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LEAP

Low Pressure Steam Heat Pump

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2 Introduction

Energy and resource efficiency are becoming increasingly important for industry to comply with strategic environmental goals, enforced legal obligations and increasing cost pressure. Therefore, reduction of CO_2 emissions and energy consumption, as well as an increasing share of electrified processes to use more renewable energy are important drivers for investment decisions.

Heat pumps for industrial applications are a central element in the future energy infrastructure and can make an important contribution to increasing the efficiency of industrial processes and avoiding CO_2 emissions. The integration of heat pumps in industrial processes is often complex, as they are usually integrated into existing processes. The heat pump must be designed according to the existing infrastructure such as other heat supply equipment, storage tanks and process heat consumers. Other requirements of the process, such as intermittent heat demand, batch processes or waste heat in contaminated media must be considered for the integration of the heat pump. Therefore, process integration is of great importance and decides on the efficiency and economic performance of the heat pump.

However, all over the world, industrial processes are still producing large amounts of low temperature waste heat in the form of exhaust gases and wastewater. Due to the low temperature level, these waste heat streams can no longer be used in an efficient way and are emitted. Compression heat pumps allow for efficient waste heat recovery, upgrading waste heat to higher temperature by using electricity.

2.1 Task

Steam is one very important energy carrier in industry and is usually provided with boilers fired with natural gas or other fossil resources. Compared to hot water, steam is characterized by higher heat transfer through condensation and higher energy density. Although further developments of industrial heat pumps towards new applications, higher temperatures and capacities, and innovative research activities, industrial heat pumps and especially steam-generating heat pumps are still in an early phase of diffusion in Austria but also in industry in general. Despite the potential for final energy[1] savings and decarbonization, there is no heat pump for steam supply in operation in Austria so far (status 01/2024). The results of LEAP are intended to support the integration of steam-generating heat pumps in industry.

2.2 Focal points of the project

LEAP addresses the need of waste heat recovery by using heat pumps for low pressure steam generation. By using waste heat and electrical energy, heat pumps are a future-proof heat supply system not depending on fossil energy sources. In LEAP it was intended that the final energy efficiency of steam supply is increased by final energy savings up to 64% with heat pumps compared to the combustion of natural gas. CO_2 emissions will be significantly reduced (-66%), as will energy costs, especially by considering CO_2 prices (up to 22%).

[1] In this document the definition of the Umweltbundesamt [1] for final energy and primary energy is used.

The integration of heat pump systems for low-pressure steam supply is investigated in detail based on the industrial processes of the two industrial partners Lenzing AG (LAG) and Austrotherm GmbH (AAT).
For this purpose, possible integration points for each industrial partner are identified and the most promising ones are selected for more further analysis toward a potential demonstrator. The investigations will also provide the basis for upscaling in order to exploit the full waste heat potential at the industrial sites under consideration. Furthermore, the investigations in the LEAP project should provide the basis for the development of new business models.

The heat pump has the potential to be key technology for the decarbonization of Austrian industry. The findings from the LEAP project will be used to identify the framework conditions and economic requirements for promoting the integration of steam-generating heat pumps in existing industrial processes.
The goals of the LEAP project can be summarized as follows:

- Investigations on the integration of two steam-generating heat pumps, one each at LAG and AAT
- Assessment of a significant reduction in CO_2 emissions
- Conceptualization of a future-proof process heat supply with energy cost reduction
- Scaling of the heat pump concept to utilize the waste heat potential of LAG and AAT
- Contribution to the diffusion of industrial heat pumps and creating a basis for the development of new business models.

2.3 Structure of the work and methods used

The project was structured to consider the four aspects shown in Figure 1.

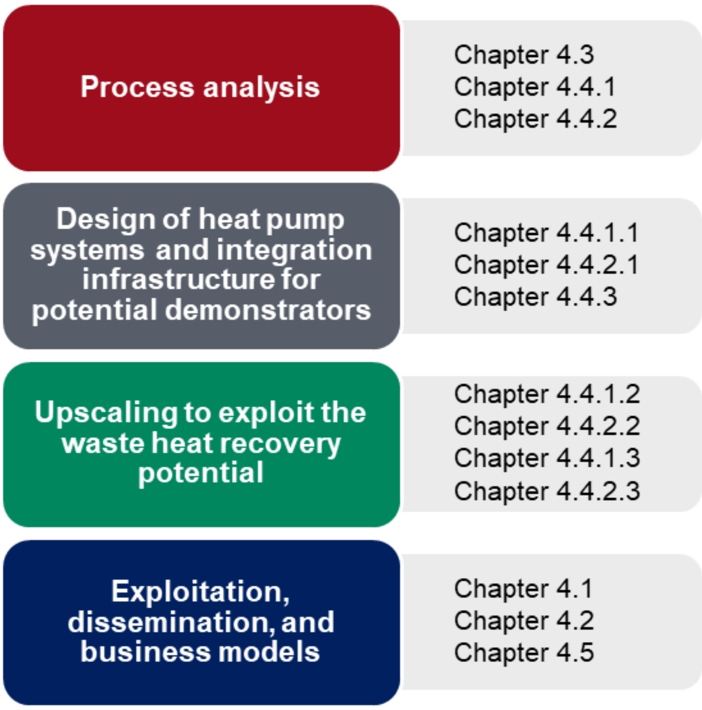


Figure 1: Structure of work.

Furthermore, the methods used for the investigations are described below for the respective aspect considered in the project:

- **Process analysis:** Data (for example measurements) and information collection of promising sources and sinks for a potential demonstrator and selection of integration points for this demonstrator based on various decision criteria. Development of a general description for the procedure to evaluate heat pump integration points. Modelling and simulation for example of different heat pump configurations.
- **Design of heat pump systems and integration infrastructure:** Preparing and sending out manufacturer enquiry documents. Discussions with heat pump manufacturers. Requesting and evaluating offers. Studies on integration infrastructure, for example with system planners (Basic Engineering). Techno-economic analysis of the potential heat pump demonstrator.
- **Upscaling to exploit the waste heat recovery potential:** Update information and data for available source and sinks. Definition of a full-scale scenario in coordination with the industrial partners. Depending on the industry partner, calculation of the efficiency of the heat pump system based on manufacturer information, modeling and simulation. Techno-economic analysis of the full-scale scenario based on selected criteria, energy savings, primary energy savings, CO_2 emission savings, payback period, net present value for various reference cases.
- **Exploitation, dissemination and business models:** Presentation of project and results at various events and NEFI Homepage. Provision of content for NEFI social media posts. Stakeholder analysis based on an end-user survey which was distributed via social media channel and a newsletter. The results were analyzed, processed, summarized, and sent to the survey participants. Collection, analysis, and processing of information on the steam-generating heat pump market. Sensitivity analysis to investigate advantageous framework conditions for the integration of steam-generating heat pumps. Basic assessment of the topic’s economy of scale and business models.

2.4 Consortium

The consortium consists of the non-university research institution **AIT Austrian Institute of Technology GmbH** (**AIT**), the business agency of the Upper Austrian government **Business Upper Austria - OÖ Wirtschaftsagentur GmbH** (**BIZ-UP**) and two industrial partners, **Lenzing AG** (**LAG**) and **Austrotherm GmbH** (**AAT**).

LAG produces high-quality fibers from wood with environmentally friendly and innovative technologies. As dissolving wood pulp and fiber production are energy-intensive processes, energy use, climate change, and air emissions are a priority for **LAG**.

AAT is a company specialized in the production of high-quality and future-oriented thermal and acoustic insulation with 26 production sites worldwide (two in Austria). **AAT**’s products contribute significantly to the reduction of CO_2 emissions of buildings. Energy efficiency, environmental protection and waste avoidance are also of utmost importance in their production facilities.

2.5 Placement in the programme

LEAP is part of the NEFI innovation network. NEFI develops solution for climate neutral industry and aims to secure industrial and economic location in Austria by technology made in Austria.
LEAP contributes to all three superior NEFI goals by addressing the innovation fields Energy Efficiency & New Processes as well as New Business Models.
Innovation Field *Energy Efficiency & New Processes*: Heat pump systems are a valuable efficiency technology for industrial waste heat recovery. Since the required energy for steam production will be reduced compared to natural gas, the dissemination and identification of necessary framework conditions for the economically advantageous integration of this technology is an important milestone towards the 100% decarbonization goal of NEFI; further, steam is one very important energy carrier in industrial processes, therefore, this innovation is easily transferable to other industrial processes and sectors.
Innovation Field *New Business Models*: The investigation of steam-generating heat pump systems for two industrial processes as well as the investigation of the influence of different framework conditions for economic integration and operation is the basis for new business models.
The results of the project and their dissemination are intended to contribute to the NEFI objectives Value Creation Through Technology Made in Austria and Securing Production Sites and Jobs Through User Integration.

3 Content presentation

The results of the LEAP project are intended to drive forward the distribution of heat pumps and, in particular, steam-generating heat pumps in industrial processes. At the beginning of the project, the end users were identified as the main stakeholders, although the results of the LEAP project can also be useful for funding bodies, legislators, heat pump manufacturers, system manufacturers and consulting companies. For stakeholder analysis, an online end-user survey was created and distributed via social media channels and by a newsletter. The survey consists of 26 questions, asking for general data such as the size of the company and the industrial sector to which the company belongs, as well as questions on the general attitude towards heat pumps and the importance of various technical and economic criteria. Energy-specific and process-specific information was also requested, such as the current energy source for steam generation and the temperature level of the waste heat source and the steam required, as well as the annual energy consumption. Moreover, a market overview of heat pumps for steam generation was prepared based on the information published in the course of the IEA HPT Annex 58 Task 1-Technologies [2]. Also, information from this and other projects has been included.

In the course of the project, it became clear that for the evaluation of an integration point it is important to develop an understanding of how the efficiency of a heat pump can be estimated. With the efficiency of the heat pump, ecological parameters such as CO_2 and energy savings and economic parameters such as operating cost savings and payback time can be determined. A general description of the procedure for evaluating heat pump integration points was developed. The aim of this procedure is to obtain an initial estimate of the potential and the associated costs. Only individual integration points are considered here, assuming that it has already been established that the source cannot be used for direct heat recovery.

The investigated procedure only refers to individual integration points that have already been identified; it does not include a site-wide consideration such as Pinch analysis, nor does it include cost optimization of possible integration variants. Another aspect that is not included in the consideration is the evaluation of the temporal behavior of source and sink flows. This can be particularly important for example regarding any necessary application of thermal storages.

Promising integration points for a potential steam-generating heat pump demonstrator were identified at both industrial partners. Based on the prior knowledge of the industry partners and with the support of the research partner, possible integration points were selected and information on these was collected so that an analyzation and selection based on different decision criteria could be made. Manufacturer inquiries were sent out and the demonstrators were evaluated. The required integration infrastructure was also examined in more detail.

In addition, for both industrial partners upscaling scenarios were investigated. For the industrial partner LAG the focus is on utilizing all waste heat sources at a site as much as possible. For industry partner AAT, the supply of several identical expanded polystyrene (EPS) production processes is considered, for example at one site, but a Europe-wide scenario was also evaluated.

