Industrial heat pumps in Germany: Potentials, technological development and market barriers

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Industrial heat pumps in Germany: Potentials, technological development and market barriers

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Abstract
The industrial Sector plays a major role with respect to Germany's final energy demand as well as CO_2 emissions. In order to fulfill the German CO_2 emission targets, the CO_2 intensity of the industrial sector has to be reduced greatly. As about three quarters of the industrial final energy demand are needed in form of heat, heat pumps can make a substantial contribution to meet these targets. In this paper the latest developments in heat pump technology are shown. The individual advantages of the four most used heat pump types are described. The importance of the development of high temperature refrigerants for the application of heat pumps in industrial processes is pointed out. Today's industrial heat pumps can deliver temperatures up to 80 °C. Due to the development of new very promising refrigerants temperatures of 160 °C will be possible to reach in the near future. Furthermore this paper gives an overview on promising industrial processes that can be supplied by heat pumps. Based on the typical temperature levels and the energy demand of the different industrial branches the technical potential for the application of heat pumps in the German industry is evaluated. It shows that at a temperature level of 80 °C 14 % of the industrial heat demand can be covered by heat pumps available today. With the development of high temperature heat pumps the potential rises to 32 %. Although the technology is already available heat pump applications are still quite rare. Insufficient knowledge about the abilities of this technology is found to be the main barrier for the wide spread use of heat pumps in industry.

Introduction
The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) points out, that a major part of the observed global warming is very likely due to anthropogenic sources (Alley et al. 2007). As the main influencing factor the greenhouse gas CO_2 was identified. Against this background Germany has decided to reduce its greenhouse gas emissions compared to the emissions of the base year 1990 by 40 % until 2020 and by 80 % until 2050 (BMWi 2010). In 2010 832 Mt CO_2 were emitted in Germany. 93 % of these emissions were caused by burning of fossil fuels to provide energy in form of electricity, heat or motion. With a 28 % share the industrial sector is responsible for a big part of Germany's total final energy demand of 2.517 TWh in 2010. About three quarters (524 TWh) of the industrial final energy is needed in the form of heat (BMWi 2012). This heat demand is being met mainly by the combustion of fuel oil and natural gas. This results in a major potential for CO_2 savings in the German industry. With the heat pump a technology is presented in this paper, which can contribute significantly to increasing energy efficiency and reducing CO_2 emissions (IEA Heat Pump Center 2008).

Technical development of heat pump technology
Shortly after the discovery of the heat pump principle in 1852 by the British physicist William Thomson (Lord Kelvin), the Austrian Peter Ritter von Rittinger presented the first fully functional heat pump. In 1859 the Frenchman Ferdinand Carré followed with the first ammonia absorption machine (Laue 2002). Since those days heat pumps have grown to a mature technology, which is widely used in the residential sector. The individual advantages of different heat pump cycles and refrigerants are shown in this paper.

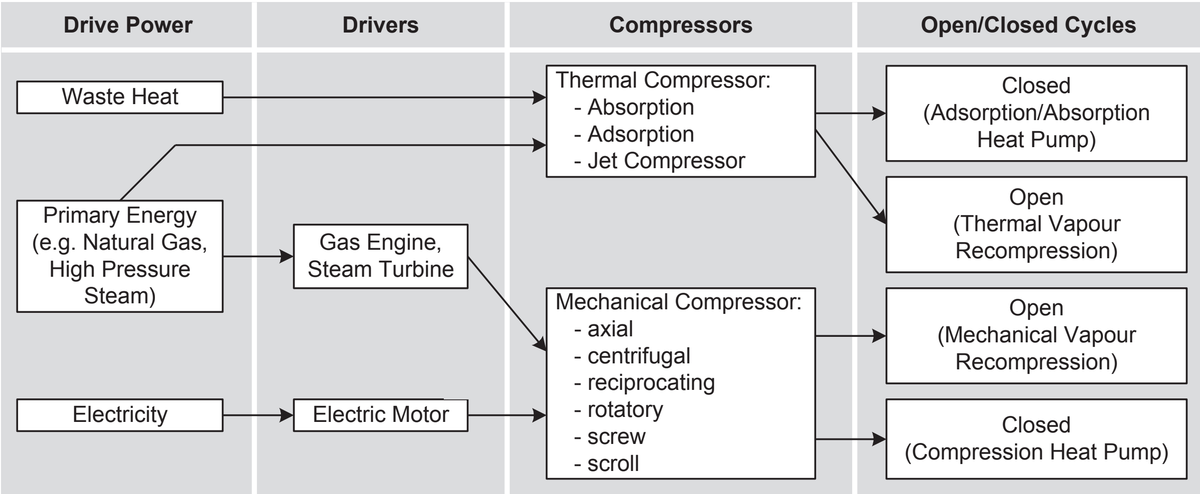

Figure 1: Types of heat pumps (Ranade 1989, own research).

