cost-effective solution for the generation of industrial heat and district heating. They take up thermal energy from a low-temperature heat source (e.g. waste heat from industries or ambient heat from sea, lakes, rivers, or geothermal sources) and supply thermal energy at higher temperature to a heat sink.

During the next years, heat supply will be electrified and decarbonized step by step, due to the gradual replacement of fossil-fired heat supply by natural gas, coal, and oil. As the electricity generation will be decarbonized further in the upcoming years, more and more renewable electric energy will be available to achieve a climate neutral heat supply.

Siemens Energy has long-term experiences with large-scale heat pump solutions up to 95°C and 30 MW of thermal output per heat pump unit. Several industrial segments need heat pumps with even higher temperatures and higher thermal output. Thus, new heat pump solutions and an enhanced heat pump portfolio to higher temperatures (up to 150°C) and larger thermal output (up to 70 MW in one unit) are being developed. Low pressure steam requirements can be met by these high temperature heat pumps. By adding an additional steam compressor to the high temperature heat pump, even higher steam temperatures and pressures can be achieved (up to 270°C and 55 bara).

Heat pump solutions and possible applications for industrial hot water, steam supply and district heating are presented in this paper. Furthermore, ongoing and future projects of large-scale heat pump installations are shown.

Keywords: High temperature heat pump; Industrial heat pump; Industrial heat supply; Steam generation

1. Introduction

According to the International Energy Agency (IEA), heat is the world's largest energy end use, accounting for almost half of global final energy consumption in 2021. Industrial processes are responsible for 51% of the energy consumed for heat, while another 46% is consumed in buildings for space and water heating. Along with this heat consumption comes a significant amount of CO_2 emissions. Heat consumption and its related supply structure contributed to more than 40% of global energy-related CO_2 emissions in 2020 [1].

Worldwide industrial heat consumption remains heavily fossil fuel dependent. The share of renewable heat for industrial heat stagnated over the last decade, see figure 1. The growth rate of the renewable share in the heating sector (building and industry) is anticipated to grow from 11% in 2020 to 13% in 2026. To achieve IEA's "Net Zero Emissions Scenario" (NZE), the renewable share would need to grow 2.5 times faster than currently anticipated [1].

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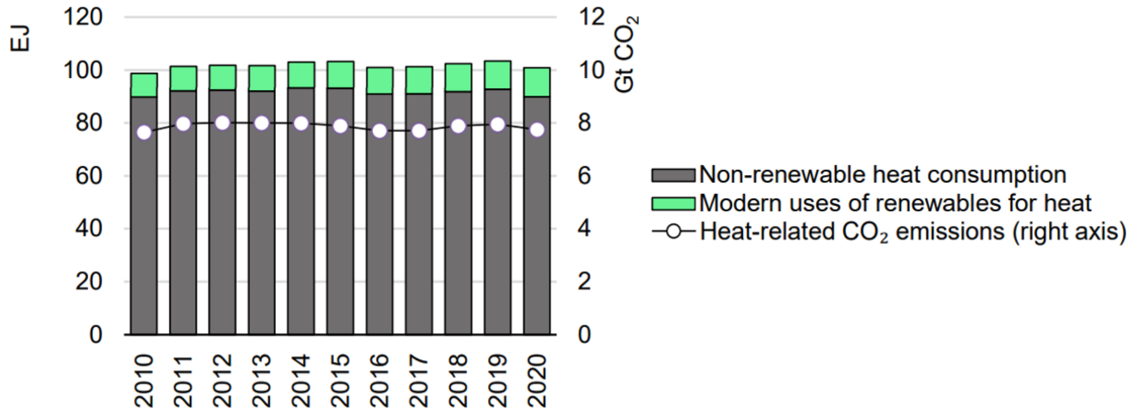

Fig. 1. Renewable and non-renewable heat consumption and heat-related CO_2 emissions in industry (world). Renewable heat covers bioenergy, solar thermal and geothermal energy, renewable electricity for heat, etc. reference [1]

There are several technologies that can supply renewable heat such as solar thermal, geothermal, synthetic climate-neutral fuels (e.g. hydrogen), biomass, and electricity-based systems like electric heaters and heat pumps. The applicability and economic viability of these different technologies depend on the application and its corresponding required temperature levels. For example, it is very efficient and economically viable to apply heat pumps for space and water heating in buildings due to the relative low temperature and easy access to heat sources for heat pumps such as ambient air. The IEA projects for the NZE that more than 50% of all buildings worldwide will be heated by heat pumps (approximately 1.8 billion units) in 2050 [2], see figure 2.