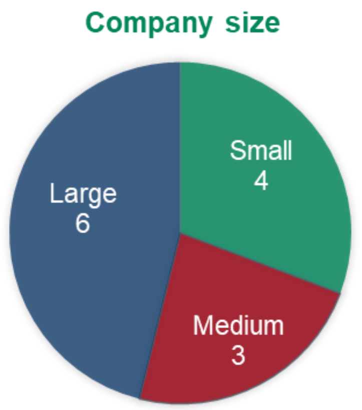
Moreover, sensitivity analyses were carried out to investigate the influence of various factors on the payback period of a heat pump system. The factors CO_2 price, gas price, electricity price, investment costs and operating hours were varied. The results of this study provide an indication of the framework conditions that incentive heat pump system integration. It was also discussed whether economies of scale will occur in the future for heat pumps for industrial applications and thus bring economic benefits.
Likewise, various business models were considered that could be used for heat pumps and in particular steam-generating heat pumps and their advantages such as risk minimization for the end user were highlighted.

4 Results and conclusions

In the following, the main publishable results of the LEAP project are presented, according to a structure based on the description in Chapter 3.

4.1 End-user survey

In total, the survey was completed by 13 participants from eight different industrial sectors between February 2022 and May 2022. Figure 2 shows the breakdown of participants by company size (Large, Medium, Small) and industry sector (paper, pulp and print, iron and steel, food, tabacco and beverages, non-metallic minerals, construction, chemical and petrochemical industry, textile and leather, and non-specified industry). Most of the participants were from large companies (number of employees ≥ 250, sales ≥ 50 million €). Four participants stated that they were from small companies (number of employees < 50, sales < 10 million €). Moreover, a maximum of two participants came from the same industry sector (paper, pulp and print, food, tabacco and beverages, non-metallic minerals, chemical and petrochemical industry, and non-specified industry).



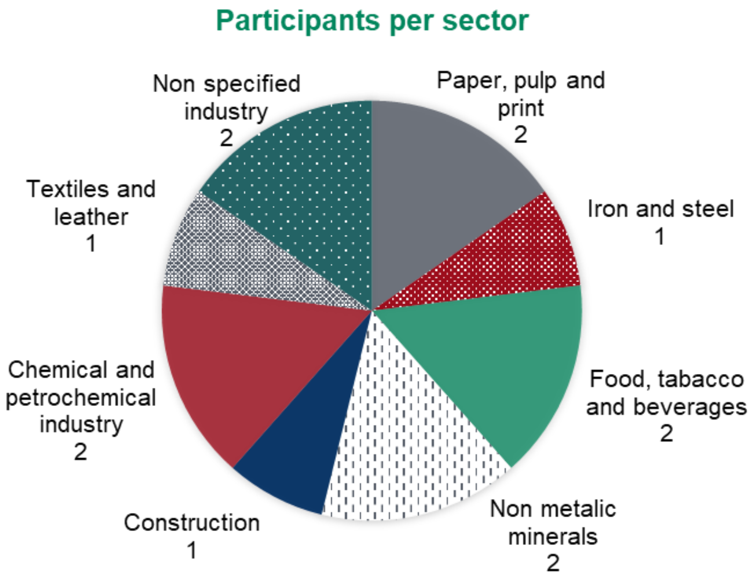


Figure 2: Presentation of participants in terms of company size and industry sector.

All 13 participants stated that energy consumption and the associated energy costs were very important to the company (≥ four points). It became apparent that many information sources were used for new relevant energy efficiency technologies, which are listed below. The list contains suggested information sources and those indicated by the participants. However, "Attendance at trade fairs and conferences" was chosen the most.

- Attendance at trade fairs and conferences
- Internal energy manager
- External consultant
- System supplier
- Energy consulting by the federal state bureau
- Universities
- Direct contact from supplier
- Professional publication
- Various newsletters

The survey also revealed that two of the participants already had an industrial heat pump. Five participants stated that they had already thought about using industrial heat pumps but were currently not using any. Further five participants had not thought about it but indicated that it could be interesting.

The most important driver for investing in energy-efficient heating and cooling technologies were the sustainability goals of the company itself, besides direct cost savings. One participant stated customer expectations were the most important motive for investing in energy-efficient technologies and three stated

"Cost of emission certificates" as the most important motive. In total five companies indicated that they are part of the emission trading system (ETS).

Figure 3 deals with the technical hurdles for investing in the steam-generating heat pump technology. The participants were able to rate the aspects shown in Figure 3 with points from 1 to 5 (1...low impact, 5…high impact). The most important arguments against the installation were the temperature level and the risk for production safety. Space requirement played a very important role for some participants, for others it was less important. Few practical examples and the need for external know how for the process integration were also important for some of the participants.

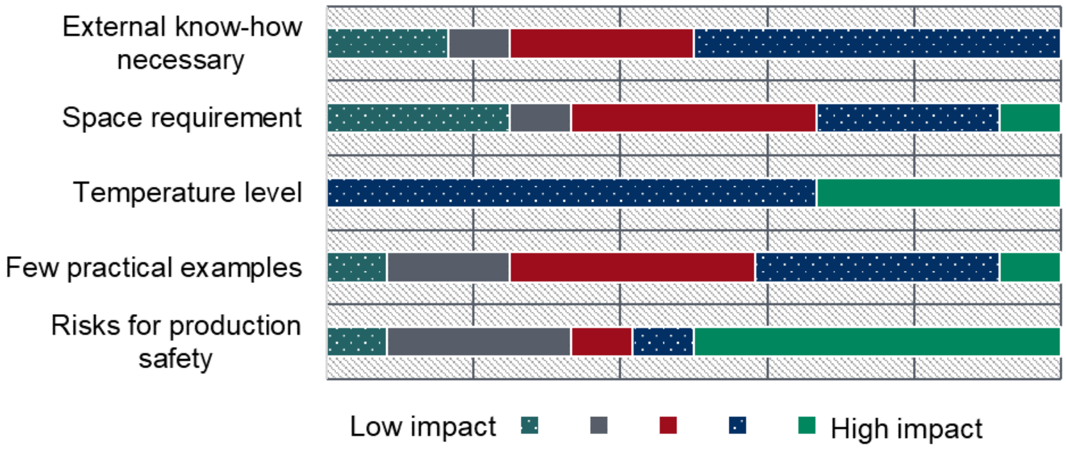


Figure 3: Technical impact on the decision to integrate a new steam-generating heat pump technology.

The evaluation of economic impacts on the decision to integrate a new steam-generating heat pump is shown in Figure 4. Also here, the participants were able to rate the aspects shown in Figure 4 with points from 1 to 5 (1...low impact, 5…high impact). It can be clearly seen that both the high investment costs and the long payback periods were the most important hurdles for implementation. Lack of subsidies and lack of information were rather of medium importance. A question was asked how long the payback period was allowed to be. Two participants stated that the payback period should be less than 3 years. Five chose less than 6 years and another five less than 10 years.

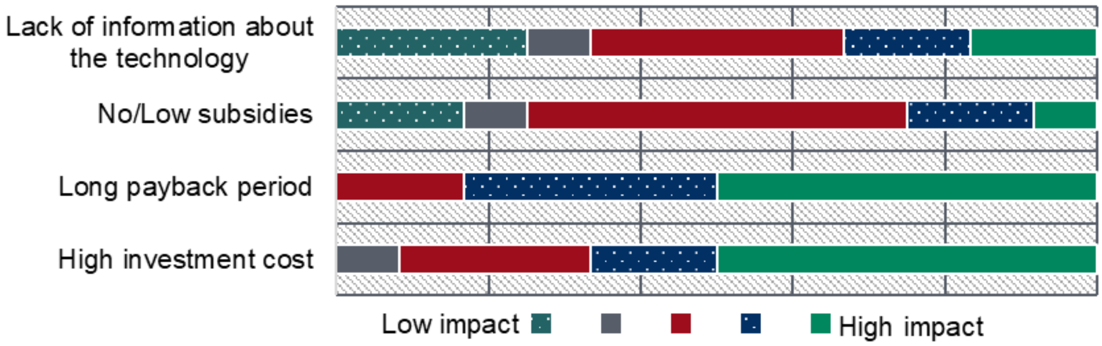


Figure 4: Economic impact on the decision to integrate a new steam-generating heat pump technology.

Moreover, the following hurdles were mentioned by the participants:

- Lack of suppliers
- Electricity price uncertainty
- Availability, cost, security
- Hardly any full-range suppliers (heat pump manufacturers sell their pumps, but no heat exchangers, no "packages")
- Too little experience and information
- Economy and efficiency
- New "young" technology

The survey showed that the participants' process heat demand was higher than their electrical energy demand. The electrical energy demand was mainly covered by grid supply (conventional or green electricity). In addition, the share of steam generation in relation to the energy demand for process heat generation was asked. On the basis of this information and the energy demand for process heat generation taken from Statistik Austria data [3] for the corresponding industrial sectors (approx. 33 TWh) the steam demand of seven sectors (approx. 13 TWh) could be calculated. In the case of multiple answers for one sector, the mean value for steam demand share was used. The result is shown in Figure 5.

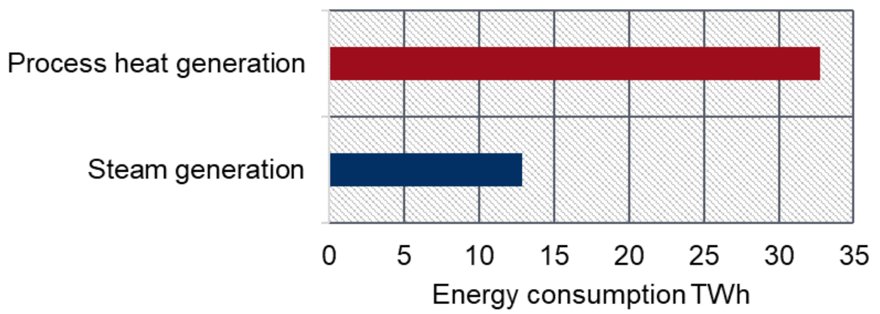


Figure 5: Steam demand compared to the total process heat demand based on [3].

The steam demand was currently mainly covered by natural gas combustion and the required steam temperature was mainly between 120-140°C and above 160°C. In addition, 50% of the participants indicated that they needed saturated steam. Also approx. 50% stated the steam demand was continuous. The steam requirement in the temperature range up to 120°C was comparatively low. It also showed that unused waste heat sources existed at various temperature levels. Figure 6 shows the useable waste heat sources selected by the participants. The most participants selected exhaust gas/air >100°C and compressed air generation as available waste heat source. Furthermore, a question showed that the steam demand was generally higher or comparable to the waste heat generated.