HEAT PUMP CYCLES

On the basis of the first developments in the 19th century, further technical implementations of the heat pump process have been developed. They mainly differ in the compression principle and in the motive power being used. All these types have in common, that they absorb heat at a low temperature level from a heat source and pump it up to a higher temperature level and release it to a heat sink by consuming electrical or thermal energy. The energy efficiency of a heat pump is characterized by a high coefficient of performance (COP). This is the ratio of useful heat to the drive energy of the compressor. The COP decreases with increasing temperature difference between heat source and heat sink according to the second law of thermodynamics. Depending on the application, different types of heat pumps have proven particularly suitable. The most important heat pump types for industrial use are shown in Figure 1.

They are either driven by thermal or mechanical energy. The type of drive energy determines the CO_2 emissions and thereby also the ecological effectiveness of the heat pump. In order to achieve an ecological advantage compared to the direct burning of fossil fuels the COP of the heat pump has to be higher than the primary energy factor of the used drive energy. This means that heat pumps which are directly driven by fossil fuels need to achieve a COP higher than 1. For electrical driven heat pumps the COP must exceed a value of 2.6. The German primary energy factor for electricity is that high, because of the high share of coal power plants in the electricity production.

In the past years the factor has decreased from 3 to 2.6, because of the rapidly rising share of renewable energies (Bundesrat 2009). Due to the planned expansion of the share of renewable energies in electricity generation to 35 % by 2020 (BMWi 2010) the primary energy factor of the German electricity mix will further decrease to a value of 1.78 (BWP 2012).

Closed cycle absorption heat pump (CCA)

In absorption heat pumps a binary mixture with one volatile and one non-volatile component is being used. The most common substance combinations are water/lithium bromide (H_2O/LiBr) and ammonia/water (NH_3/H_2O). In the heat pump cycle the volatile component absorbs heat at a low temperature level in the evaporator. After that it enters the absorber where it is absorbed by the non-volatile component with the release of usable heat at a medium temperature level. The mixture of both components is then pumped to the expeller. The volatile component evaporates by use of high temperature heat which can be provided by burning of fossil fuels or by utilization of waste heat. It then enters the condenser where it delivers heat at a medium temperature level. The now condensed volatile component is then sent back to the evaporator via an expansion valve. The non-volatile component is passed directly back to the absorber and the function circuit is closed. Absorption heat pumps only have very few moving parts which leads to low maintenance requirements. Furthermore they can be driven by waste heat, which has another positive effect on the CO_2 saving potential of this technology. However, both the technical complexity of absorption heat pumps, as well as the effort to integrate them into industrial processes is significantly higher than in closed cycle compression heat pumps. This results in higher investment costs.

Thermal vapour recompression (TVR)

The TVR heat pump is driven by high pressure steam and an ejector. It is therefore often simply called an ejector (Berntsson 1997). High pressure steam as the motive fluid goes through a nozzle and draws in steam coming from the evaporator. The mixed stream expands and its velocity is transformed into pressure. Then it enters the condenser where the stream partly condenses by transmitting heat to the heat sink fluid. Steam and condensed water are then separated. While the condensed water leaves the system, the steam enters the evaporator where it absorbs heat from the heat source fluid. TVRs have no moving parts, making them very low-maintenance. Necessary for the operation of a TVR are high pressure steam as the motive fluid and a gaseous heat source at high temperatures. The achievable temperature lift with less than 20 K is very small.

Mechanical vapour recompression (MVR)

Like TVR heat pumps MVRs also directly use a gaseous heat source like water vapour. The fluid is directly compressed by a mechanical compressor and thus brought to a higher temperature level. Subsequently, the fluid can be used directly in a process or it transfers its heat by means of a heat exchanger to a heat sink. The use of an MVR presupposes an already gaseous heat source fluid, which usually implies a high temperature heat source. Typical working conditions for a MVR are a heat source temperature exceeding 80 °C and a little temperature lift of around 20 K (Berntsson 1997). The compressor of an MVR can be driven by an electrical motor or a combustion engine.

