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Valorization of industrial waste heat by heat pumps based on case studies of the project EnPro

Veronika Wilk,^{a*} Bernd Windholz,^a Reinhard Jentsch,^a Thomas Fleckl,^a Jürgen Fluch,^b
Anna Grubbauer,^b Christoph Brunner,^b Daniel Lange,^c Dietrich Wertz,^c
Karl Ponweiser^c

^a AIT Austrian Institute of Technology GmbH, Giefinggasse 2, 1210 Vienna, Austria

^b AEE - Institut für Nachhaltige Technologien, Feldgasse 19, 8200 Gleisdorf, Austria

^c Vienna University of Technology, Institute for Energy Systems and Thermodynamics, Getreidemarkt 9 / E302, 1060 Vienna, Austria

Abstract

Industrial processes have great relevance to contributions to the European Union's climate targets of reducing greenhouse gas emissions by 40% and increasing energy efficiency and renewable energy by 27% by 2030. Reducing waste heat streams is an important measure to increase energy efficiency in industry. A number of processes, such as drying processes, generate humid exhaust gas streams that are currently vented without any further use. Those waste streams can be valorized by heat pumps. In this work, three case studies – a paper mill, a laundry and the production of expanded polystyrene foams – are analyzed in detail. Integration concepts to use humid gas streams as a heat source for heat pumps are developed. The concepts are evaluated by technical-economic assessment to quantify the effects in terms of energy, emissions, and cost savings. In all cases, the integration of a heat pump is an environmentally sound measure. Energy cost savings depend on the individual conditions of the case study and are often a limiting factor. Valorization of CO₂ emission reductions as it is intended in the emission trading system will have a strong positive effect on heat recovery with heat pumps.

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1. Introduction

Industrial processes consume 30 % of primary energy globally in 2014, and up to 34 % in OECD countries. As about 60 % of primary energy comes from non-renewable sources, industrial processes contribute to CO₂ emissions [1]. In 2015, more than 190 countries signed the Paris Agreement to take action to limit global warming to below 2 °C. The European Union (EU) set itself the target of reducing greenhouse gas emission by 40 % below 1990 level, increasing energy efficiency by 27 % compared to the business-as-usual scenario without action and raising the share of renewable energy to 27 % of total energy consumption by 2030.

Heat pumps and solar thermal energy supplies are important technologies to increase the share of renewable heat in industrial processes. As they contribute to the climate target, they play an important role in European guidelines as well as in national regulations (European Parliament, 2009). In ambitious scenarios energy efficiency

* Corresponding author. Tel.: +43 50550-6494; fax: +43 50550-6679.
E-mail address: veronika.wilk@ait.ac.at

measures and enhanced use of renewable energy in industry have the potential to reduce global emissions by 66 % by 2030 [2].

The integration of heat pumps and solar thermal energy in industrial processes is studied in the Austrian research project “EnPro”. A total of 12 case studies are being carried out in different sectors ranging from food, paper, metal production and processing, and laundries to the insulation industry.

The aim is to identify processes that are suitable for the integration of heat pumps and solar heat. The reduction and re-integration of waste heat streams is an essential step to increase energy efficiency in industry. Currently, as much as 20-50 % of the energy used is ultimately lost in the form of waste heat contained in exhaust gas and water streams [4].

This work focuses on processes that generate humid exhaust gas, such as paper drying or laundry processes. Heat pumps can recover a part of the condensation energy of the dissolved water and provide heat at a higher usable temperature level. Concepts using exhaust gas as a heat source for heat pumps are presented. The concepts are evaluated by technical-economic assessment to quantify the effects of renewable process heat in terms of energy, emissions and cost savings.

2. Methodology

2.1. Process analysis

To find untapped waste heat potentials, a detailed process analysis was carried out in 12 different industrial companies. The European Standard EN 16247 sets out requirements and provide guidance on how to carry out energy audits in accordance with the European Energy Efficiency Directive. Based on that standard, the energy supply and consumption of the processes was analyzed to determine the energy demand of the processes, the possibilities for process and system optimization and integration of heat pumps and solar thermal energy.

2.2. Flow sheet simulation

Flowsheet simulation was used to calculate the process parameters before and after heat pump integration. The simulation tool IPSEpro was applied, which is well suited for industrial processes. It uses an equation-oriented solver for the calculation of mass and energy balances of stationary processes.

The setup implemented in IPSEpro corresponds to the actual setup of the different processes. The units of the process (gas boiler, heat exchangers, dryers, etc.) are connected by streams that transfer mass and energy. The process units are balanced according to conservation of mass and energy. Mass and energy balances are strictly fulfilled for all process units.