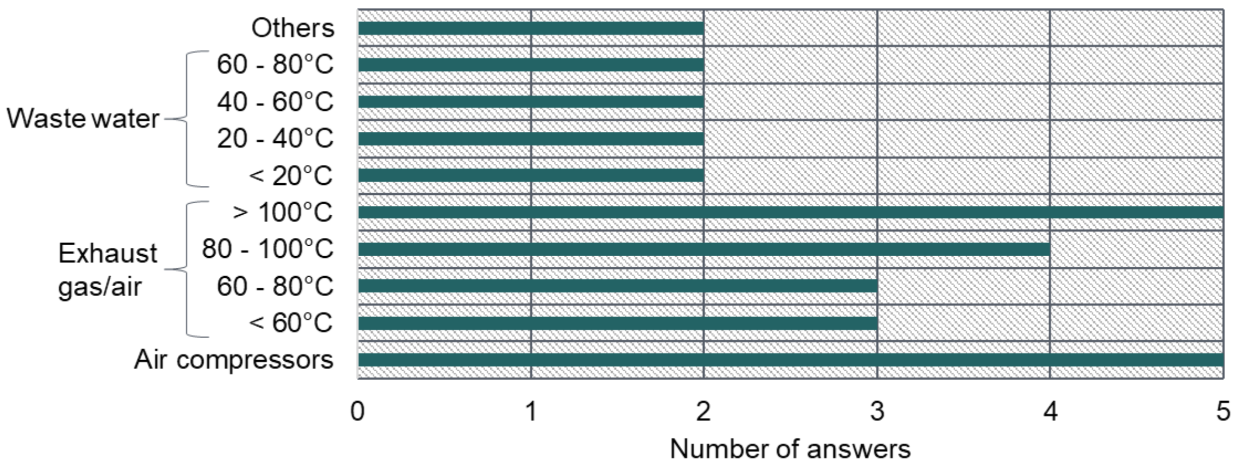


Figure 6: Usable waste heat sources selected by participants.

4.2 Steam-generating heat pump market

Basically, three types of steam-generating heat pump technologies can be distinguished: Direct steam-generating heat pumps, heat pumps with a steam-generating unit and steam compressors.
Direct steam-generating heat pumps (closed loop vapor compression heat pump) are characterized by the integration of a steam-generating condenser (e. g. plate-and-shell heat exchanger) into the refrigerant cycle. This means that the refrigerant condenses on one side of the heat exchanger while the water evaporates on the other side.
Heat pumps with a steam-generating unit means that common water-to-water high-temperature heat pumps are coupled with a steam generation unit (e.g., flash tank). Steam compressors also called mechanical vapor recompression (MVR) or mechanical vapor compression (MVC), is an energy-efficient way of raising steam to a higher pressure and temperature level. Moreover, other steam-generating components (heat exchanger, direct steam-generating heat pumps or heat pumps with steam-generating unit) can be combined with steam compressors.

The following explanations are mainly based on the assessment of information published as part of the IEA HPT Annex 58 Task 1-Technologies [2]. At the time the analysis was carried out, 13 manufacturers supplying complete steam-generating heat pump systems were identified. These manufacturers include one that does not sell its products in Europe. Furthermore, the products differ in their basic principles (subcritical compression heat pump, Stirling heat pump, absorption heat transformer), their configuration (e.g., direct steam-generating heat pumps or heat pumps with steam-generating unit) and their range of application (temperature range and capacity). The maximum supply temperature specified by one manufacturer is 250°C. Eight manufacturers specify a maximum supply temperature below or equal to 160°C. The manufacturers' products also differ in the temperature application range on the source side of the heat pump, although this is not known for all manufacturers. Two manufacturers specify a maximum source temperature above 100°C the remaining manufacturers for whom the source temperature range is known defined a maximum source temperature below 100°C. Depending on the product, the source must

also exceed a minimum temperature. The heat capacities of the heat pump products are between 0.03 MW and 80 MW. The technology readiness levels (TRLs) are specified between 5 and 9.
Heat pumps for hot water generation above 100°C are also available on the market. However, as already mentioned, these must be combined with a steam-generating unit. For steam compressors, eight manufacturers were identified that only have steam compressors in their product portfolio.

4.3 Procedure for assessment of heat pump integration

The procedure to assess heat pump integration points is shown in Figure 7. Moreover, it is also planned to publish the procedure as a guideline.
The first step is determining waste heat potential and process heat demand. Therefore, the source (waste heat) and sink parameters such as temperature and mass flow must be defined. In general, the sink outlet temperature corresponds to the temperature required by the process. For steam-generating heat pumps, this is the phase change temperature at the required steam pressure (for saturated steam). The sink inlet temperature corresponds to the feed water temperature. If the waste heat potential and the process demand are known, the efficiency of possible heat pump solutions can be determined.

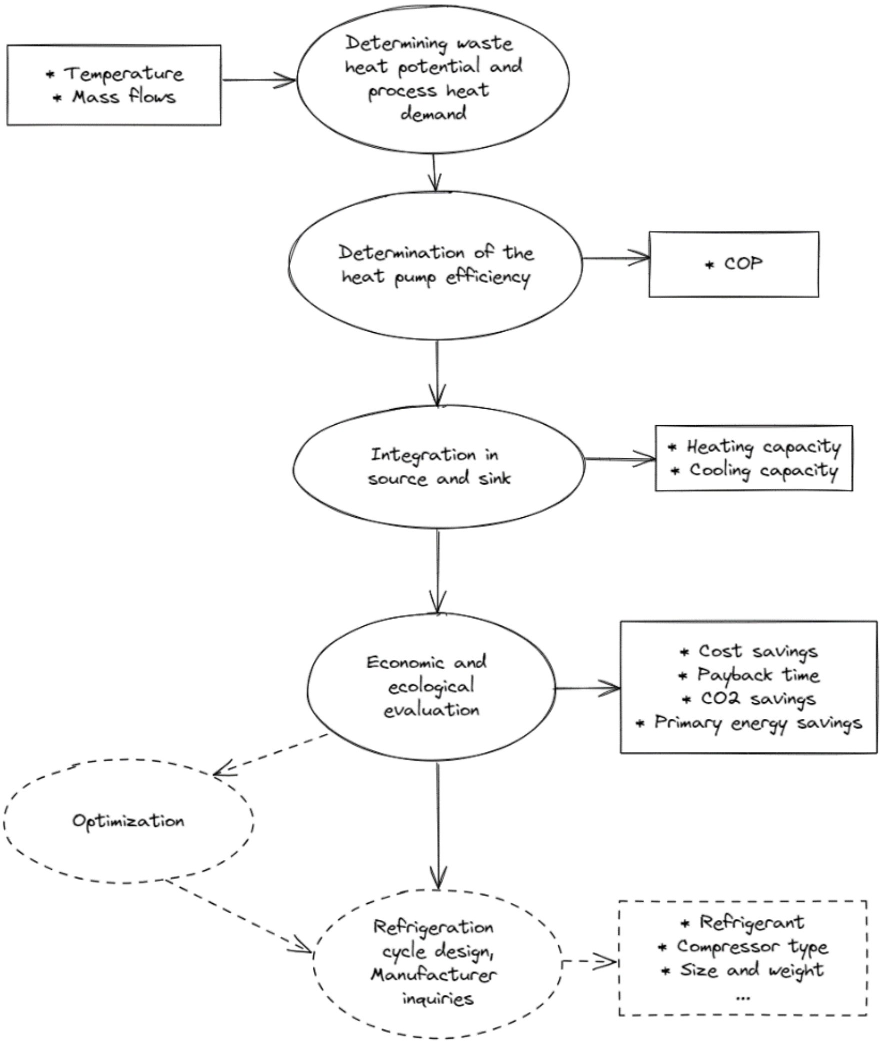


Figure 7: Procedure for the assessment of integration points.

The coefficient of performance (COP) describes the efficiency of the heat pump and is defined by the ratio of benefit to effort. In a system without cooling requirements, the COP corresponds to the ratio of the heat capacity to the electrical power consumption of the compressor. A COP that refers to the ideal reference process, the Carnot process, can be calculated using the source and sink outlet temperatures. It is related to the COP of the real process via the second law efficiency is usually in the range 0.4 - 0.55.

The effect of the integration on the source and the sink can be determined in the next step. If the COP of the heat pump is known, the electrical power demand and the possible heat capacity can be determined using the source potential (neglecting losses). The energy balance of a heat pump is shown in Figure 8 (neglecting losses). If the heat capacity is less than the heat demand, only part of this demand can be covered by the source capacity (cooling capacity) under consideration. If the heat capacity is greater than the demand, the new required electrical power demand and the required source capacity (cooling capacity) can be calculated by equalizing the heat capacity of the heat pump with the heat demand. Reduced capacity utilization of the source can be achieved either by reducing the source mass flow or by cooling the source less. There is potential for optimization here. If the source is cooled down less, the COP can be increased by reducing the required temperature lift.

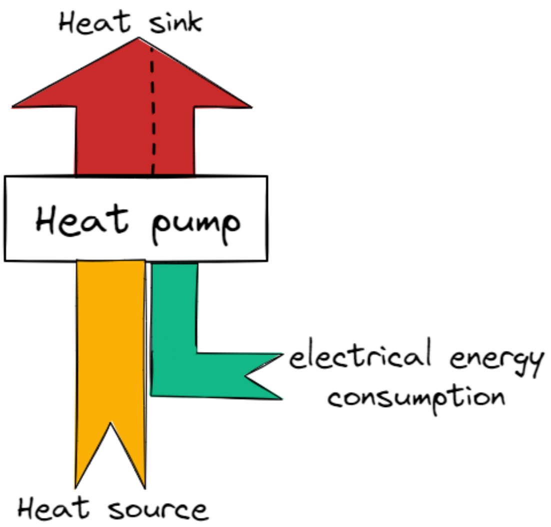


Figure 8: Energy balance of a heat pump.

The next step is the ecological and economic evaluation of the heat pump system. The basis for the economic and ecological assessment is the final energy saved by using waste heat with a heat pump compared to a reference process. The operating hours are also crucial for the overall assessment. The most important ecological factors are the primary energy savings and the reduction in CO_2 emissions. For this purpose, the electrical consumption of the heat pump and the final energy consumption of the comparison process are multiplied by corresponding (primary energy or emission) factors.
Payback period often plays a key role in the economic evaluation. The payback period describes the time span after which the accumulated operating cost savings compared to the reference process correspond to the investment costs. To calculate this, the operating costs for the heat pump system and the reference system must be determined. The investment costs for the heat pump system must also be determined.

The operating costs (OpEx) for the heat pump and the reference process are calculated from the respective electricity and fuel costs and the costs for the associated CO_2 emissions.

A general assessment of the heat pump investment costs is difficult. They generally consist of component costs depending on the heat pump capacity and costs for the integration. An easy approach to include the costs for integration can be multiplying the component costs for the heat pump by an appropriate factor. This factor can in turn be increased depending on the effort involved, for example through additional construction, safety or electrical engineering work. A general assessment of integration costs is difficult, as they are very site-specific.

Possible next steps based on the economic and ecological evaluation is to carry out manufacturer inquiries, whereby an (iterative) optimization step can also be considered here. Optimization can involve the repetition of individual steps that have already been carried out. In general, the COP can be increased by raising the source outlet temperature.