Closed cycle compression heat pump (CCC)

The closed cycle compression heat pump has a similar working principle like the MVR, with the difference that the heat source fluid isn't used directly. Because of its intermediary refrigerant cycle CCC heat pumps can be used more flexible than MVRs. They don't demand a gaseous heat source. By absorbing heat from the heat source at a low temperature level the refrigerant is evaporated in the evaporator. Then a compressor brings it to a higher pressure and thus to a higher temperature level. Subsequently the refrigerant enters the condenser where it releases heat to the heat sink at a high temperature level. Via an expansion valve, the refrigerant is then depressurized and it returns to the evaporator again to complete the function circuit. This type of heat pump is recommended if the heat source and heat sink should be physically separated from each other and if a large temperature lift has to be achieved. Just as in a MVR the compressor of a CCC heat pump can be driven by an electrical motor or a combustion engine. By the use of an electrical motor no local exhaust gas emissions are caused. On the other hand a compression heat pump driven by a combustion engine offers the opportunity to utilize the waste heat of the engine to reach higher temperature levels.

REFRIGERANTS

In the development of industrial closed cycle compression heat pumps refrigerants play a central role. To reach temperature levels of 100 °C and higher, which are often required in the industry, the refrigerant has to have a very high critical temperature. At the same time the critical pressure should be as low as possible (Klein 2009), as a higher pressure requires the use of more sophisticated components and materials. The normal boiling point (NBP) of a refrigerant represents the boiling temperature at atmospheric pressure. This should be 5 to 10 K lower than the heat source temperature.

During the first boom of heat pumps in the late 1970s and early 1980s also the first industrial heat pumps were installed. They often used the chlorofluorocarbon (CFC) refrigerant R114, because of its advantageous properties like a high critical temperature and a low pressure level. An important drawback of this refrigerant is its harmfulness to the earth's ozone layer. This harmful effect is quantified by the ozone depletion potential (ODP). With the ratification of the Montreal protocol enacted in 1987 chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants have been banned in Germany since 1996 for most applications. Today, they may no longer be used (UBA 2002). Since the ban of the CFCs and HCFCs for a long time there was no suitable refrigerant available which could be used in industrial high temperature heat pumps.

Also the high global warming potential (GWP) of today's refrigerants is considered increasingly critical. As a reference for the evaluation of the GWP, CO_2 is used with a value of 1. In addition to these requirements a refrigerant should be neither toxic nor flammable which is expressed in the safety group A1. Beside to the now banned R114 the today commonly used and possible future refrigerants for industrial CCC heat pumps are listed in Table 1.

Common refrigerants

In most heat pumps offered today the synthetic refrigerant mixture R410a is used. They are designed for new and energetically renovated residential buildings. Heat pumps using R134a can also be applied to provide hot water and space heating in older buildings. The critical temperature of both refrigerants is too low for the utilization in most industrial processes. Heat pumps using R410a can provide hot water at temperatures up to 60 °C, while those using R134s can reach up to 80 °C.

Table 1: Past, present and future refrigerants for industrial heat pumps.

Type	Composition	Ratio [m %]	ODP *	GWP *	NBP * [°C]	T_{crit} [°C]	p_{crit} [bar]	Safety group
R114	$C_2Cl_2F_4$ [a]	-	1 [a]	9800 [a]	3.8 [a]	145.7 [a]	32.6 [a]	A1 [b]
R410a	R32/R125 [a]	50/50 [a]	0 [b]	1730 [b]	-51.6 [a]	72.6 [b]	49.0 [b]	A1 [g]
R134a	$C_2H_2F_4$ [a]	-	0 [a]	1300 [a]	-26.1 [a]	101.0 [a]	40.6 [a]	A1 [g]
R245fa	$C_3H_3F_5$ [a]	-	0 [c]	950 [c]	15.3 [a]	154.0 [c]	36.4 [c]	B1 [e]
R600	C_4H_{10} [b]	-	0 [b]	< 1 [b]	-0.5 [b]	152.0 [b]	38.0 [b]	A3 [b]
R717	NH_3 [g]	-	0 [g]	0 [g]	-33.0 [g]	133.0 [g]	114.2 [a]	B2 [g]
R744	CO_2 [g]	-	0 [g]	1 [g]	-57.0 [g]	31.0 [g]	73.8 [a]	A1 [g]
SES36	R365mfc/PFPE [f]	65/35 [f]	0 [f]	3126 [f]	35.6 [f]	177.6 [f]	28.5 [f]	unknown
DR-2	unknown	-	0 [d]	9.4 [d]	33.4 [d]	171.3 [d]	29.0 [d]	A1 (expected) [d]