For the simulation, a simplified heat pump model was developed at AIT. The model uses the temperature of the heat source and sink and a Carnot efficiency factor to calculate the power consumption, heat input and heat output of the heat pump. It is not necessary to specify the refrigerant or type of compressor in this model, so it can be used for potential assessment in a wide range of temperatures. The Carnot efficiency factor was chosen to be 0.50, because experiments with a laboratory prototype of a high temperature heat pump have shown that this factor can be expected with an optimized heat pump. [5] The main process parameters in the simulations are the temperature, humidity and mass flow of the exhaust gas that are either measured in the process or calculated with IPSEpro in a mass and energy balance. The temperature of the intended heat sink is also required.

2.3. Techno-economic analysis

The simulation results provide the basis for the techno-economic analysis. Potential reduction in CO₂ emissions, end energy and primary energy consumption are calculated by comparing the original process to the process with heat pump. In the original process, heat is supplied by steam boilers fired by natural gas. With the use of the heat pump, natural gas consumption is reduced but electricity is needed for the compressor.

The CO₂ emission factor relates the amount of CO₂ emitted into the atmosphere to the end energy available as process heat. Other greenhouse gases such as methane are also considered (CO₂ equivalent). The primary energy factor shows how much energy is needed for extraction, processing, storage, transport, conversion, transmission, and distribution to provide end energy. CO₂ emissions and primary energy consumption mainly depend on the energy carriers used for electricity generation. For this calculation, the Austrian electricity mix in 2011 was used,

of which about 52 % of electricity is supplied by renewable energy carriers (mainly hydro power). Table 1 summarizes the factors for electricity and natural gas.

Table 1: Factors for CO₂ emissions and primary energy

		Natural gas	Electricity	Ratio electricity/gas
CO ₂ equivalent emission factor	g/kWh	248	300	1.2
Primary energy factor	kWh/kWh	1.18	1.79	1.5

For economic assessment, the price ratio of electricity and natural gas is decisive. Important differences in electricity price are related to the network level. The higher the electricity demand of the industrial site, the higher is the network level, which results in lower tariffs for grid usage. A low price ratio is applicable for low network levels or if the gas price is comparably high. High price ratios relate to high electricity prices or low gas prices. As exact price information is sensitive data, the energy prices are grouped in low, medium and high ratios that are indicated in Table 2.

Table 2: Price ratios

	Ratio electricity/gas
low (low electricity price or high gas price)	1.6
medium	2.0
high (high electricity price or low gas price)	3.5

3. Tissue paper mill

3.1. Process description

The studied tissue mill produces creped soft paper, which is the basis for hygiene products such as napkins, toilet paper, and towels for households, institutions, hotels, and so on. At the production site, two paper machines produce tissue, which is converted into ready-to-sell products in a number of converting lines. Raw materials for tissue production comprise pulp and recovered paper, whereas toilet paper is made from 100 % recovered paper that is recycled on site. A paper mill typically needs energy supplies in the form of electricity, steam, and natural gas. The production site has a combined heat and power plant (CHP) consisting of two natural gas fired turbines that provide electricity. The off-gases of the gas turbines are used in a waste heat boiler to produce steam for process heat. Steam is distributed around the production site by a high pressure grid at 17 bar and a low pressure grid at 3 bar. The CHP plant also provides heat for the district heating network of the adjacent town.

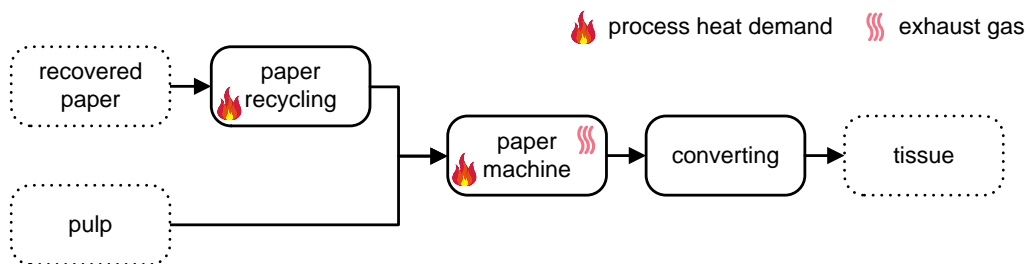


Fig. 1: Process flow diagram of tissue production with focus on thermal energy demand

Fig. 1 illustrates the most important process steps of tissue production with a focus on thermal energy demand. Process heat demand and exhaust gas streams are also indicated. Low pressure steam is used in the paper recycling step for hygienization. Most energy is consumed by tissue drying in the paper machine. In the paper machine, tissue is formed from a suspension of fibers and water. It is first dewatered mechanically on sieves and presses. The remaining moisture content is removed thermally in drying cylinders that are heated with high pressure steam

and natural gas. Moisture is evaporated and humid exhaust gas is formed. Heat recovery from the exhaust gas stream is already implemented and provides warm water for process and heating applications. After heat recovery, the exhaust gas stream has a temperature of 50 - 80 °C and is nearly saturated with water vapor. The exhaust gas stream is currently vented because there is no use for heat at this low temperature level.