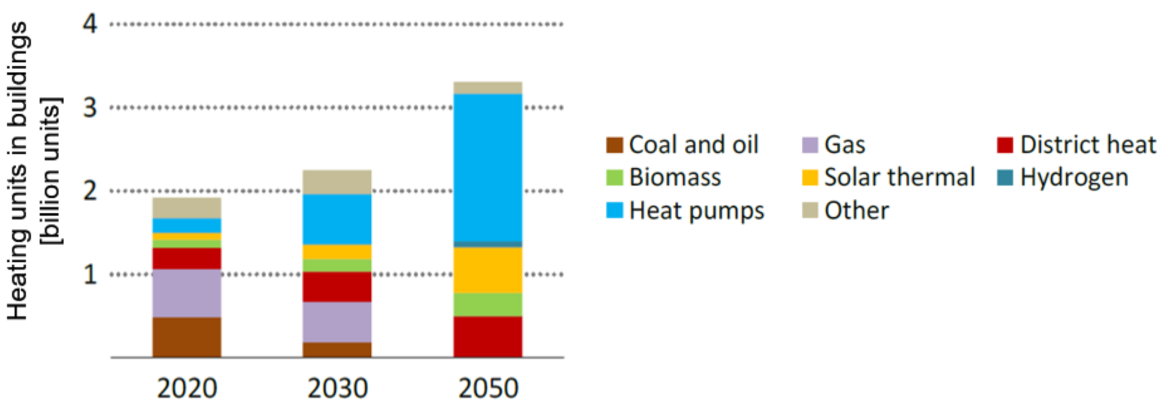

Fig. 2. Global building heating equipment stock by type in 2020 and projection in the NZE for 2030 and 2050 [2]

The industrial heating sector shows other requirements regarding the temperature level and energy density. Consequently, the projection of the IEA for the NZE shows a more diverse technology distribution for the heat demand up to 400 °C, see figure 3 [2]. Electricity-based technologies such as heat pumps and electric heaters have the highest share followed by biomass and hydrogen [2].

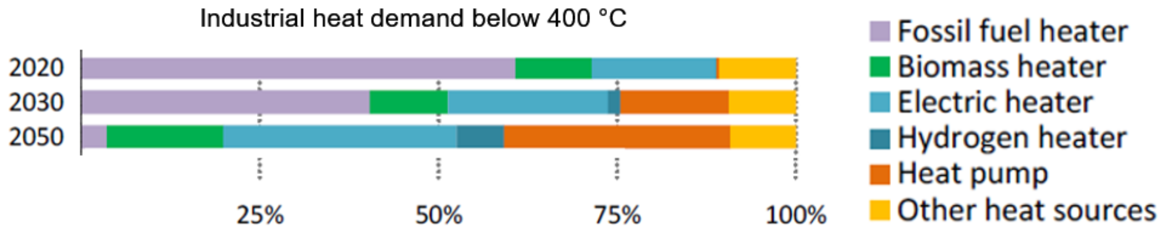

Fig. 3. Global share of heating technology for industries in 2020 and projection in the NZE for 2030 and 2050 [2]

Today, the share of heat pumps for industrial heating is insignificant and needs to grow very fast to meet the projections in 2030 and 2050. For that the IEA states that "around 500 MW of industrial heat pumps need to be installed every month over the next 30 years" [2]. It is a huge effort for all stakeholders like heat pump manufacturers, heat suppliers, and numerous industry branches to achieve such a growth worldwide.

There are already a few countries in which the number of applications of industrial heat pumps grew substantially in recent years. Figure 4 shows Denmark and Austria as an example [3, 4].

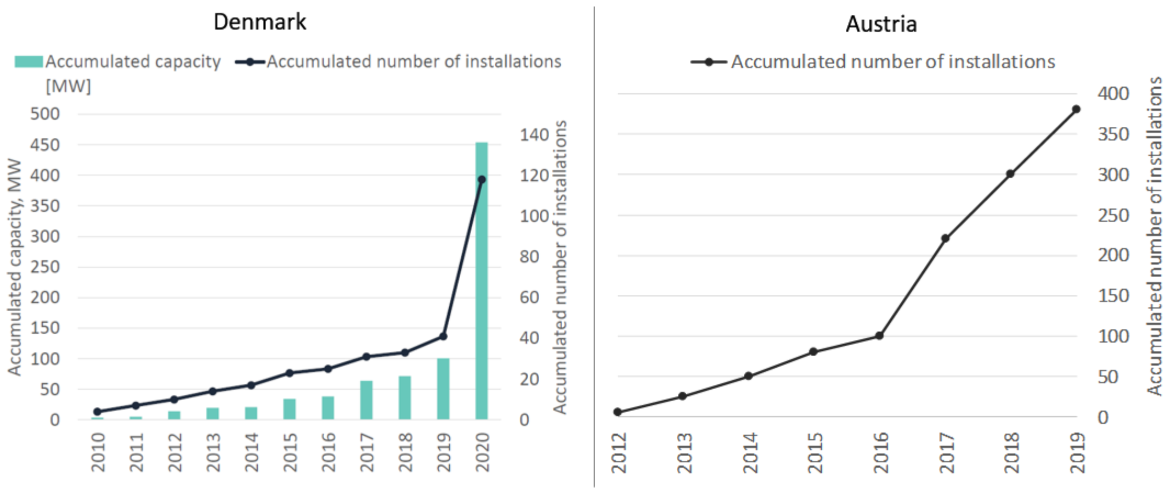

Fig. 4. Installed industrial heat pumps, left: Denmark accumulated capacity and accumulated number of installations; Right: Austria accumulated number of installations [3, 4]