**) ODP: Ozone Depletion Potential GWP: Global Warming Potential NBP: Normal Boiling Point*

Sources:
a) IFA, b) Solvay Fluor GmbH 2010, c) Honeywell International Inc. 2010, d) Kontomaris 1/10/2011, e) Klein 2009, f) Riva et al. 2006, g) Bitzer Kühlmaschinenbau GmbH 2010

R600 (Butane)

Butane, as well as ammonia and carbon dioxide is a natural refrigerant. Its critical temperature of 154 °C is high enough to cover a wide range of industrial applications. In addition its global warming potential is very low. However, butane is highly flammable and should thus only be used in small plants that only need small quantities of refrigerant.

R717 (Ammonia)

Such as butane, ammonia is flammable, but in addition to that it is also toxic. Therefore appropriate safety measures have to be applied when using this refrigerant. Contrary to butane the needed refrigerant amount of ammonia is relatively low, due to its high refrigerating effect per unit of swept volume. Ammonia has a high critical temperature of 133 °C, but due to its high working pressure the maximum reachable temperature of currently available ammonia CCC heat pumps is 90 °C. For higher temperatures very sophisticated constructed compressors have to be used. More than 110 °C at a pressure of 76 bars are currently not technical feasible (Emerson Climate Technologies 2011).

R744 (Carbon dioxide)

In the early years of refrigeration CO_2 was a widely used refrigerant. A manual from 1915 lists 24 manufacturers of CO_2-compressors in Germany alone. With the introduction of synthetical halogenated refrigerants in 1931 the use of CO_2 declined rapidly (Cavallini 2004). In recent years it experienced a renaissance due to its unique properties which can be utilized by today's available advanced technology. It is nontoxic, nonflammable, non-corrosive, has no ODP and a GWP of 1. At first its low critical temperature seems to contradict the requirements of an industrial heat pump. To reach the required temperatures CO_2 has to be compressed to a supercritical state. It then releases its heat at a high temperature by means of a gas heat exchanger instead of a condenser. Due to its supercritical state CO_2 has a big temperature glide in the heat exchanger. By adjusting the CO_2 flow rate the average temperature difference in the heat exchanger can be reduced, when the heat pump is used to heat cold water to a high temperature. This reduces the exergetic losses in the heat exchanger and therefore increases the energy efficiency of the heat pump (Rieberer et al. 2006). Because of the critical temperature of 31 °C the temperature of the heat source should not be higher than 30 °C. Today available CO_2 heat pumps can provide hot water at temperatures up to 130 °C (Wilming 2010).

R245fa

The synthetic refrigerant R245fa is not flammable but toxic. Therefore it is classified in safety group B1. It has a high critical temperature and a moderate pressure level. Since R245fa is a pure substance, it has no temperature glide in the condenser. Therefore this refrigerant can be used to heat water with small temperature lifts or to produce steam. Theoretically CCC heat pumps using R245fa can provide Temperatures up to 140 °C. Although this refrigerant has been on the market for a while, no information about its utilization in high temperature heat pumps could be found in the scientific literature. A first demonstration plant is currently planned.

New refrigerants

Some of the currently developed low GWP refrigerants have very interesting properties for the utilization in industrial heat pumps. The refrigerant mixture SES36 is produced by Solvay and in its properties it resembles the refrigerant DR-2, which is developed by DuPont. Both refrigerants have a very low pressure and a high critical temperature above 170 °C. They also have no ODP. While SES36 has a very high GWP, a very low value is expected for DR-2. In addition the expected safety group classification for DR-2 is A1, which means that it will be neither flammable nor toxic. Due to its relatively high NBP only heat sources with a temperature higher than 40 °C can be used. These characteristics make SES36 and DR-2 promising candidates for future high temperature heat pumps.

Industrial heat pump applications

Standard heat pumps developed for the residential sector can't reach higher temperatures than 80 °C. This is because of the limitations of the utilized refrigerants. For a large number of industrial processes, this temperature level is too low. The use of high temperature refrigerants enables the provision of process heat up to 140 ° C. With newly developed refrigerants it will be possible to build high temperature heat pumps which can reach temperatures even up to 160 °C. Since the efficiency of a heat pump decreases with the rise of the temperature lift, relatively high temperature heat sources are needed. With a temperature lift between heat source and heat sink of 50 K or less a COP of over 3 can be achieved, thus guaranteeing a good ecological and economic efficiency (Lambauer et al. 2008). The application of heat pumps is particularly advantageous when integrated into the process over the pinch point (IEA Heat Pump Center 1995). Then the heat pump absorbs heat from the cooling streams to provide process heat. Thus both heating and cooling utility capacities can be reduced. An overview of common processes as well as their typical operating temperatures is given in Figure 2. Furthermore the maximum reachable temperatures are marked for the different refrigerants. It can be clearly stated that the number of covered processes rises significantly with the application of high temperature refrigerants. In the following sections some promising processes as well as processes where heat pumps are already being used are presented.