3.2. Assumptions for heat pump integration

The exhaust gas from tissue drying can be used in a heat pump. Thereby, the latent heat content can also be partially recovered due to condensation. Heat provided by the heat pump is fed into the low pressure grid at temperatures of 160 °C. The heat recovery potential was assessed for the humid exhaust gas of one paper machine.

The temperature of the exhaust gas varies due to the already existing heat recovery, and thus three different situations are considered. In summer, the exhaust gas temperature is higher because less heat is recovered for heating. In winter, the lowest temperatures occur. Exhaust gas temperatures of 80, 65 and 50 °C are considered. At 65 and 50 °C, the humid exhaust gas is fully saturated after heat recovery; at 80 °C, the saturation temperature of the gas is 75 °C.

3.3. Results of heat pump integration

The heat pump further cools the exhaust gas. The outlet temperature of the gas is varied in the simulation from 78 to 30 °C. The heat output of the heat pump increases with increasing cooling of the gas. There is a steep increase when the saturation temperature is reached and latent energy can be recovered (Fig. 2, left). With increasing cooling, the temperature lift increases as well and the coefficient of performance (COP) decreases considerably (Fig. 2, right). The COP ranges from 2.6 to 1.6. The heat output of the heat pump is compared to the total thermal energy that is needed for tissue production. Depending on the initial exhaust gas temperature, up to 10 – 55 % of the thermal energy can be provided by the heat pump. If the temperature lift is high and the COP is lower than 2, more heat is provided by the compressor than is extracted from the heat source. Practical limits for the recovered heat are defined by the thermal energy demand of the process. A total of 18 % of the energy demand is currently low pressure steam; the rest is high pressure steam and natural gas that is used in burners for tissue drying. Several thresholds are also indicated in Fig. 2. If the COP has a higher value than the threshold for CO₂ emission reduction (green line) and primary energy reduction (blue line), reductions are realized. This is true for all exhaust gas temperatures. Different energy price ratios are shown as dashed lines. Energy cost reduction is possible if the COP is higher than the respective threshold (black, gray and yellow lines). Low price ratios allow for energy cost reduction in all cases. At high price ratios, the integration of a heat pump does not have economic benefits.

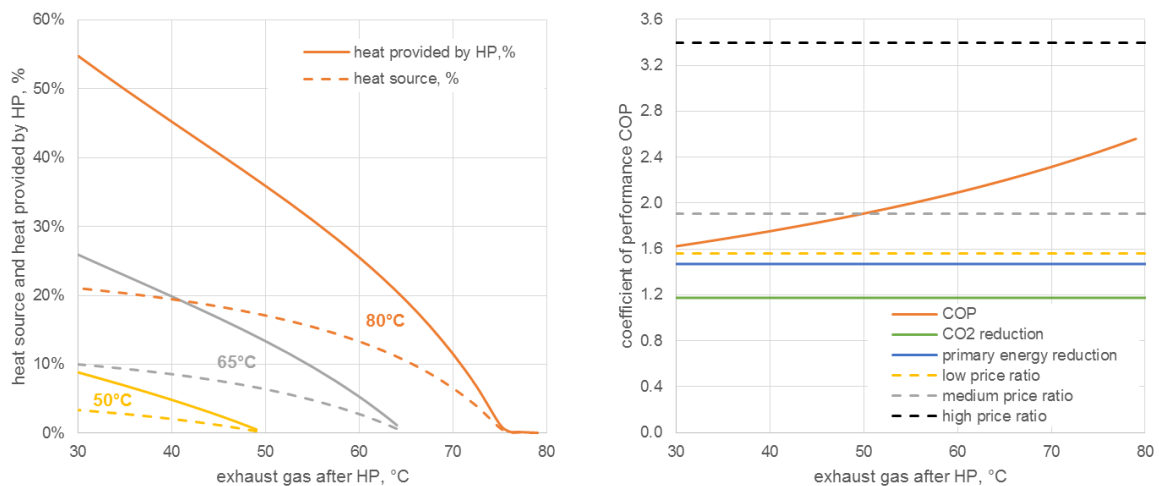


Fig. 2: Humid exhaust gas of a tissue mill as heat source for a heat pump (HP) (left: heat source and output; right: coefficient of performance (COP) and thresholds for environmental and economic benefits)