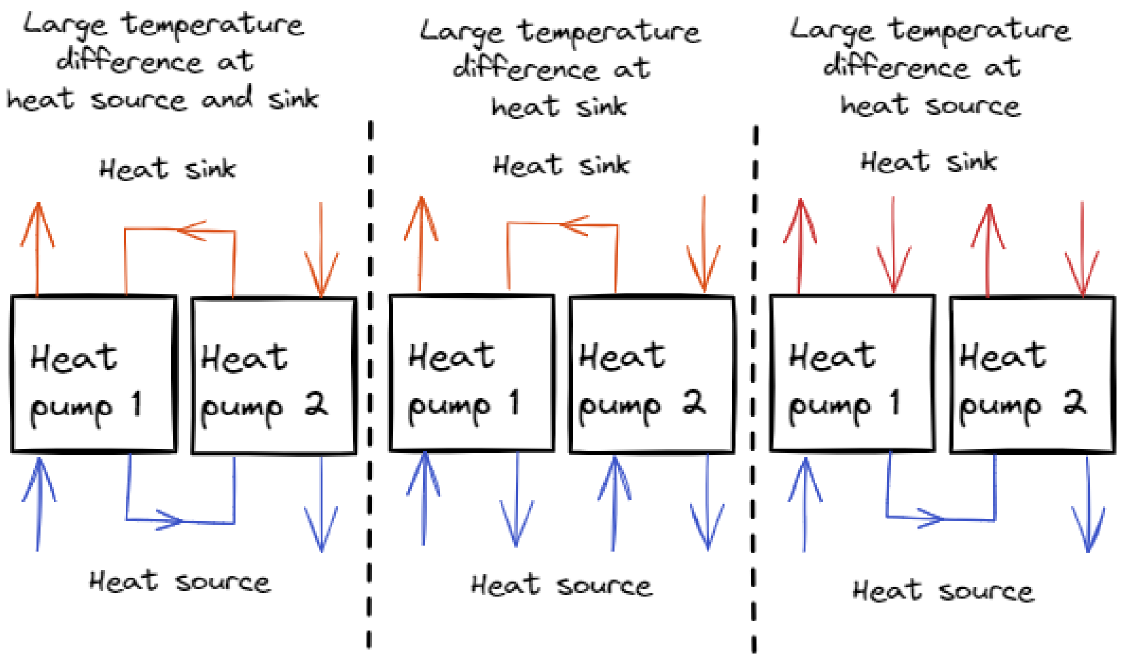


Figure 9: Multi-cycle arrangement according to [4]. Left: serial connection on source and sink side; Center: parallel connection on source side and serial connection on sink side; Right: serial connection on source side and parallel connection on sink side.

Another optimization option is the use of multi-cycle or cascade arrangement. In the multi-cycle arrangement as shown in Figure 9, the evaporators or condensers of the refrigeration cycles of several heat pumps are connected in series or parallel. The decisive factor here is whether large temperature differences or mass flows are required or expected at the source or sink side. The serial arrangement can reduce the temperature lift per cycle. This typically improves the COP compared to a single cycle. A parallel arrangement may be necessary for high mass flows.

In a cascadic arrangement as shown in Figure 10, two refrigeration circuits are connected via a heat exchanger. This serves as a condenser for the lower refrigeration cycle and simultaneously as an evaporator for the upper refrigeration cycle. This arrangement divides the temperature lift between two refrigeration cycles and is therefore lower for each individual refrigeration cycle. Furthermore, each individual refrigeration cycle can be optimized for the corresponding conditions. For example, the use of different refrigerants is possible compared to the single cycle. The increase in efficiency is offset by increased technical effort and therefore higher costs. A cascade arrangement is usually advantageous for temperature ranges from 60 - 80°C.

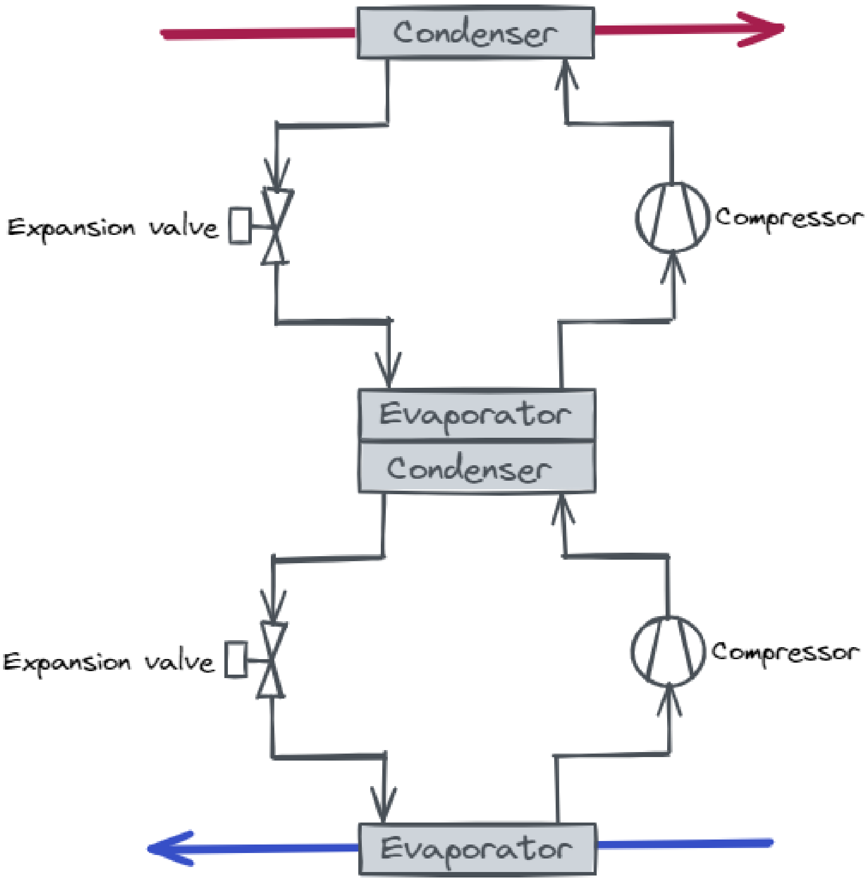


Figure 10: Cascade arrangement.

Furthermore, the refrigeration cycle of the heat pump itself can be optimized, for example with the selection of the refrigerant, through the configuration (e.g.: use of a subcooler) and selection of the compressor. Furthermore, the use of an internal heat exchanger can be advantageous. Here, as shown in Figure 11, the refrigerant after the condenser is used to further heat the refrigerant after the evaporator. This is advantageous for certain refrigerants as it ensures that the compressor does not compress the refrigerant into the two-phase region, as the design of the refrigeration cycle and its components is generally carried out by the manufacturer.

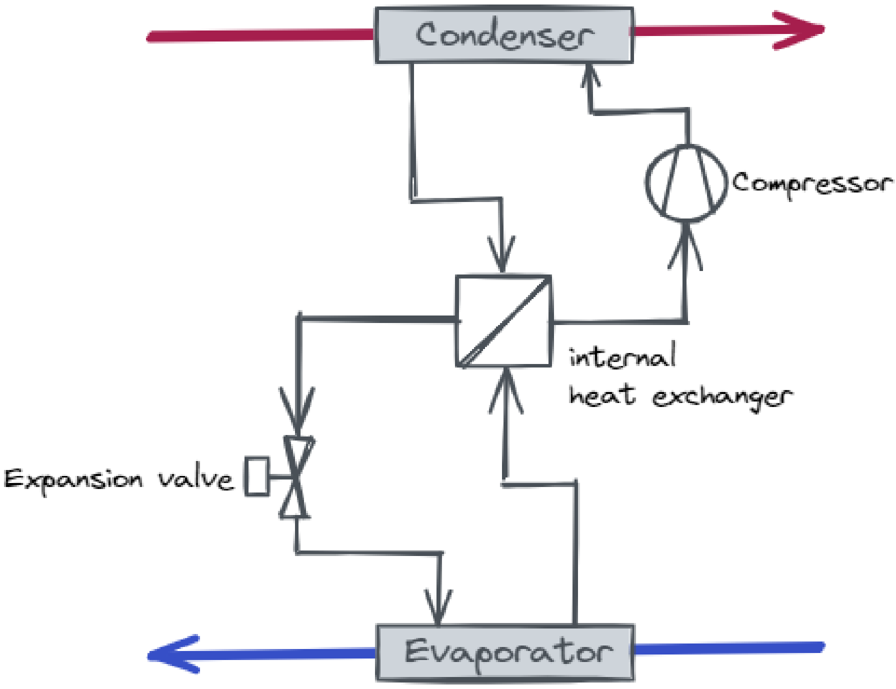


Figure 11: Heat pump cycle with internal heat exchanger.

4.4 Application examples for steam-generating heat pumps

In the following, the procedure from the identification of possible integration points, over the selection of the most promising integration point to the evaluation of a potential demonstrator is described and results are shown for a selected site of each of the two industrial partners. In addition, for both industrial partners upscaling scenarios are presented.

4.4.1 Application example industry partner LAG

Five sources and three sinks were initially available for the selection of an integration point for a potential demonstrator at the industrial partner LAG. The possible sources are (i) a water-based closed loop heat recovery system for the utilization of low temperature heat for heating of ventilation air, (ii) clean water after wastewater treatment plant, (iii) cooling water from process cooling, (iv) warm off gas and (v) humid exhaust air from dryer. The three sinks under consideration are the feed into two different steam networks (saturated steam at approx. 1.75 bar_a and 2.4 bar_a) and a hot water demand at around 80°C. Currently, the hot water demand is also covered by the steam network (2.4 bar_a).
When selecting the integration point at LAG, not only process related parameters such as waste heat temperature, steam pressure and waste heat capacity were evaluated but also the distance between source and sink. The availability of sufficient space for the heat pump and the needed integration equipment was also a selection criterion.
As integration point two sinks are chosen to be supplied with a potential heat pump demonstrator. The first sink is the steam network with saturated steam at 1.75 bar_a. This steam demand was selected as a higher COP can be expected than when generating steam at higher pressure level. However, additional steam generation by the heat pump at this pressure level (1.75 bar_a) is not all the time required. Therefore, to increase the operating hours and the saving potential (operating costs and CO_2 emissions) of the heat

pump, it should be designed in such a way that when the heat pump is not required for steam generation, it can generate hot water to cover part of the corresponding hot water demand. This means that the steam demand can be reduced even at times when the heat pump is not generating steam but hot water.
The water-based closed heat recovery system was selected as the source for the investigations. This source was chosen because it is the best place to provide the space required for a heat pump demonstrator, including equipment for integration. Furthermore, short distances between the chosen sinks and source can be realized.

Different configurations for steam and hot water generation with a single heat pump system were investigated and compared to each other regarding various criteria. In addition, simulations were carried out in IPSEpro [5] to estimate the efficiency for selected configurations. In this simulation tool, steady-state calculations were performed for different operating points and heat pump configurations.

One configuration that was examined in detail is shown in Figure 12. In this configuration two condensers, one for steam generation (steam generation mode) and one for hot water production (hot water production mode) is included. This configuration includes two condensers, one for steam generation and one for hot water generation. Simultaneous operation of both condensers is not foreseen here. Thus, with this configuration either the condenser for hot water generation or the condenser for steam generation is in operation. Moreover, a subcooler was included in the configuration to generate hot water both in steam generation operating mode and in hot water operating mode. In the course of a presentation at the 3rd High-Temperature Heat Pump Symposium 2022 [6] investigations of this configuration (without internal heat exchanger) were presented.