EVAPORATION

The evaporation process is mainly used in food industry. It serves to reduce the liquid content of a product by up to 95 %. The contained water of a product is evaporated by the supply of heat. The vapour is removed from the evaporator and compressed by an open cycle MVR unit. After the compression the steam now has a higher temperature and enters a heat exchanger to heat the evaporator. In this very energy efficient evaporation system just the motive energy for the MVR has to be supplied. An auxiliary heater is only needed, to heat up the product at the beginning of the evaporation process. The conditions of the evaporation (gaseous heat source and low temperature lift) are ideal for the application of a MVR heat pump. The leading manufacturers of evaporators already use MVRs as a standardized component of high efficiency evaporators.

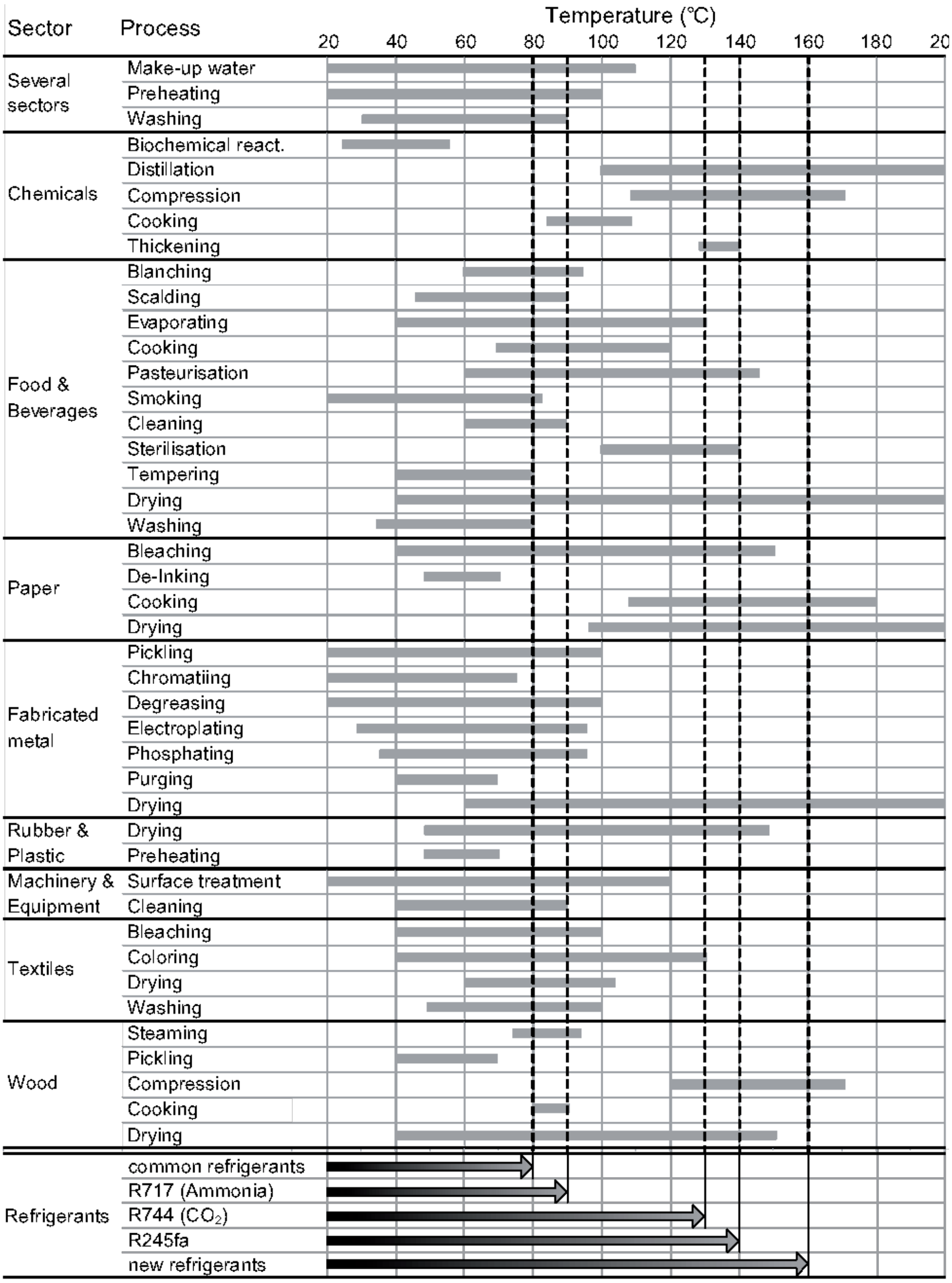

Figure 2: Typical temperature levels of common industrial processes and the limitations of refrigerants (Lauterbach et al. 2011, own research).

DRYING

The drying process is one of the world's most widely used industrial processes. It is used in many industrial branches and it operates usually at temperatures below 100 °C. Heat pumps have ideal working conditions in energy efficient drying chambers that recirculate the air. Therefore these drying units have to be well insulated and the air exchange with the environment has to be minimized. By heating the air it absorbs a part of the liquid contained in the drying product. In a continuous process humid air is led to the heat pump which absorbs its heat and cools the air down under dew point temperature. The absorbed water condenses before the air is reheated by the heat pump. The now dehumidified air is led to the drying chamber again. Compared to conventional drying processes the heat pump drying can lead to great energy savings. Because the air doesn't leave the drying chamber especially in the food industry the product quality can be increased (Colak 2009). Due to these advantages, heat pump dryers have already been established in the industry, mainly in timber and food industry.

PASTEURIZATION

In the pasteurization process bacteria are eliminated by heating products up to temperatures between 60 °C and 135 °C. It is mostly used in dairies to extend the shelf life of milk products. Like the drying process this process also needs heating and cooling at the same time. In a standard pasteurization process milk enters the pasteurizer at a temperature of about 5 °C. It is then heated up to 135 °C for a very short time (1 to 2 seconds) and is then cooled down again to 5 °C. A regenerative heat exchanger between the hot and the cold milk stream is already used. A heat pump can be used to compensate the energy losses of this process. It can absorb heat from the pasteurized milk to further heat the hot milk which comes from the heat exchanger. This process is ideally suited for the utilization of a CO_2 heat pump as the milk keeps liquid over the whole process. A German heat pump manufacturer advertises its products specifically for use in the pasteurization of milk.