Fig. 3 provides more details on the primary energy, end energy and CO₂ emission reduction (left) and energy cost reductions (right). Compared to the existing process, the integration of a heat pump allows for energy and

emission reductions and is therefore an environmentally sound measure. The more waste heat is recovered by the heat pump, the more end energy is saved. In terms of primary energy, a maximum occurs for each case. At an exhaust gas temperature of 80 °C after heat recovery, most primary energy reduction is achieved if the exhaust gas is cooled to 50 °C. At 65 and 50 °C, the reductions are smaller, because the existing process is more efficient due to conventional heat recovery. Still, primary energy demand can be reduced by up to 11 % and CO₂ emissions by up to 7 %. For the economic assessment, the operating costs of the original process and the process with a heat pump are compared. For this industrial site, a medium price ratio applies and therefore, heat pump operation becomes uneconomic if the COP is lower than 2.0. At an exhaust gas temperature of 80 °C, a maximum reduction in energy costs of 2.5 % is achieved if the exhaust gas is cooled to 65 °C. Although environment benefits can be realized, no cost reduction occurs at exhaust gas temperatures below 50 °C. A valorization of CO₂ emission savings as intended in the EU Emission Trading Scheme (ETS) would make lower exhaust gas temperatures profitable, because there the highest CO₂ emission reduction is achieved there.

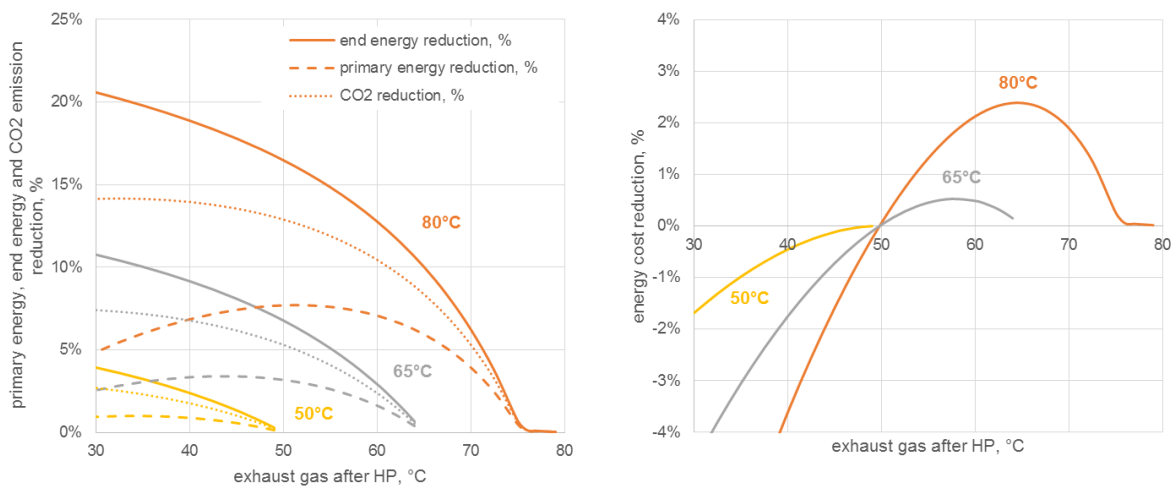


Fig. 3: Techno-environmental assessment of the heat pump (HP) (left: primary energy, end energy and CO₂ emission reduction; right: energy cost reduction)

4. Laundry

4.1. Process description

This laundry specializes in the cleaning of work wear. As illustrated in Fig. 4, dirty laundry is sorted, washed, and dried in different types of dryers. Depending on the type of fabric, gas- and steam-heated tumble dryers are used for pre-drying. In the finisher, a gas-heated tunnel dryer, the garments are made moldable by steam, straightened by hot air flow and fully dried. Pressing machines are used to iron shirts and the like. The process units are heated with natural gas and steam that is supplied by a natural gas boiler. The most important consumers of thermal energy are the washing machines, the dryers, and the finisher.

All types of dryers are used to evaporate water from garments and generate humid exhaust gas. The gas- and steam dryers for pre-drying are loaded manually and are operated in batch mode. In the steam dryer, air is heated to 160 °C in a steam heat exchanger. In the gas dryer, hot exhaust gas from the gas burner is used as the drying air. All dryers operate with circulatory air. Exhaust gas leaves the dryer at around 70 °C. Due to batch operation, the moisture content and temperature of the exhaust gas vary considerably.