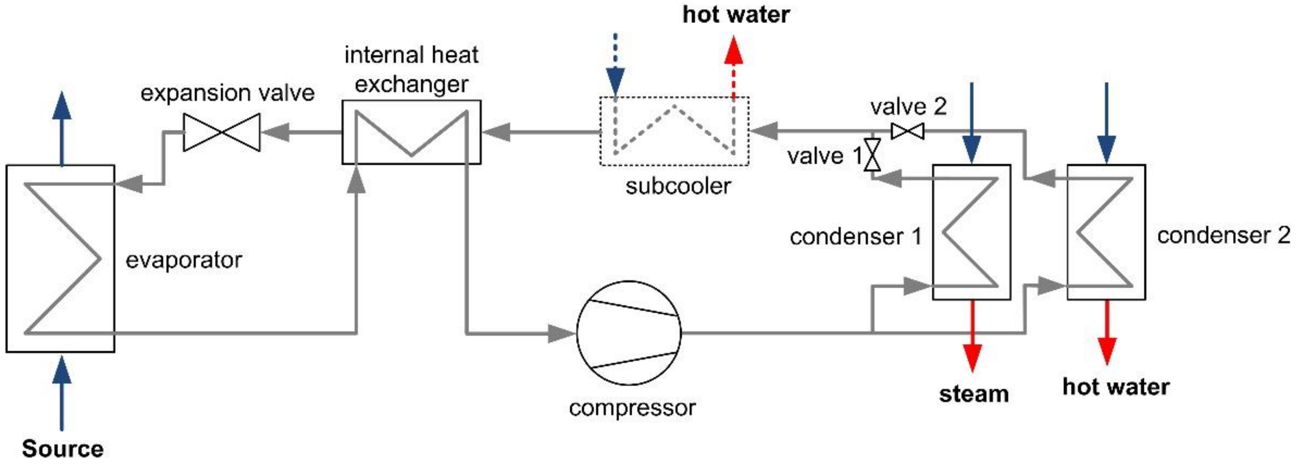


Figure 12: Heat pump system for steam and hot water generation with subcooler.

4.4.1.1 Evaluation of a potential heat pump demonstrator

For the LAG potential heat pump demonstrator, a heat pump configuration as shown in Figure 12 was considered. The heat pump generates saturated steam at a pressure of 1.75 bar_a (steam generation mode) for around 4250 operating hours with a heating capacity of 702 kW and at the same time hot water at 80°C via a subcooler (330 kW) with a COP of 4.2 in this operating mode. Approx. 7% of the steam requirement is covered at the corresponding pressure level and 15% of the hot water demand. For a further 4250 operating hours, only hot water is produced with the condenser heat capacity of 1062 kW and a heat capacity of 75 kW at the subcooler. In this operating mode a COP of 7 was estimated, which is significantly higher than in the steam-generating mode as the temperature lift is lower. This results in the hot water requirement being covered by 53%. If the hot water is covered by steam, this means a saving of around 1.6 t/h of steam. In both operating modes the source is cooled from 55°C to 50°C.

In the following, the heat pump integration is compared with three theoretical reference cases, whereby the reference provides the same heating output as the heat pump system with the simplification of using only energy carrier in each reference case. In the first reference case (Case 1), the heat capacity is provided using natural gas combustion with an efficiency of 90%. In the second reference case (Case 2), an electric boiler is used and in the third case (Case 3), biogas combustion is used with an efficiency of 90%. It was assumed that both the electric boiler and the heat pump are supplied with green electricity. Therefore, the last two reference cases represent decarbonized alternatives. The reference cases differ from the actual situation at LAG. Currently a high share of fuels are biogenous fuels (e.g.: liquors from pulp production, bark and residues as fuels in boilers).
Table 1 summarizes the assumptions required for the assessment. As indicated in Table 1, a primary energy factor of 1.63 is assumed for electricity, which corresponds to a general supply mix and not green electricity. It can be assumed that the factor for green electricity is lower and therefore even higher primary energy savings can be expected than those calculated here. Moreover, the assumption for the biogas price was made based on the compensation price indicated in [7].

Table 1: Assumptions for the evaluation of the LAG heat pump system

Designation	Value	Source
Primary energy factor natural gas, kWh/kWh	1.1	[8]
Primary energy factor electricity (supply mix), kWh/kWh	1.6	[8]
Primary energy factor biogas, kWh/kWh	1.4	[8]
CO_2 emission factor natural gas, $g_{CO2\text{-}equiv}$/kWh	201	[9]
Natural gas price, €/MWh	51.5	internal
Biogas price, €/MWh	200	[7]
Electricity price, €/MWh	102	internal
CO_2 certificate price, €/t_{CO2}	78	[10]
Investment cost heat pump system (incl. costs for integration) k€	2 288	internal
Specific investment cost electro boiler (excl. costs for integration) €/kW	160	[11]
Specific investment cost biogas boiler (excl. costs for integration) €/kW	40	[11]

Based on the assumptions of using green electricity for suppling the heat pump the CO_2 emission savings results in 100% compared to the first reference case. If an emission factor representative for the current Austrian electricity mix of 170 g/kWh [9] is taken into account, this results in CO_2 emission savings of 86%.

Figure 13 shows further evaluation results for all three reference cases. Depending on the reference case, the final energy saving is between 81% and 83%, and the primary energy saving between 75% and 81%. The operating cost savings are highest (91%) for Case 3 (biogas). The lowest operating cost savings (73%) occur for Case 1 (natural gas). For Case 2 (electric boiler) there are 80% operating cost savings. It should be mentioned here that annual maintenance costs of 1% of the heat pump investment costs (without integration) were assumed for the operating costs of the heat pump. As seen for the operating cost savings, the payback period is shortest (approx. 1.2 years) for Case 3 (biogas) and longest (approx. 4.5 years) for Case 1 (natural gas). The investment costs shown in Table 1 were considered for both the electric boiler and the biogas boiler, whereby it was assumed that the natural gas boiler already exists.

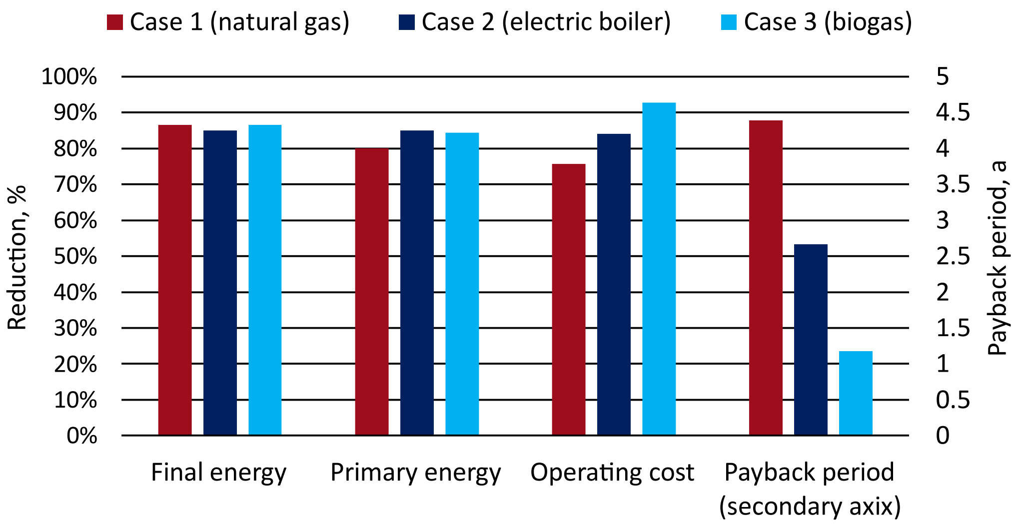


Figure 13: Evaluation results of the LAG case in terms of final energy and primary energy savings as well as payback period for three reference cases.

With all reference cases, a payback period of less than five years can be achieved for the assumptions made. The net present value is shown for all three reference cases in Figure 14. A discounting rate of 8% is considered here. A positive value is achieved for Case 1 (natural gas) after around 5 years. Both for the calculation of the net present value and for the calculation of the payback period, the investment costs for the electric boiler or biogas boiler were subtracted from the investment costs of the heat pump system for Case 2 (electric boiler) and Case 3 (biogas).

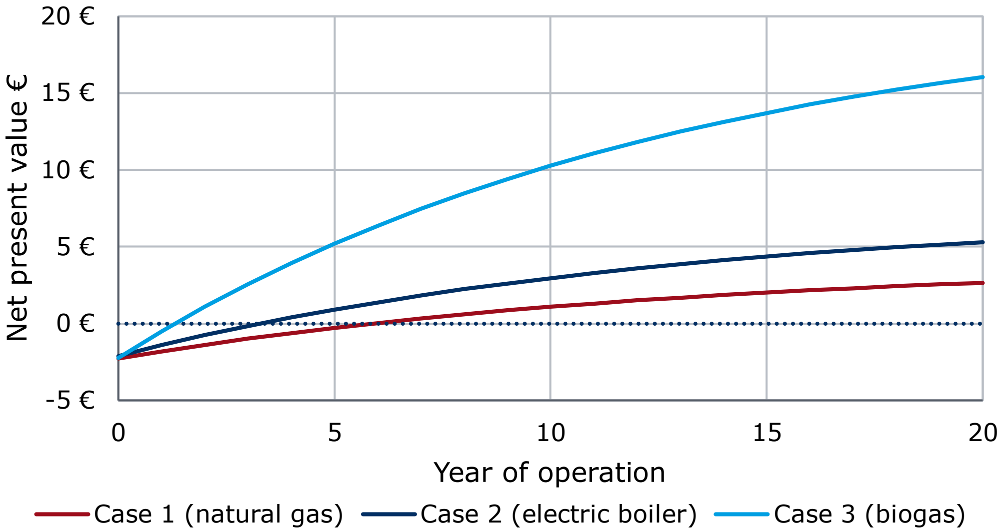


Figure 14: Net present value of the LAG heat pump system in relation to three different reference cases.

4.4.1.2 Full-Scale Scenario

For the consideration of the full-scale scenario, the information on available sources, referred to as So1-So4, and sinks, referred to as Si1-Si3, was updated. An additional heat source was identified, while one heat source was no longer available compared to the status at the start of the project. The source So5 is flue gas. For a possible future use of this waste heat source, however, it is important to know the composition of the flue gas and the dew point temperature of all components. An additional heat sink (Si4) was also included for the full-scale scenario. This sink is steam at a pressure of 4.5 bar_a (Si4). This sink was not considered for the potential demonstrator due to the comparatively high steam pressure compared to the other sinks. For some sources, the parameters varied over the course of the year. Different parameters with corresponding operating hours were considered for these sources. The investigated operating points with the associated source and sink parameters considered for the full-scale scenario are summarized in Table 2. Overall, the waste heat potential of all sources is 1.2 TWh/a.

The demand considered in the full-scale scenario includes steam (Si1, Si2 and Si4) and hot water demand (Si3). As hot water is currently generated with steam, providing hot water using a heat pump would also reduce the steam demand. The energy demand for the four sinks under consideration is 2.2 TWh/a.