SPACE HEATING

Production buildings must be heated in winter, mostly because of insufficient internal heat gains which cannot compensate the heat losses to the environment. At the same time waste heat from process cooling has to be dissipated because its temperature level of about 30 to 40 °C isn't high enough to directly use it for space heating. Here an ordinary heat pump which is also used in the residential sector can be used to upgrade the heat to a higher temperature level. Those systems are the most common retrofit heat pump systems in the German industry. As heating demand is seasonally it should be checked first whether there is an industrial process with many early operating hours that could use the upgraded heat instead. This would increase the running time of the heat pump and thus decrease its payback period.

WASHING

Washing and cleaning are processes occurring in many industries. Both run mostly at temperatures below 100 °C. Heat pumps are already used in automatic belt washing systems. Similar to the application of heat pumps in drying technology they dehumidify the air coming out of the machine and use the absorbed energy to heat the water tank of the washing machine. In addition to higher energy efficiency the heat pump also reduces the heat and moisture emitted by the washing machine. This means less need for conditioning the ambient air at the site of the plant. Furthermore, currently the use of a high-temperature heat pump using the refrigerant R245fa in a batch washing process is planned.

Potential for heat pumps in industrial processes

The technical potential for the use of heat pumps in industrial processes can be estimated from the energy consumption of each industrial branch and the temperature levels of the used processes. The energy demand for process heat, space heating and hot water production in the German industry was 524 TWh in 2010. The results of the potential assessment which are shown in Figure 3 indicate that 75 TWh of heat could be provided by today's standard technology heat pumps. This equals 14 % of the industrial heat demand. With the introduction of high temperature heat pumps which can provide temperatures up to 140 °C another 91 TWh heat could be provided. In total heat pumps can provide 166 TWh or 32 % of the heat demand in the German industry.

Particularly in the food and the chemical industry great potentials exist. In the food industry the processes pasteurization, sterilization, drying and evaporation show the biggest potential for the application of heat pumps. In the chemical industry, it is the melting of plastics and the production of rubber.