By contrast, the finisher is operated continuously, as garments are moved by a conveying system through the drying tunnel. Steam is injected to prepare the garments for straightening. The subsequent drying zones are heated to 130 - 150 °C with gas burners operated with circulatory air. Saturated air leaves the dryer and is replaced by fresh air. The exhaust air has a temperature of about 40 - 80 °C and is currently vented without further use.

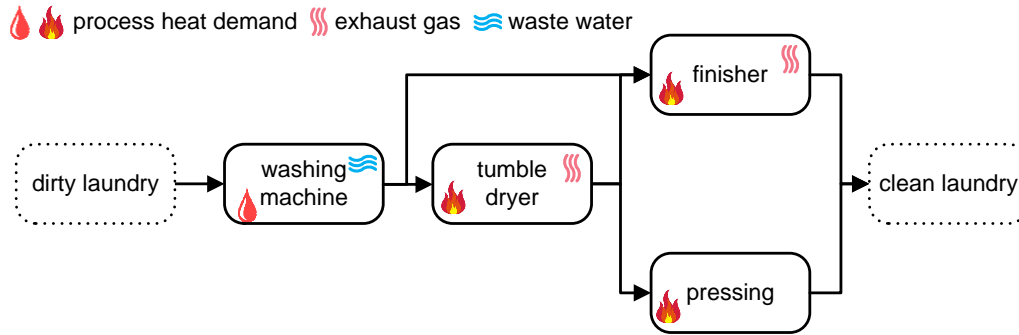


Fig. 4: Process flow diagram of tissue production with a focus on thermal energy demand

4.2. Assumptions for heat pump integration

A heat pump that uses the exhaust air of the finisher as its heat source can be used to preheat the boiler feed water or to provide low pressure steam. The steam boiler is an interesting heat sink, because about 40 % of the steam is consumed in the processes and is replaced by fresh water. Preheating of the boiler feed water also increases the efficiency of the steam boiler. Low pressure steam could be used in the finisher and in other pressing machines.

The finisher is equipped with two exhaust pipes, one in the front and one at the end of the tunnel. At the front, the air contains more moisture but has a lower temperature. At the end, the moisture content is lower but the temperature is higher. To assess the potential, a mixture of both gas streams is used in the simulation. The gas mixture has a temperature of 60 °C and the dew point is 49 °C. In the simulation, the exhaust gas is cooled to 52 – 30 °C.

4.3. Results of heat pump integration

Once the dew point is passed, heat output increases rapidly due to condensation. Fig. 5 illustrates how much heat is provided compared to the total energy demand to treat a ton of laundry for the two heat sinks, low pressure steam at 142 °C and hot water for the boiler at 80 °C. The heat output covers 33 % of the total thermal energy demand in the case of low pressure steam and up to 21 % in the case of hot water. The applicable amount of heat recovery is limited by the specific requirements of low pressure steam for dryers, pressing machines and space heating, which can be up to 25 % of the total thermal energy demand of the laundry. The rest requires steam with higher pressure. Feed water preheating amounts to 3 % of the thermal energy demand.

Fig. 5 also shows the influence of the temperature lift. If low pressure steam is produced, significantly more heat is provided, especially at low exhaust gas temperatures, because of the increasing share of compressor work. The COP for steam production ranges from 2.1 to 1.6. By contrast, the production of hot water is considerably more efficient with a COP in the range of 4.7 to 3.0. The thresholds in Fig. 5 show that CO₂ and primary energy reductions are achieved in all cases. As Fig. 6 (left) shows, heat recovery from the finisher exhaust gas has positive effects on the environment in all cases, because up to 6 – 12 % of the primary energy can be saved. A total of 12 – 14 % of the current CO₂ emissions can be avoided. For the economic assessment, a high price ratio of 3.5 was applied. According to the thresholds in Fig. 5, only hot water production is profitable. Maximum savings occur at an exhaust gas temperature of 43 °C (Fig. 6, right)