2. Heat pump technologies for large scale heat supply at medium, high and very high temperatures

Industrial heat demand shows a large variety of required temperature levels depending on industry segment and its heat demanding processes [5]. It is important to distinguish heat pumps upon their achievable temperature level as the state of technology is very different depending on the temperature level. Within this paper the following nomenclature is used to categorize heat pumps upon their achievable temperature level:

- Medium temperature: below 100 °C
- High temperature: between 100 °C and 150 °C
- Very high temperature above 150 °C

2.1. Medium temperature heat pumps (MTHP)

Medium temperature heat pumps (MTHP) are a well-proven and widely implemented technology. There are numerous heat pump installations at large scale (single- and double-digit Megawatt range of thermal output). These large-scale MTHP are mostly applied for district heating, with the first ones installed in the 1980s. There are several heat pump installations that operate since then for over four decades already. For example, Averfalk et al. [6] and David [7] list about 150 heat pump installations for district heating in 13 countries with an overall installed thermal output of approximately 1.5 GW.

Among them are 50 MTHP units of Siemens Energy that were installed in the 1980s and 1990s. 40 units of them are still in operation today. These units have a thermal output of 5 to 30 MW and an overall combined thermal output of 850 MW [8]. New large-scale MTHP are being installed e.g., for district heating in the city of Mannheim in Germany with up to 20 MW thermal output. This heat pump installation will be commissioned end of 2023 and is described in detail in section 3.

2.2. High temperature heat pumps (HTHP)

Over the last decade, the development of HTHP technology gained momentum. There are several technological developments of research institutes and companies, which increased the applicable temperature range of heat pumps to 150 °C [9-12].

Some of these developments led to new heat pump products and solutions. First large-scale pilot plants for full-scale operation are being commissioned. A HTHP in the city of Berlin in Germany with 8 MW thermal output and temperatures up to 120 °C is installed. This heat pump installation and its application is described in detail in section 3.

2.3. Very high temperature heat pumps (VHTHP)

There are several heat pump concepts with applicable temperature levels above 150 °C. It is important to distinguish these concepts.

There is the well-established technology of mechanical vapor recompression. It is a very efficient method of waste heat recovery under the requirement that the heat source is steam and can directly be recompressed. It is not possible to use this technology by an indirect heat transfer of other media, which closed loop heat pumps do. Some manufacturers call their mechanical vapor recompression product “heat pump” anyway [12]. Due to the previous mentioned requirement and thus widely limited application potential, mechanical vapor recompression as single technology alone is not further considered in this paper.

Some VHTHP concepts use Brayton or Joule cycles in which the working fluid shows no phase change and thus has a sensible heat transfer to the heat source and sink. There are some technological developments with such cycles [12]. However, the largest application potential at temperature levels above 150 °C in the industry is for steam generation. Steam generation requires isothermal heat transfer as liquid water evaporates at a constant temperature to become steam. Thus, a sensible heat transfer is not efficient to generate steam. Consequently, Brayton or Joule cycles are not considered further in this paper.

VHTHP concepts that allow a predominantly isothermal heat transfer to the heat sink and thus are suitable for e.g. steam generation are reverse Rankine cycles. Recently published concepts for large-scale that are currently in technological development consist of one closed loop heat pump cycle combined with a steam compressor. Siemens Energy has developed several of such concepts for applications in the refinery, paper and chemical industry. One of these concepts is described in detail in section 3. A first pilot plant in full scale operation for steam generation in the industry is anticipated to be commissioned in the coming years.

3. Large-scale heat pump applications at medium, high and very high temperatures

Most existing urban district heating networks still operate on a maximum required temperature typically between 90 and 130 °C [13]. Consequently, most district heating applications with heat pumps can be realized by using MTHP or HTHP under the conditions that a suitable heat source is present. Existing MTHP, for example, use sea water, lake water, river water, sewage water or industrial waste heat as heat source [7].

Industrial heat demand shows a much broader temperature range than district heating. Figure 5 shows the industrial final energy demand end-use of the 28 European Union countries in the year 2015 by temperature [14].

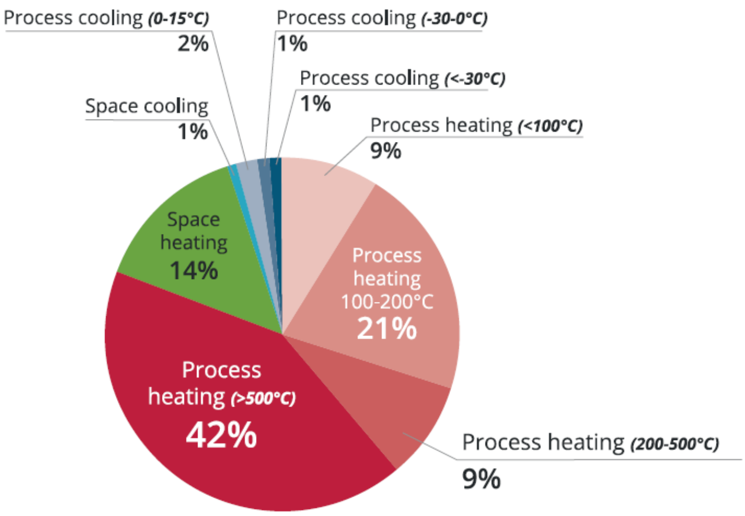

Fig. 5. Industrial final energy demand end-use of the 28 European Union countries in the year 2015 by temperature [14]