Table 2: Overview of operating points for the LAG full-scale analysis

Operating point	**1**	**2**	**3**	**4**
Operating hours, h	6660	100	1640	100
Inlet temperature So1 (Water), °C	55	55	55	55
Outlet temperature So1 (Water), °C	30	30	50	50
Capacity So1 (Water), MW	8.6	8.6	1.7	1.7
Inlet temperature So2 (Water), °C	36	36	31	31
Outlet temperature So2 (Water), °C	20	20	20	20
Capacity So2 (Water), MW	51.9	51.9	35.8	35.8
Inlet temperature So3 (Water), °C	33	33	33	33
Outlet temperature So3 (Water), °C	20	20	20	20
Capacity So3 (Water), MW	21.7	21.7	21.7	21.7
Inlet temperature So4 (Humid exhaust air), °C	70	70	70	70

Rel. humidity So4 (Humid exhaust air), %	85	85	85	85
Outlet temperature So4 (Humid exhaust air), °C	35	35	35	35
Capacity So4 (Humid exhaust air), MW	7.3	7.3	7.3	7.3
Inlet temperature So5 (Flue gas), °C	145	145	145	145
Rel. humidity So5 (Flue gas), %	5	5	5	5
Outlet temperature So5 (Flue gas), °C	35	35	35	35
Capacity So5 (Flue gas), MW	55.2	41.4	55.2	41.4
Inlet temperature Si1 (Steam), °C	35	35	35	35
Outlet temperature Si1 (Steam), °C	116 (1.75 bar_a)	116 (1.75 bar_a)	116 (1.75 bar_a)	116 (1.75 bar_a)
Max mass flow Si1 (Steam), t/h	15	15	15	15
Inlet temperature Si2 (Steam), °C	25	25	25	25
Outlet temperature Si2 (Steam), °C	126 (2.4 bar_a)	126 (2.4 bar_a)	126 (2.4 bar_a)	126 (2.4 bar_a)
Max mass flow Si2 (Steam), t/h	180	180	180	180
Inlet temperature Si3 (Water), °C	35	35	35	35
Outlet temperature Si3 (Water), °C	80	80	80	80
Max mass flow Si3 (Water), t/h	40.92	40.92	40.92	40.92
Inlet temperature Si4 (Steam), °C	25	25	25	25
Outlet temperature Si4 (Steam), °C	158 (4.51 bar_a)	158 (4.51 bar_a)	158 (4.51 bar_a)	158 (4.51 bar_a)
Max mass flow Si4 (Steam), t/h	165	165	165	165

For the investigations the assumptions from Table 1, with the assumptions from Table 3 being used for the investment and integration costs of the individual components. Moreover, the reference cases already presented in Chapter 4.4.1.1 were used for the evaluation of the full-scale scenario.

The proportion of the heat demand that cannot be provided by the heat pump system is also provided by the supply option of the corresponding reference system. As with the evaluation of heat pump system in Chapter 4.4.1.1, no investment costs were considered for Case 1 (natural gas). Annual maintenance costs of 1% of the investment costs (without integration) were only considered for the heat pump system. The assumptions in terms of investment cost for the electric boiler and the biogas boiler stays the same as for the evaluation of the heat pump system in Chapter 4.4.1.1 (no costs for integration considered).

Table 3: Assumptions for the evaluation of the full-scale scenario at LAG

Designation	Value	Source
Investment cost heat pump €/kW	800	[2], internal
Investment costs for heat exchanger €/kW	40	internal
Investment costs for steam compressor (based on steam output cooling down to 105°C) €/kW	400	[2]
Integration cost factor in relation to the heat pump investment costs	1.5	internal

Figure 15 shows the investigated heat pump system. To get an efficient system not only heat pumps but also heat exchangers are included. Almost all heat sources (So1, So2, So3, So4) are used by heat pumps and feed into the heat transfer network. This network is used because the sources and sinks are distributed across the entire site and such a network facilitates implementation. All sources and all sinks of the heat transfer network are connected in parallel. Due to the high temperature of source So5, this source is used by means of heat exchangers to preheat feed water (HX1 and HX3) and to cover Si3 (HX2). Partial evaporation occurs during the preheating of the feed water for the heat pumps (HP1a, HP1b and HP6). However, the Si3 sink is only supplied by source So5 if the demand cannot be covered by heat pump

HP1a. Furthermore, the remaining output of the heat source So5 is used by the heat pump to feed into the heat transfer network. The source So4 is humid air, here an intermediate water cycle with heat exchanger between the heat pump evaporator and the humid air was considered.

In addition, source So1 is used by means of a heat pump (HP1a) to directly supply sink Si1 (steam). Moreover, the heat pump HP1a has a subcooler supplying Si3. If the entire required mass flow of sink Si3 is covered by this subcooler and the demand of sink Si1 is not yet fully covered, a partial mass flow of So1 that is still available is used to provide the steam still required for sink Si1 with the heat pump HP1b. If the demand of the sink Si1 is covered by the two heat pumps HP1a and HP1b, but a partial mass flow from source So1 is still available for use by the heat pump, this is used in the HP1c heat pump to generate hot water for the heat transfer network. It was assumed that the extracted mass flow is cooled by 5K when using the heat transfer network.

The remaining energy available in the heat transfer network is used to generate steam at 2.3 bar_a (Si2) by means of a heat pump (HP5). Thus, the heat transfer network is cooled by 5K. If the sink Si1 cannot be fully supplied by the heat pump (HP1a), the necessary proportion of the steam is expanded to 1.75 bar_a to the pressure needed in Si1. If sufficient steam is available, the remaining steam at 2.4 bar_a is used to cover Si2 and is also brought to the pressure needed for Si4 by using a steam compressor (SC). This produces superheated steam which is cooled down by means of feed water injection. It was assumed that the temperature of the steam is 10K higher than required to consider possible heat losses due to long transportation distances.

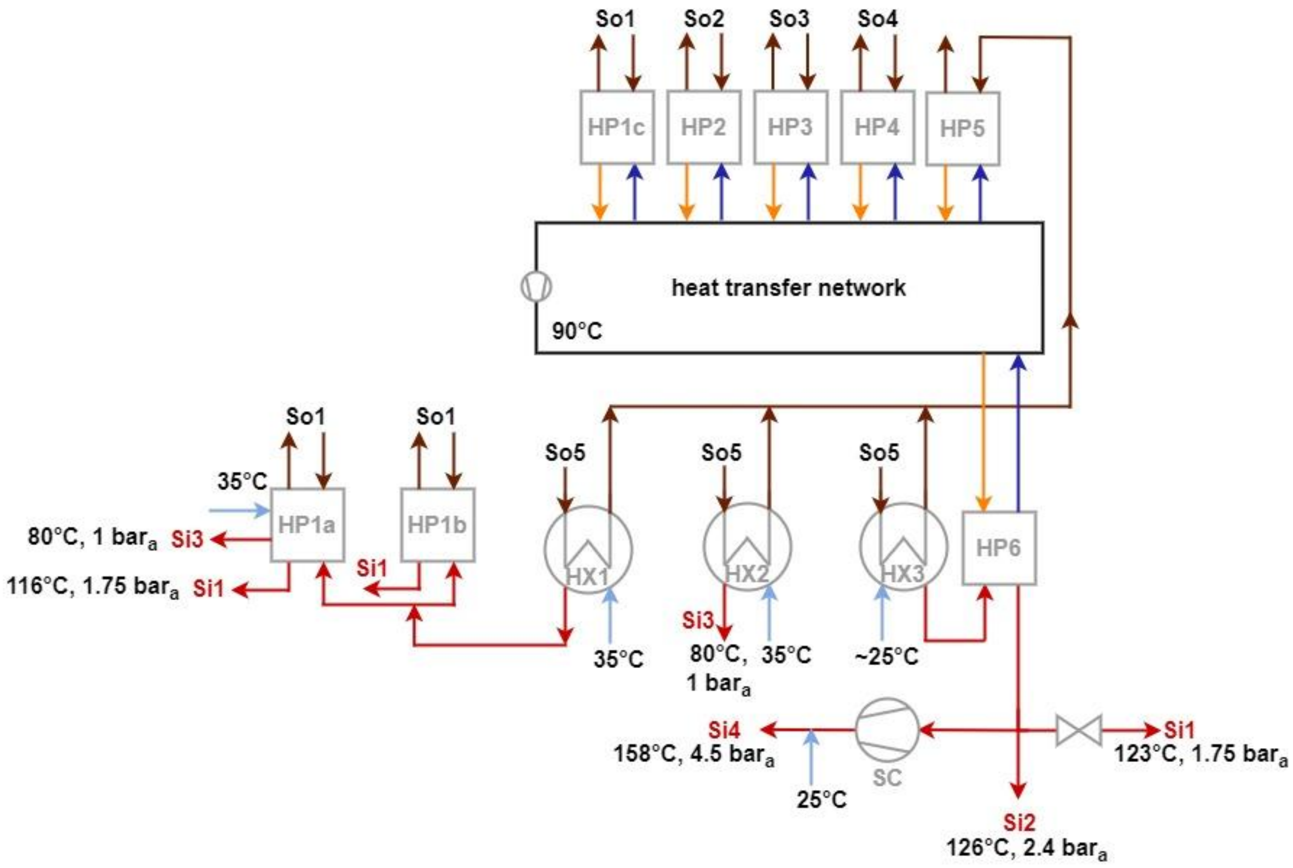


Figure 15: Heat pump system LAG full-scale.

For the investigations a model was created in IPSEpro [5] , whereby the heat pumps were modeled based a second law efficiency and a system efficiency (including losses). The second law efficiencies and system efficiencies were determined based on manufacturer information for different operating points collected during the project and information published in the course of IEA Annex 58 Task 1 [2]. For the heat pump with subcooler, a factor was used that indicates the share of the subcooler's heating capacity in the total heating capacity of the heat pump. This factor was also estimated based on manufacturer information. The temperature lifts of the heat pumps are between 45K – 94K. Depending on the heat pump and operating point, this results in COPs between 2.6 and 4.3. With the proposed heat pump system Si1, Si2 and Si3 can be fully covered at all operating points. For the isentropic efficiency of the steam compressor 0.6 was assumed. Moreover, all heat exchangers in the system were assumed to be counterflow heat exchangers. A temperature difference of 10K between the hot side at the outlet and the cold side at the inlet was determined for the heat exchangers.

The heat pump system requires 833 GWh of electrical energy per year. The evaluation showed a CO_2 emission saving of 82% in Case 1 (natural gas), as well as a reduction in final energy demand of 45-49% and a primary energy reduction of 33-45% depending on the case. The operating cost savings are between 29-64% depending on the case. Payback periods of 16 years result for Case 1 (natural gas). Case 2 (electric boiler) and Case 3 (biogas) resulted in payback periods of 7 and 2 years. The results are shown in Figure 16.