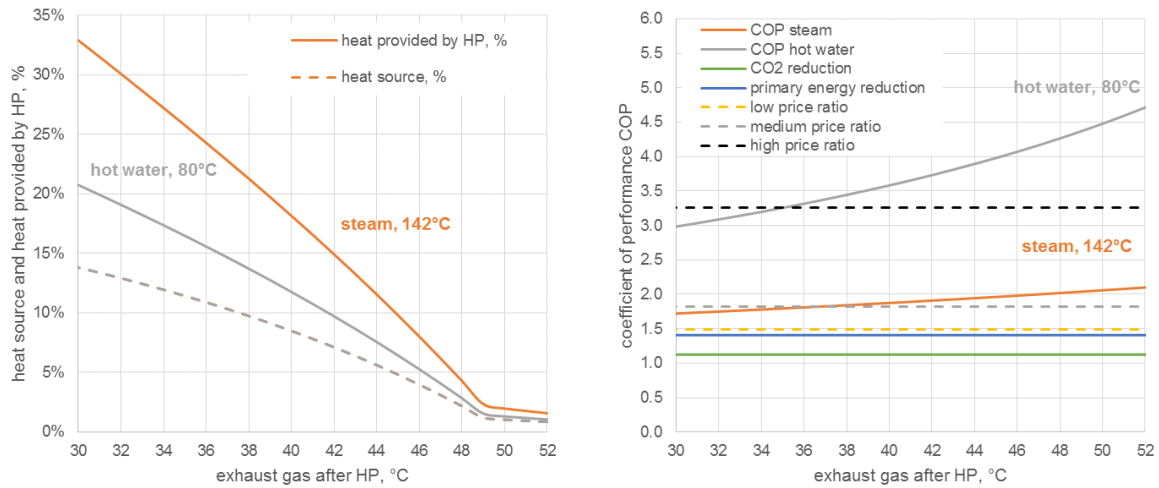


Fig. 5: Humid exhaust gas of a laundry finisher as the heat source for a heat pump (HP) (left: heat source and output; right: coefficient of performance (COP) and thresholds for environmental and economic benefits)

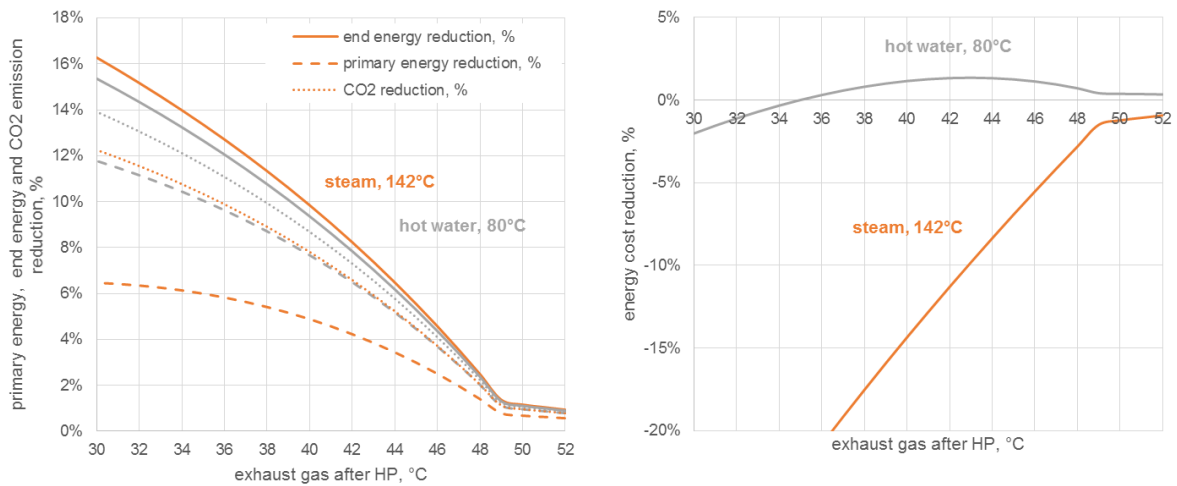


Fig. 6: Techno-environmental assessment of the heat pump (HP) (left: primary energy, end energy, and CO₂ emission reduction; right: energy cost reduction)

5. Production of foams

5.1. Process description

The analyzed company belongs to the insulation and foam-processing industry and has its primary focus on the production of foam insulation made from expanded polystyrene (EPS). In general, the production of EPS consists of three steps [6], as illustrated in Fig. 7.

The raw material fed to the pre-expansion process is sphere-shaped expandable polystyrene beads that already carry the blowing agent pentane. During the pre-expansion process, expandable polystyrene beads are heated in the so called pre-foamer above the boiling temperature of the blowing agent, which leads to the expansion of the beads by a factor 40 to 50 [6]. The thermal energy needed for the pre-expansion processes is delivered by steam at a pressure of approximately 1 bar. The EPS beads leave the pre-expansion process in a state of low mechanical strength due to an internal vacuum inside the beads caused by the rapid expansion. Therefore, it is necessary to allow the expanded polystyrene beads to harmonize their internal pressure with the atmospheric pressure via means of air diffusion into the beads. This is carried out during the second process step, the maturing. In addition to mechanical stabilization of the EPS beads the maturing process is also necessary to decrease the amount of water carried inside the beads, which reduces the energy demand in the third process step, the final foaming or molding.