Currently developed VHTHP and further anticipated mid-term developments of heat pump technology do not allow to cover the whole temperature range of industrial heat demand. Space heating and process heating below 100 °C can be supplied by MTHP technology. Process heating between 100 and 200 °C can be supplied by HTHP and VHTHP technology. Process heating above 200°C can be partially supplied by VHTHP. This makes up a share that can be supplied by heat pumps of approximately half of the industrial heat demand when considering only the supply temperature. It is important to note that these heat pumps always require a suitable heat source. The higher the heat supply temperature the more challenging it is to identify a suitable heat source that allows an economically viable heat pump operation.

In the following, applications of MTHP, HTHP and VHTHP will be shown. Some of them are existing installations that are commissioned in 2022 or will be commissioned in 2023 (section 3.1). Others are concepts of applications that are very promising to be realized in pilot plants in the coming years (section 3.2).

3.1. Large-scale MTHP and HTHP for district heating

3.1.1. Large-scale MTHP for district heating, existing installation, Mannheim, Germany

Siemens Energy has started building a new large-scale heat pump installation in April 2022 in Germany in the city of Mannheim (under construction as of 16th February 2023). It is built for the utility MVV (Mannheimer Versorgungs- und Verkehrsgesellschaft) next to the power plant “Grosskraftwerk Mannheim”. This heat pump is part of the “Living Lab” for Energy Transition with the title “Large-scale heat pumps in district heating networks”. It is a funded program of the German Federal Ministry for Economic Affairs and Climate Action.

This heat pump bases on a reverse Rankine closed loop cycle with refrigerant R1234ze(E). Figure 6 shows the basic cycle configuration of this heat pump. This heat pumps uses the water of the river Rhine as heat source. The Rhine water has a temperature of about 5 to 25 °C depending on the season. The heat source is used to evaporate and superheat the refrigerant in the evaporator. A two-stage centrifugal compressor driven by an electric motor sucks the refrigerant and discharges it at higher pressure and temperature to the condenser. In the condenser and subcooler, heat is transferred from the refrigerant to the district heating water. The heat pump supplies up to 20 MW of thermal output to the district heating network at temperatures up to 99 °C. The expected average COP for the overall system including all kinds of losses (thermal, electrical, mechanical, pressure and so on) is 2.7. After the subcooler, the cycle has two expansion stages. There is a flash tank in between the stages. The part of the refrigerant flow, which is in vapor phase in the flash tank, is fed directly to the second compressor stage. This increases the overall cycle efficiency. Figure 7 shows a model of the heat pump type used for this heat pump installation.

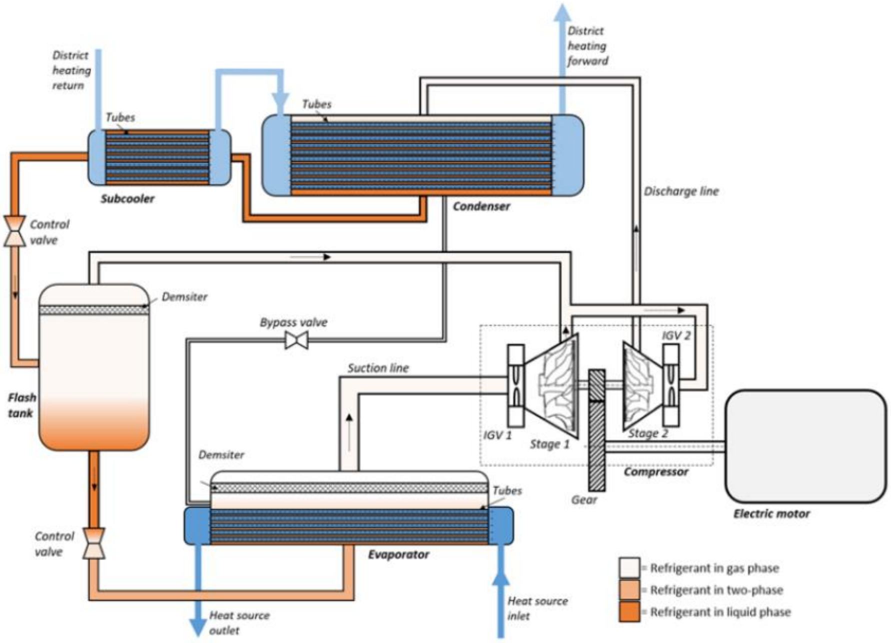

Fig. 6. Basic cycle configuration of MTHP for utility MVV in Mannheim, Germany

Fig. 7. Model of MTHP type used for utility MVV in Mannheim, Germany

It is expected that this heat pump supplies heat to approximately 3,500 households and will save around 10,000 metric tons of CO_2 emissions per year.