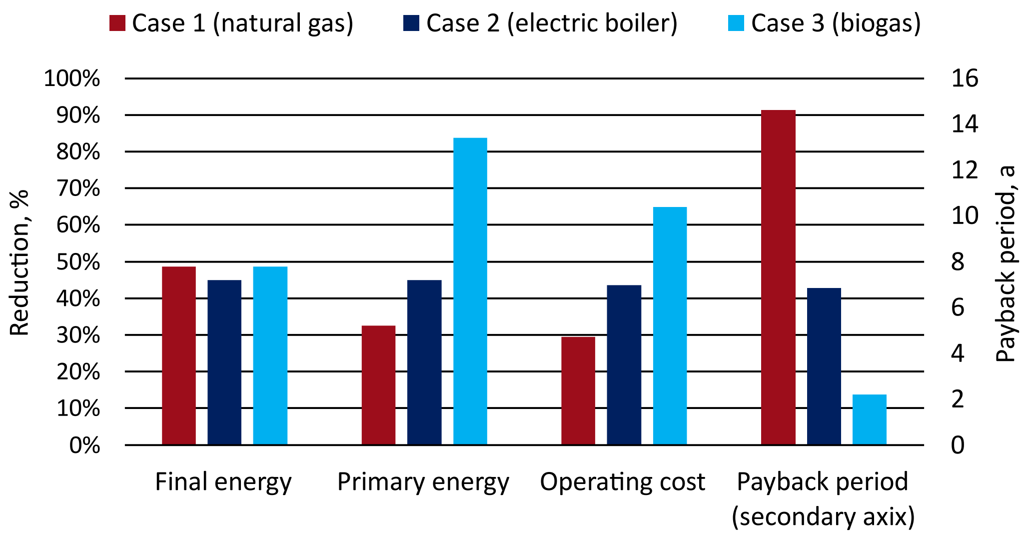


Figure 16: Evaluation results of LAG full-scale scenario in terms of final energy and primary energy savings as well as payback period for three reference cases.

Figure 17 shows the net present value for all three cases, assuming a discounting rate of 8%. For Case 1 (natural gas) no positive value can be achieved during the assumed lifetime of the heat pump system.

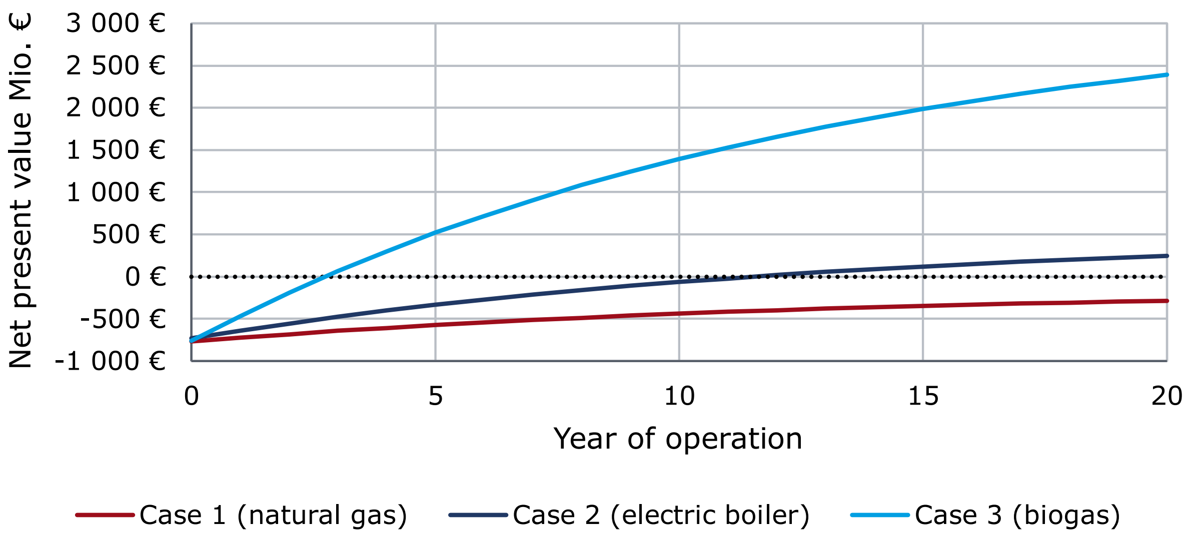


Figure 17: Net present value of the full-scale LAG for three reference cases.

4.4.1.3 Conclusion

The evaluation of the potential demonstrator and the full-scale scenario has shown that emission savings of higher than 66% compared to natural gas combustion are possible. In addition, there are final energy savings of 49% to 83% and primary energy savings of 33% to 45% depending on the scenario (Case 1). Operating costs can also be reduced by up to 73% (full-scale) compared to natural gas combustion, depending on the scenario. The payback period for the evaluated demonstrator (approx. 4.5 years) is significantly shorter than for the full-scale scenario (approx. 16 years) for Case 1. However, the heat pump system of the full-scale scenario shows good results compared to the decarbonized reference systems (electric boiler and biogas combustion). Higher COPs and lower operating costs for the full-scale scenario could be achieved if the sources are less cooled down. If the sources are cooled down less, the COP can be increased, but in this case less heating capacity can be provided by the heat pump system.

4.4.2 Application example industry partner AAT

The integration of a heat pump into an EPS block molding line was investigated for the industrial partner AAT. Figure 18 shows such a line schematically. Both steam demand and waste heat occur along this production line.

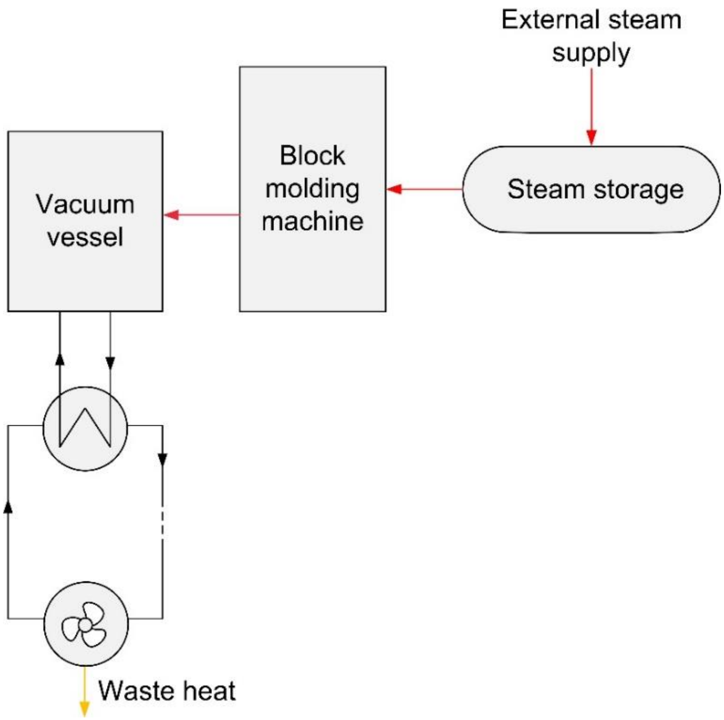


Figure 18: EPS block molding line

Steam is fed into the block mold from a steam storage and then extracted in a vacuum tank. In this case, it is a batch process. In addition, there is a cyclone between the block form and the vacuum tank, which is not shown in Figure 18. During extraction into the vacuum tank, most of the steam condenses and the water contained in the vacuum tank heats up. Afterwards, this warmed water, must be cooled before the process can start again. Cooling currently takes place with a roof cooler via a water/glycol intermediate cycle. A plate heat exchanger is located between the vacuum tank and the water/glycol intermediate cycle.

Production lines for EPS are generally always structured in the same way and there can be several production lines at one industrial site. A steam storage can also supply more than one production line. At the site under consideration, the steam storage vessel is charged with steam purchased externally. At other sites, the steam is generated directly on site, for example in natural gas fired boilers. In addition, such a block molding line generally includes a pre-expander which also has a steam demand. The demand of the pre-expander was not considered in the investigations.

Several integration points were considered along the production line, both for feeding in the steam generated by the heat pump and for utilizing the waste heat. All necessary data was collected or estimated to evaluate the possible integration points. Additional measurements were also installed to better quantify the available waste heat output. The steam requirement per block and the necessary steam parameters were specified.
Four integration points were considered for the source side of the heat pump: Directly after the block mold (So1), after the cyclone (So2), after the vacuum tank (So3) and in the water/glycol intermediate cycle before the rooftop cooler (So4). The COP increases with higher temperatures of the heat source, as the necessary temperature lift for producing saturated steam at 3.2 bar_a is lower. The source temperatures at the various integration points and resulting COP were estimated for the selection of the integration point.

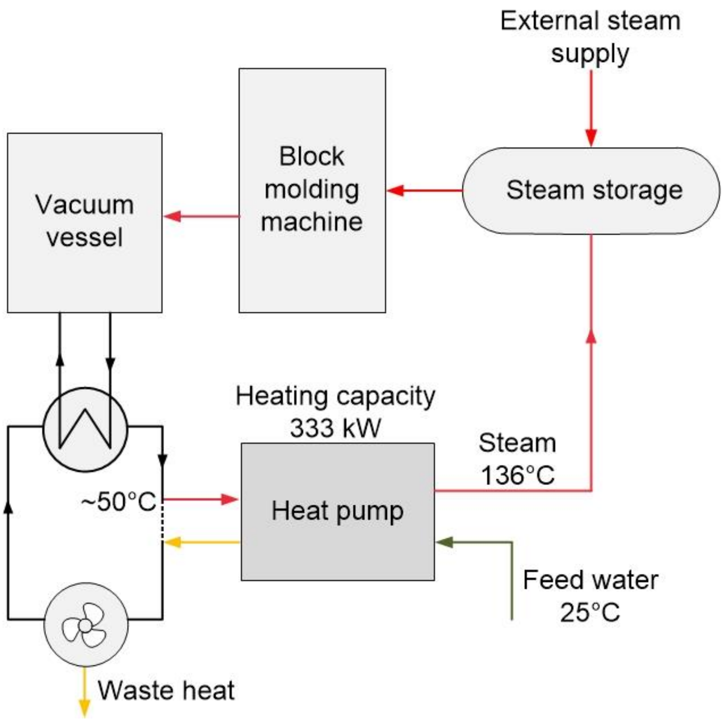


Figure 19: Integration of a heat pump into a block molding line.

Although the COP of the heat is to be expected as the highest when integrating the source side of the heat pump directly after the block mold or the cyclone the integration at this point was classified as critical due to contamination. In addition, the source would be discontinuous at this point and the production process could be influenced. It can be assumed that if the integration points are used downstream of the vacuum vessel or in the water/glycol intermediate cycle, the fluctuations in the production process are already reduced by the vacuum vessel. It was important to select an integration point where the integration of the heat pump is as simple as possible, the maintenance effort is lowest, and the production process is not influenced. It was therefore decided to consider the source side of the heat pump in the water/glycol cycle after the plate heat exchanger as an integration point, as shown in Figure 19.

4.4.2.1 Evaluation of a potential heat pump demonstrator

The source has a temperature of around 50°C and a heat pump with 333 kW generates steam at 3.2 bar_a which is fed into the steam storage vessel. The waste heat potential was set at around 233 kW, whereby it was assumed that approx. 90% of this waste heat is used by the heat pump. The remaining cooling capacity is covered by the existing system. The heat pump system under consideration is a single-stage close-loop heat pump that generates steam directly in the condenser. It also includes an internal heat exchanger and a subcooler on the refrigerant side after the condenser to preheat the feed water.
With a COP of approx. 2.6, the heat pump provides a heating capacity of 333 kW, whereby the electrical energy consumption of the heat pump is approx. 129 kW. Thus, the heat pump system covers around 70% of the steam requirement of the block form.