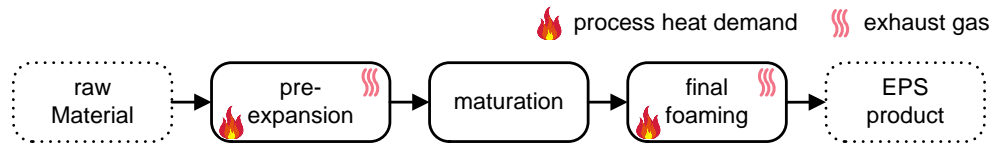


Fig. 7: Basic EPS manufacturing process steps

Depending on the type of molding machine the molding process can be either continuous or discontinuous. In this case study, the molding process is carried out with discontinuous vacuum-supported block molds. The molding process in general consists of a number of predefined cycles (filling, steaming, cooling, and demolding) [7], whose parameters vary with the desired product attributes. At the end of the production process, the finished EPS block is ejected from the mold and temporarily stored for drying purposes until it reaches the desired humidity. In a last step, the EPS block can be cut into tiles, for example, with hotwire equipment.

5.2. Assumptions for heat pump integration

The EPS production process has several waste heat streams that can be used as a source for heat pump cycles if they are not yet integrated for the purpose of heat recovery. Examples of such waste heat streams identified in the case study are:

- Humid gas released to the atmosphere during the filling cycle of the block mold at 90 °C.
- Humid gas released to the atmosphere via the vacuum pump at 57 °C.
- Thermal energy to be withdrawn from the condenser of the vacuum tank at 60 °C.

These waste heat streams have a significant advantage when they are used as a source for a heat pump cycle that can deliver steam at the desired pressure level of the molding process. They occur at the same time as the steam demand and are therefore easy to integrate in the production process.

5.3. Results of heat pump integration

In the simulation, the heat pump produces low pressure steam at 1.8 bar and 120 °C from three different sources. As shown in Fig. 8, most energy can be recovered from the condenser, which is kept constantly at 60 °C. The amount of steam produced by the condenser exceeds the steam demand that is needed to produce one block. The gas streams of the filling pump and vacuum pump contain a very high amount of moisture and are close to saturation. In the simulation, they are cooled by the heat pump to various temperatures ranging from 90 to 30 °C. Due to condensation, a steep increase in heat output occurs. Considerably more energy can be recovered from the filling pump than from the vacuum pump because of the higher temperature and moisture content. The gas stream of the filling pump provides up to 40 % of the steam to produce one block. If all heat sources are used, up to 150 % of the steam for one block can be provided. The COP ranges from 5.5 to 2.1 for the gas streams. A COP of 3.1 is reached for the condenser. In all cases, reductions in CO₂ emission and primary energy are realized. The highest primary energy reduction can be achieved for the filling pump if the gas stream is cooled to 60 °C. CO₂ emission reduction amounts to 70 % for the condenser and up to 20 % for the filling pump (Fig. 9).

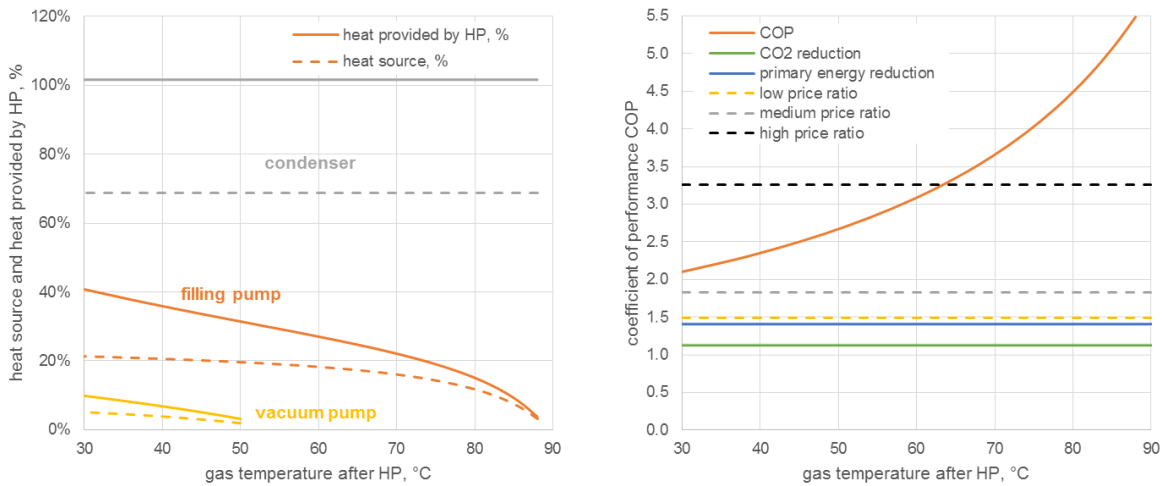


Fig. 8: Different gas streams of EPS production as heat source for a heat pump (HP) (left: heat source and output; right: coefficient of performance (COP) and thresholds for environmental and economic benefits)