3.1.2. Large-scale HTHP for district heating, existing installation, Berlin, Germany

Siemens Energy started building a new large-scale heat pump installation at the end of 2021 in Germany in the city of Berlin (construction finished, under commissioning as of 16th February 2023). It is built for the utility Vattenfall within their existing site chiller plant (“Kaeltezentrale”), which supplies cold water to a district cooling grid in the center of Berlin. This heat pump project is funded by the German Federal Ministry for Economic Affairs and Climate Action within the program “EnEff:Waerme”.

At Vattenfall’s site, there are several compression chillers that produce waste heat. This waste heat is currently re-cooled by wet cooling towers at the building’s roof. The heat pump is integrated in a way, that the waste heat can be recovered and utilized for district heating. Figure 8 shows the integration of the heat pump.

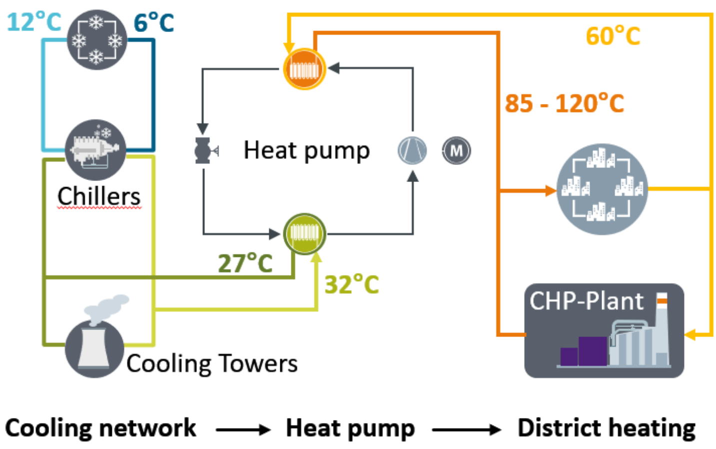

Fig. 8. Integration of HTHP at utility Vattenfall in Berlin, Germany, CHP stands for combined heat and power

The evaporator of the heat pump cools the waste heat of the chillers from 32 to 27 °C and thus recovers this waste heat. The refrigerant R1233zd(E) evaporates and superheats by the heat transfer from the waste heat in the evaporator. A single-shaft centrifugal compressor, see figure 9, sucks the refrigerant and discharges it at higher pressure to the condenser. In the condenser, heat is transferred from the refrigerant to the district heating water. The district heating water enters with about 60 °C and is heated up to between 85 and 120 °C depending on district heating network requirements.

Fig. 9. Picture of the centrifugal compressor of the heat pump for utility Vattenfall in Berlin, Germany after delivery to site

The heat pump has a thermal output of 8 MW and delivers about 55 GWh of district heat per year at an expected average COP of 3 for the overall system including all kinds of losses (thermal, electrical, mechanical, pressure and so on). It is expected that approximately 6,500 metric tons of CO_2 emissions will be saved per year. Another advantage is that less cooling water for the cooling towers will be needed, i.e. around 120,000 m³ of cooling water will be saved per year.

3.2. Large-scale VHTHP for steam production in industry

Steam is a universal heat carrier for industrial plants with heat demand e.g. in chemical, refinery and paper industries. Most plants with heat demand in these industries use steam as heat carrier. Usually there is a steam distribution system that supplies the heat to the various production plants. The steam distribution system has a certain pressure level or consists of different pressure levels enabling the heat supply at different temperature levels.

The pressure levels, amount of steam demand per level and time-dependent demand per level varies greatly among different industrial steam distribution systems. It is crucial for the heat pump technology that steam can be supplied to those different systems in a very flexible way.

Siemens Energy has developed a flexible heat pump system where a closed loop heat pump cycle generates steam with pressures up to 3.5 bara. If a high superheat is required at this pressure, the heat pump can be combined with an electric superheater. For even higher steam pressures, the heat pump can be combined with a steam compressor.

The combination of heat pump with an electric superheater is described exemplary by an application developed with a company from the paper industry (see section 3.2.1). The combination of heat pump with a steam compressor is described by an application developed with a company from the chemical industry (see section 3.2.2).

3.2.1. Large-scale VHTHP for steam generation in fiber industry

The following application example has been developed together with a company from the paper industry. The company operates an industrial site with several waste heat flows that are not recovered currently. At the same time, steam at a pressure of 3.3 bara and at a temperature of 157 °C is required, which is currently supplied by natural gas boilers. Figure 10 shows the heat pump integration concept into the industrial site’s heat sources and heat sink.