This huge technical potential has barely been tapped so far. On the one hand heat pumps that could supply temperatures higher than 80 °C haven't been available in Germany, on the other hand they have to compete with relatively cheap gas or oil fired boilers. Due to their relatively complex design, heat pumps have high investment costs. In eight case studies carried out by (Lambauer et al. 2008) it could be shown, that heat pumps can supply heat at up to 30 % lower running costs. Even though in only two case studies a recommended payback period of less than two years could be reached. The payback period varied from 1.5 to 6.7 years.

In Figure 4 the market development of heat pumps in residential and industrial sector are compared. New buildings

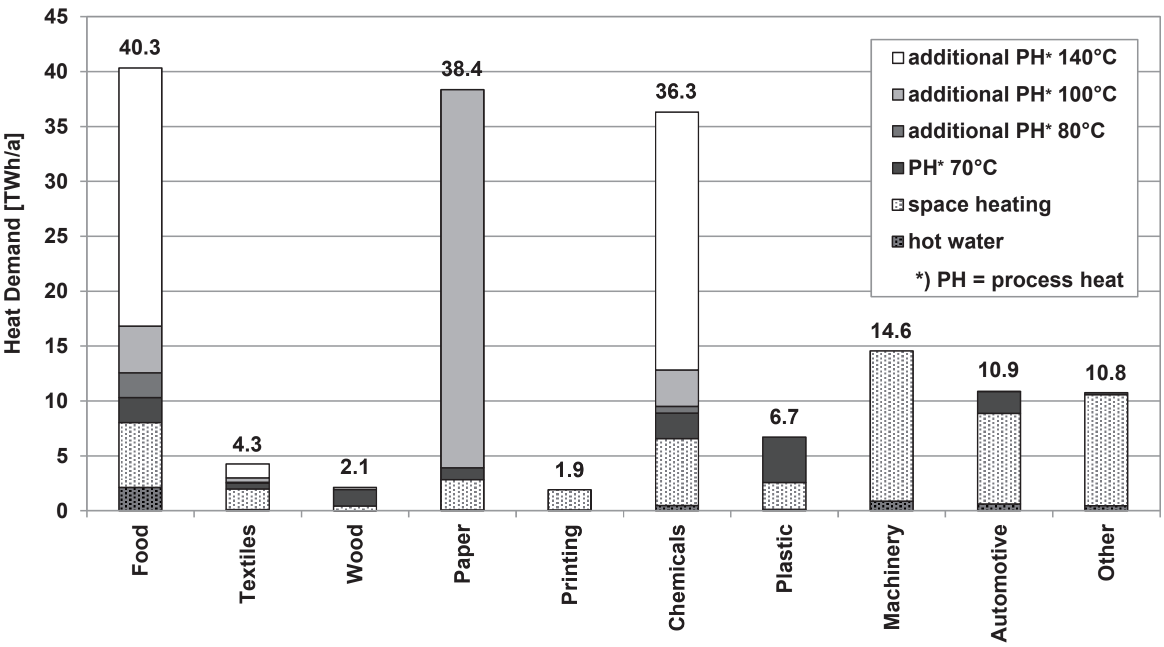

Figure 3: Technical potential for heat supplied by heat pumps in the German industry (Blesl et al. 2012).