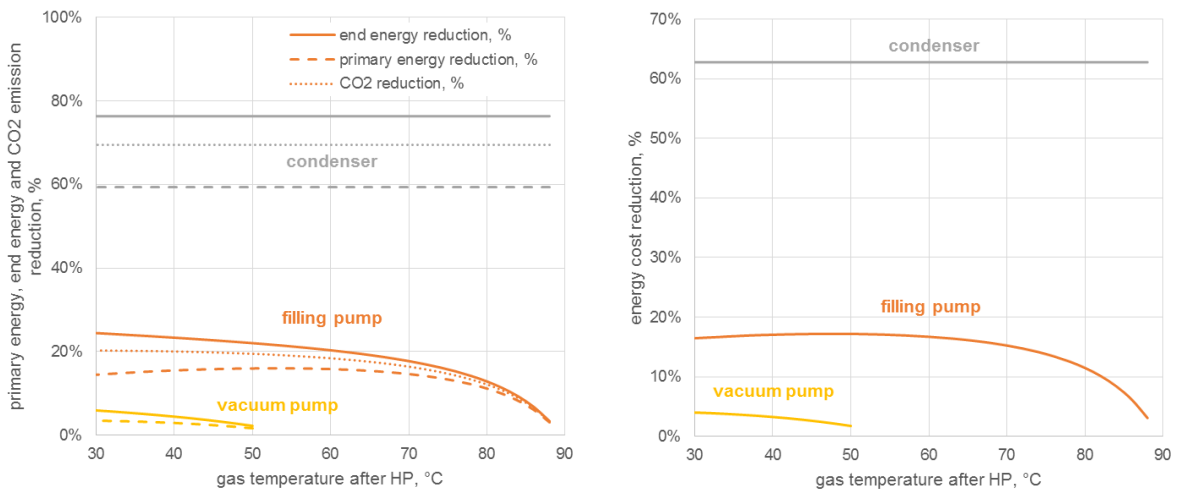


Fig. 9: Techno-environmental assessment of a heat pump (HP) (left: primary energy, end energy, and CO₂ emission reduction; right: energy cost reduction)

The price ratio for this industrial site is low, and therefore substantial cost reductions can be realized with the integration of a heat pump. According to the threshold in Fig. 8, all cases result in energy cost reduction. Use of waste heat in the condenser reduces the energy costs by 63 %. The most economic use of the gas stream from the filling pump is to cool it to 48 °C, where costs can be reduced by 17 %.

6. Conclusions and outlook

The case studies show that humid exhaust gas streams carry a significant amount of energy that is currently not used. To realize the full potential of these streams, it is important to cool them below the dew point temperature so that condensation starts. Thereby, a part of the condensation energy of the dissolved water can be recovered. Usually, these temperatures are too low to use the gas streams in heat exchangers. Heat pumps allow for valorization of the gas streams, because they can provide heat at a higher temperature level, such as low pressure steam or hot water.

For a successful integration of a heat pump, suitable heat sinks are required. The case study of the laundry shows that the humid exhaust gas of the finisher can be used in an efficient way to provide hot water. Although the production of low pressure steam has environmental benefits such as reductions of primary energy and CO₂ emission, energy costs would increase if the heat pump was used.

In the paper mill, the heat pump can be integrated into the low pressure steam grid. Thus, less high pressure steam has to be produced in the power plant, reducing the demand for natural gas. The COP is lower if more energy is recovered from the gas stream. Again, there are different optimal solutions for how to operate the heat pump. If CO₂ emission reduction needs to be maximized, the heat pump cools the gas stream to 30 °C. For economic operation, cooling is limited to 50 °C, otherwise the energy cost would increase. The valorization of CO₂ emission reduction is therefore an important measure to increase the attractiveness of efficiency measures such as heat pumps. Another practical limitation is the temperature of the low pressure steam grid, which amounts to 160 °C. Currently, heat pumps available on the market reach 120 °C. Higher temperatures of up to 160° have been realized in prototypes and laboratory facilities and are expected to enter the market in the next years.

The most promising case study is the EPS factory. Due to comparably warm heat sources, the integration of the heat pump is very efficient. As the price ratio is low, the heat pump also allows for significant energy cost reduction. The required temperature of 120 °C can be realized with heat pumps available on the market.

Recovery of humid exhaust gases is a promising field of application for heat pumps. The reduction and re-integration of waste heat streams is an essential step to increase energy efficiency in industry, which is an important step in reaching national and international climate targets.

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