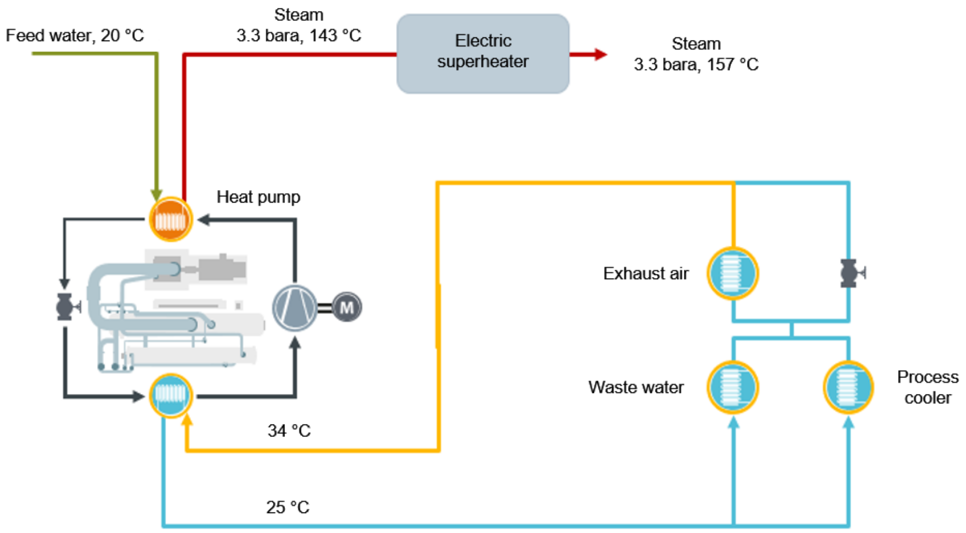

Fig. 10. VHTHP integration concept, combination of heat pump and electric superheater, application in paper industry

Three different heat sources (process cooler, waste water and exhaust air) are combined and recovered. The heat from the heat sources is transferred to the refrigerant in the evaporator. A centrifugal compressor, driven by an electric motor, sucks and compresses the refrigerant to a higher pressure. The refrigerant enters the condenser and transfers heat to the feed water (heat sink). The feed water enters the condenser with 20 °C and is heated up and evaporated to steam at 3.3 bara and 143 °C. The electric superheater increases the temperature of the steam to the required temperature at 157 °C. The expected average COP for the overall system including all kinds of losses (thermal, electrical, mechanical, pressure and so on) is 1.9.

This heat pump integration is one example of many different possibilities with this combination of closed loop heat pump cycle and electric superheater. As long as there is a sufficient heat source, the heat pump can supply steam at pressure from 1 bara to 3.5 bara and the electric superheater can be flexibly adapted to the required steam temperature.

3.2.2. Large-scale VHTHP for steam generation in chemical industry

The following application example has been developed together with a company from the chemical industry. The company operates an industrial site at which process water is available as heat source, which is currently not recovered. At the same time, steam at a pressure of 7 bara and at a temperature of 195 °C is required, which is currently supplied by natural gas boilers. Figure 11 shows the heat pump integration concept into the industrial site’s heat sources and heat sink.

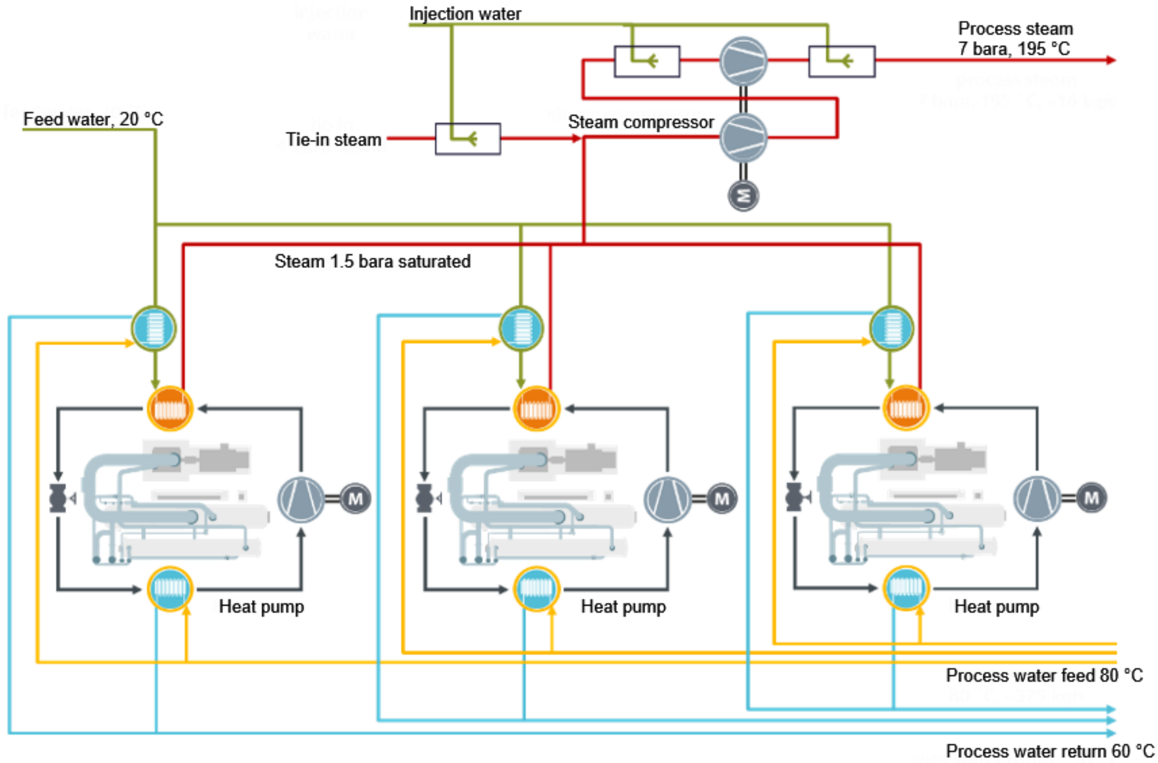

Fig. 11. VHTHP integration concept, combination of heat pump and steam compressor, application in chemical industry

The concept consists of three heat pumps in parallel that are identical in construction. There are several reasons for the parallelization like redundancy and part-load capability.