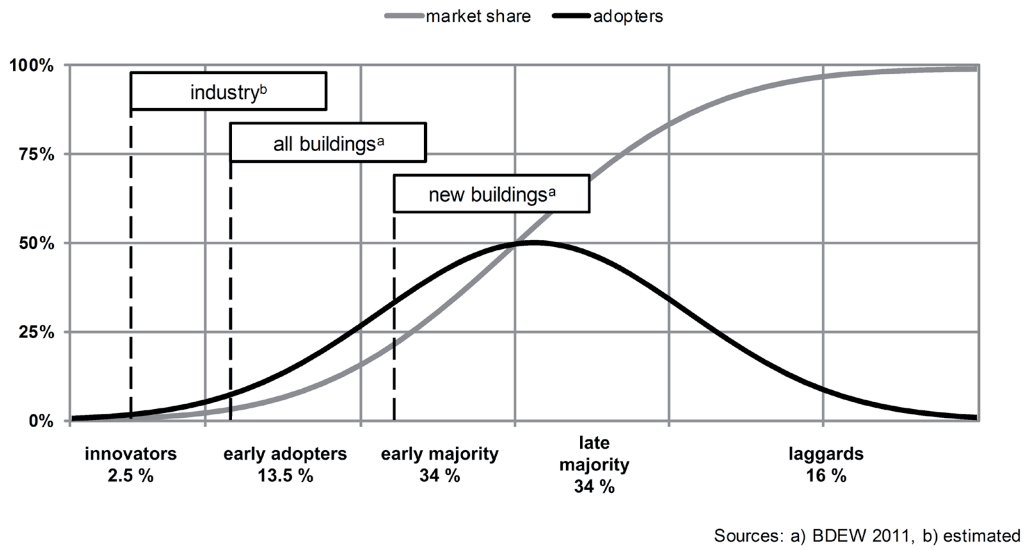

Figure 4: Market development of heat pumps in Germany.

have high insulation standards and therefore only need supply temperatures of 30 to 40 °C for heating. This lowers the temperature gap between heat sink and heat source, which allows the heat pump to work more efficient at lower running costs. In new buildings heat pumps are already in the phase of an early majority. Considering the whole residential sector market shares of heat pumps are rising in the recent years, but they are still in the phase of early adopters.

As the industrial energy prices are much lower compared to those for the residential sector, the need to change the heating system is much lower. In the previous chapter some processes have been identified, where heat pumps have already become a standard technology in newly installed plants. When it comes to the retrofit of existing plants hardly any heat pump installations can be found in the industry.

In conclusion it can be said that the economic potential is still much lower than the technical. But with the implementation of heat pumps into standard process designs and rising industrial energy prices the economic potential is growing.

Barriers for the use of heat pumps in the industry

Currently just a little share of the technical potential for industrial heat pumps in Germany is exploited. A survey conducted among industrial system planners could essentially support the results of a former study (Lambauer et al. 2008). The following barriers could be identified.

- **Lack of knowledge:** There is a lack of knowledge about the specific problems of industrial heat pump applications. The installer has to have knowledge about the recent developments in the heat pump technology and at the same time also about the process properties. This makes the installation of a heat pump relatively complex. Therefore better information material has to be provided and installers have to be trained for the special requirements of the integration of heat pumps into industrial processes.
- **Long payback periods:** Compared to gas or oil fired boilers, heat pumps have relatively high investment costs. To be a cost efficient alternative low running costs have to lead to the required payback periods of less than two years. This can be achieved if heat pumps are integrated wisely. This requires a low temperature lift between heat source and sink, a simultaneous replacing of heating (sink side) and cooling (source side) equipment and long running periods. Heat pumps are even more attractive when they replace electrical heaters. Furthermore serial production of industrial heat pumps can help to lower investment costs.
- **Customer concerns:** Many installers named customer concerns as a major barrier. They often choose the well proven conventional technology, as the supply with process heat is a critical factor for the production. Information about successful realized industrial heat pumps is still rare. To overcome this lack of information and trust, best practice examples for different processes have to be documented and published.
- **Low awareness of heat consumption in companies:** Most companies don't know their energy demand and most certainly not the energy demand of different processes. With limited information it is very difficult to find a heat source that could provide enough heat at a suitable temperature level for a high temperature heat pump. This means that costly and time consuming measurements have to be carried out before the installation of a heat pump can be considered. In Germany from 2013 on energy management systems become obligatory for companies with a high energy demand, if they want to profit from tax reductions. This can help to raise awareness of energy demand in these companies.

Conclusion

In this paper it has been shown that there is a broad variety of heat pumps which are ready to be used to recover heat in many industrial processes. With new refrigerants high temperature heat pumps, that can deliver temperatures up to 160 °C, become possible. Demonstration plants have to be implemented, measured and documented to show the technical advantages of those high temperature heat pumps. In a potential assessment for the use of heat pumps in the German industry it could be shown that up to 32 % of the total industrial heat demand can be provided. Although the technology is ready to use there are still some barriers that have to be eliminated. As one of the main barriers an insufficient knowledge about heat pumps both on the system planner as well as on the customer side could be identified. Information material about industrial heat pumps has to be spread by the branch associations. More best-practice examples of process integrated heat pumps have to be published. When it comes to the knowledge about energy demands on the customer side the implementation of energy management systems can be helpful. In summary the heat pump technology is ready for the industrial application. For a widespread use economic and information barriers still have to be overcome.

Glossary

CCA closed cycle absorption
CCC closed cycle compression
COP coefficient of performance
GWP global warming potential
MVR mechanical vapour recompression
NBP normal boiling point
ODP ozone depletion potential
TVR thermal vapour recompression

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