The heat source (process water) is recovered by cooling it from 80 °C to 60 °C in the evaporators of the heat pumps and partly in the pre-heaters of the heat sink. The heat from the heat source in the evaporators is transferred to the refrigerant to evaporate and superheat it. Centrifugal compressors, driven by electric motors, suck and compress the refrigerant to a higher pressure. The refrigerant enters the condensers and transfers heat to the feed water (heat sink). At first, the feed water is preheated by the heat sources and then enters the condensers. In the condensers, the feed water is heated up and evaporated to saturated steam at 1.5 bara. A two-stage steam compressor sucks the steam and increases the pressure to 7 bara in two stages. There are water injections before, between and after the stages to decrease the superheat. After the last stage, the required pressure of 7 bara and temperature of 195 °C is reached. The expected average COP for the overall system including all kinds of losses (thermal, electrical, mechanical, pressure and so on) is 2.8.

This heat pump integration is one example of many different possibilities with this combination of closed loop heat pump cycle and steam compressor. As long as there is a sufficient heat source, the heat pump can supply steam at a pressure of 1.5 bara and the steam compressor and water injection system can be flexibly adapted to the required steam pressure and temperature.

3.3. Large-scale HTHP and VHTHP integrated with other energy supply systems

The transition of the heat sector from fossil fuel-based heat supply to a climate neutral heat supply requires the installation of new and adapted heat supply units in industry and for district heating. There will be a large variety of different technologies for the heat sector. In the following two heat supply systems are described that can be integrated with heat pumps to increase the overall efficiency and are anticipated to show a high market share in the future.

3.3.1. Hydrogen production by thermally integrated Electrolyzer

Hydrogen will play a major role in future climate neutral energy supply systems. Hydrogen can be produced by electrolysis in electrolyzers. The IEA "Net Zero Emission" scenario projects that in 2030 there will be 850 GW (electric power input) and in 2045 there will be 3 TW (electric power input) of electrolyzers be installed [2].

The production of hydrogen in Electrolyzers also generates waste heat. This waste heat can be recovered and upgraded in its temperature level by heat pumps. Figure 12 shows the integration of a heat pump for steam generation.

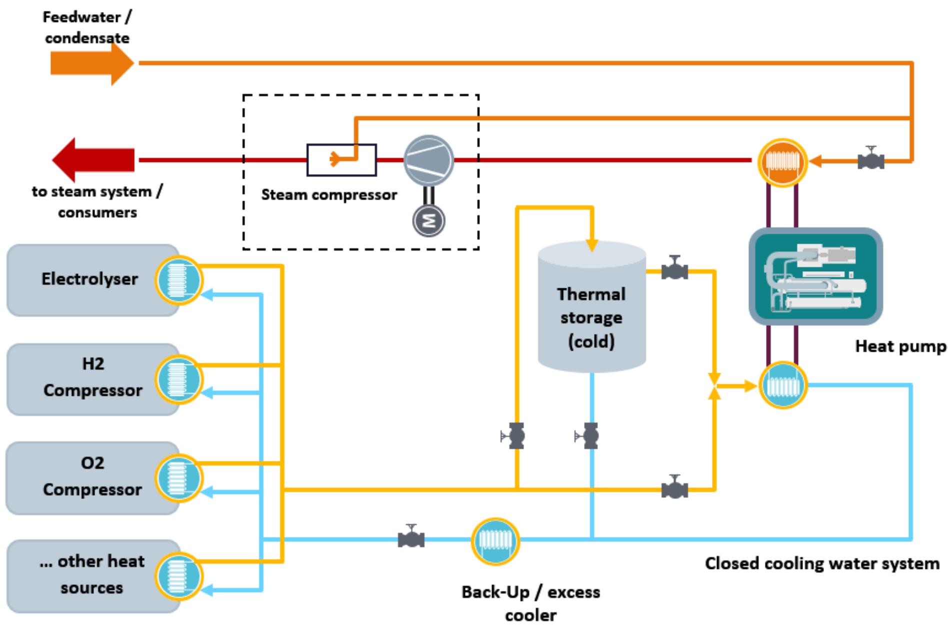

Fig. 12. Heat pump integration concept into Electrolyzer system

The heat pump can recover waste heat from various heat sources like electrolyzer, hydrogen compressor, oxygen compressor and other heat sources. A cold thermal storage that buffers the heat from the heat sources can be integrated if the electrolyzer operation is fluctuating strongly.

The waste heat is typically in the range of 35 to 50 °C. The heat pump lifts the temperature level to supply heat to a heat sink. The heat sink can be hot water or, as in figure 12 shown, steam. For steam at 8 bara and 190 °C, the expected average COP for the overall system including all kinds of losses (thermal, electrical, mechanical, pressure and so on) is 2.1.

Combinations of heat pumps and electrolyzers are being developed together with companies from different industrial branches.

3.3.2. Heat supply by exhaust gas condensation for natural gas / hydrogen fired boilers and gas turbines

Natural gas-fired boilers and gas turbines are well-established and widely used technologies. Exhaust gas condensation is often not applied at large-scale and especially when the temperature of the return flow of the heat sink is too high. The integration of a heat pump enables to further cool the exhaust gas and condense the water content in the exhaust gas. In doing so, a large amount of additional heat can be recovered from exhaust gas streams. Figure 13 shows a concept of combining a gas turbine with a heat pump.

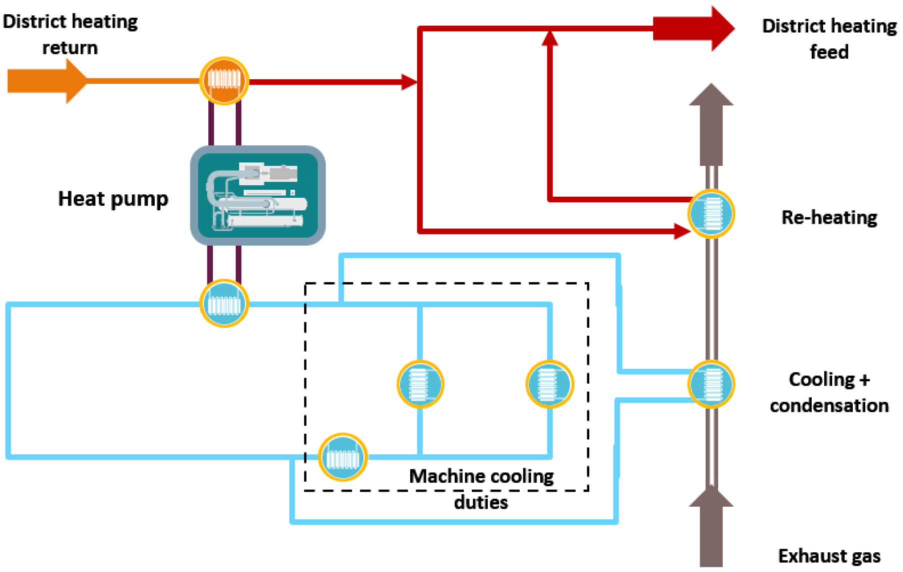

Fig. 13. Heat pump integration concept into gas turbine system

There is an intermediate loop (blue lines) that takes up the heat from the heat sources. The heat sources are various machine cooling duties like the generator of the gas turbine and the exhaust gas. The exhaust gas stream is cooled below the dew point of its containing moisture. The heat pump takes up the heat from the intermediate loop in the evaporator and supplies heat at a higher temperature for example for district heating. In some cases, a re-heating of the exhaust gas is required to ensure a stable flow through the chimney.

A typical case is the supply of district heating at 115 °C. The expected average COP for the overall system including all kinds of losses (thermal, electrical, mechanical, pressure and so on) is 2.2.

Combinations of heat pumps and gas turbines are being developed together with companies from different industrial branches and district heating network operators.

In the future it is anticipated that natural gas-fired boilers and turbines will be adapted to use hydrogen or a mixture of hydrogen and natural gas as fuel. The exhaust gas cooling and condensation also works with hydrogen or a mixture of hydrogen and natural gas as fuel.

4. Summary and conclusion

The transition of the heat sector towards climate neutral heat supply is a very challenging undertaking. District heating and industrial heat are still predominantly based on fossil fuel and thus contribute to a large portion of worldwide CO_2 emissions.

There are several technologies that will support the decarbonization of the heat sector. Large-scale heat pumps with supply temperatures below 100 °C for district heating are a well-established technology since decades. The share of these heat pumps for the overall heat supply needs to grow substantially. Siemens Energy has built 50 large-scale heat pumps in the past already and new heat pump installations are being built.

District heating also requires temperatures above 100 °C. There are numerous developing activities for products and solutions for large-scale high temperature (> 100 °C) heat pumps. Siemens Energy builds and commissions a first large-scale high temperature heat pump for district heating for the utility Vattenfall in Berlin with 8 MW of thermal output and supply temperatures of up to 120 °C. This pilot plant is an outstanding step in the advancement of heat pump technology.

Industrial heat supply requires even higher temperatures. Often, steam is used as heat carrier at industrial sites. There are numerous developing activities for products and solutions for large-scale very high temperature (> 150 °C) heat pumps. Several concepts have been developed for the steam generation with very high temperature heat pumps. These concepts can easily be adapted to meet various steam pressure and temperature requirements.

There are technologies that are anticipated to be largely present in future climate neutral energy supply systems, such as electrolyzers and hydrogen-fired gas turbines. Concepts have been elaborated to integrate heat pumps that recover the waste heat of these technologies.

It can be concluded that heat pumps will play a major role in future carbon neutral heat supply systems for district heating and industrial heat supply. More and more pilot plants of high temperature and very high temperature heat pumps will start its operation in full-scale in the coming years until these heat pump technologies are well-established and are widely accepted as standard technology by the involved stakeholders.

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