As already mentioned, the steam storage vessel of the block molding line under consideration is supplied with steam which is generated externally. For the analysis, the heat pump integration is compared to three reference cases where steam generation takes place on site. In the first reference case, the steam required by the block form is generated using natural gas combustion with an efficiency of 90%. In the second reference case, an electric boiler is used to generate steam and in the third case, biogas combustion is used with an efficiency of 90%. It was assumed that the electricity used for the heat pump and the electric boiler is green electricity. Therefore, the last two reference cases are decarbonized alternatives. As the heat pump system does not cover the entire steam demand, it is assumed that the remaining demand is covered by the corresponding reference system. For the first reference case the emissions saving corresponds to the saving on steam generated by natural gas burning (70%). If the steam would be supplied externally by natural gas-fired boilers, the CO_2 emissions savings would be achieved by the external supplier. Table 4 summarizes the assumptions required for the assessment.

Table 4: Assumptions for the evaluation of the AAT heat pump system

Designation	Value	Source
Primary energy factor natural gas, kWh/kWh	1.1	[8]
Primary energy factor electricity (supply mix), kWh/kWh	1.6	[8]
Primary energy factor biogas, kWh/kWh	1.4	[8]
CO_2 emission factor natural gas, $g_{CO2\text{-}equiv}$/kWh	201	[9]
Gas price, €/MWh	136	internal
Biogas price, €/MWh	200	[7]
Electricity price, €/MWh	139	internal[2]
Total investment cost heat pump system (incl. costs for integration) k€	915	internal
Specific investment cost electro boiler (excl. costs for integration) €/kW	160	[11]
Specific investment cost biogas boiler (excl. costs for integration) €/kW	40	[11]

Figure 20 shows the evaluation results. Depending on the reference case, the final energy saving is between 43% and 46%, and the primary energy saving between 34% and 43%. The operating cost savings

[2] Calculated based on an assumed steam price of 110 €/t for the external produced steam.

are highest (52%) for Case 3 (biogas). The lowest operating cost savings (41%) occur for Case 2 (electric boiler) and for Case 1 (natural gas) there are 43% operating cost savings. It should be mentioned here that annual maintenance costs of 1% of the heat pump investment (without integration) were assumed for the operating costs of the heat pump. As it can already be seen from the operating cost savings, the payback period is shortest (approx. 5 years) for Case 3 (biogas) and longest (approx. 9 years) for Case 2 (electric boiler). Annual operating hours of 3600 were assumed for the calculation of the payback period. The investment costs shown in Table 4 were considered for both the electric boiler and the biogas boiler, whereby it was assumed that the natural gas boiler already exists. Due to the high assumed gas price compared to the electricity price, Case 2 (electric boiler) shows poorer results in terms of operating cost savings and payback period compared to Case 1 (natural gas).

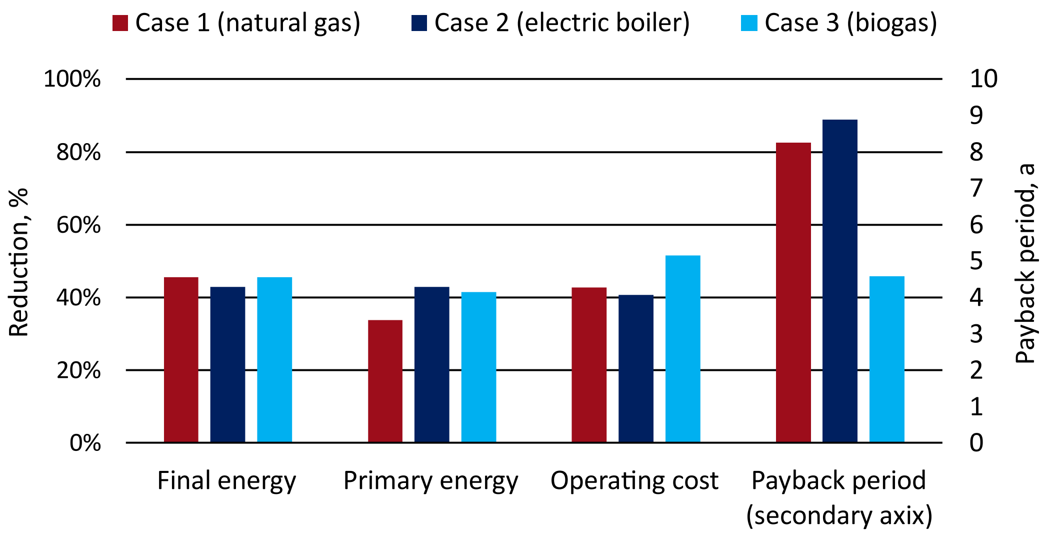


Figure 20: Evaluation results in terms of final energy and primary energy savings as well as payback period for three reference cases.

4.4.2.2 Full-Scale Scenario

For this use case, two scenarios were investigated: firstly, when a heat pump supplies several block molding lines and, secondly, when the block molds for EPS production throughout Europe is supplied with steam-generating heat pumps.

For the first scenario, it was assumed that three block forms are operated at one site. However, these three block types are not in operation at the same time. It was therefore assumed that in step 1.92 block types are in operation for 3760 operating hours per year.

Figure 21 shows the payback periods for a steam-generating heat pump supplying a single block molding line compared to supplying the assumed full-scale scenario. The payback period can be reduced in the full-scale scenario compared to the supplying a single block mold for the same specific investment costs due to the increased operating hours. The already described three different reference cases were used for the evaluation.

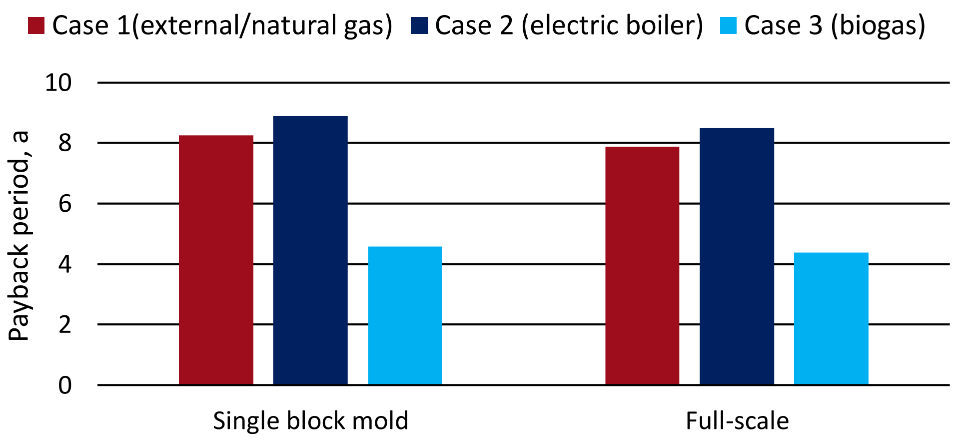


Figure 21: Payback period for a heat pump system integrated in a single block molding compared to the full-scale case for three different reference cases.

Figure 22 shows the influence of the operating hours of a heat pump on the economic performance even more clearly. The maximum possible CapEx for the heat pump system compared to the reference case of natural gas combustion is shown for a defined payback period of 10 years depending on the operating hours is shown in this diagram.

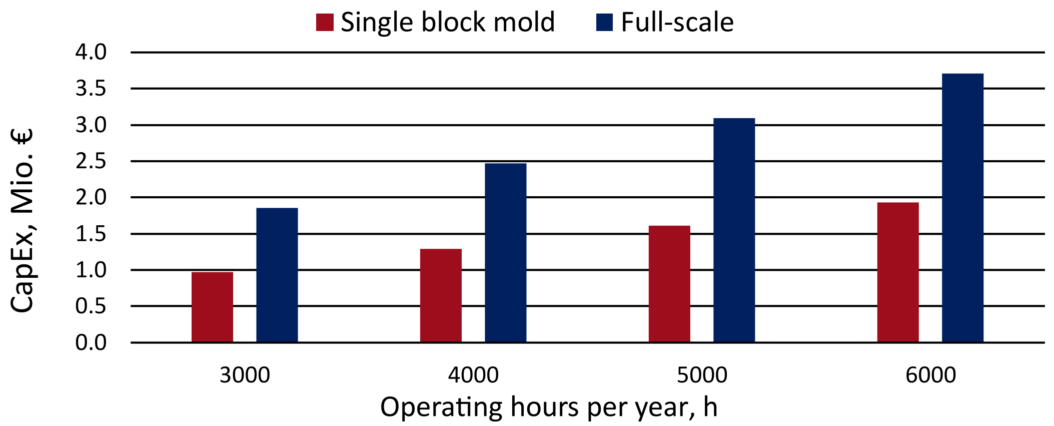


Figure 22: CapEx for different annual operating hours for Case 1 and a payback period of 10 years without maintenance costs for the heat pump system.

Results for a more detailed discussion of the influence of operating hours and other factors are presented in Chapter 4.5.1. As already mentioned, the second scenario considers the integration of steam generation for EPS production in Europe. The demand for thermal insulation in Europe in 2022 amounted to a total of 274 million m³. The demand for EPS in Europe accounts for 23%, as can be seen in Figure 23. Therefore, regarding EPS (finished goods, net), the total demand for 2022 is 63.1 million m³. This means a block volume (semi-finished goods, gross) of around 65.6 million m³ (including offcuts).
Assuming an usable waste heat from a block molding of approx. 3.2 kWh/m³ and if 90% of this waste heat is utilized by a heat pump with a COP approx. 2.6 (see Chapter 4.4.1.1) to generate steam also for this consideration the steam demand can be reduced by 70%. This could result in a CO_2 emission reduction

of approx. 67000 t/a for Europe. Moreover, this leads to an annual final energy saving of 217 GWh/a and primary energy saving of 178 GWh/a in Europe.

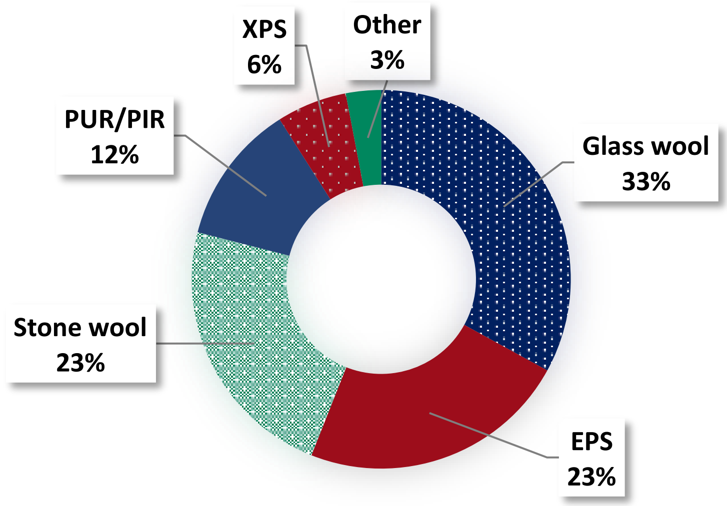


Figure 23: Thermal insulation market in Europe in 2022, according to IAL Consultants [12]

4.4.2.3 Conclusion

The evaluation of the potential demonstrator and the full-scale scenarios has shown that emission savings of higher than 66% compared to natural gas combustion are possible. In addition, there are final energy savings of 46% and primary energy savings of 34%. Operating costs can also be reduced by approx. 43% compared to natural gas combustion (external steam supply). The payback period of the demonstrator (single block mold) is approx. 8.2 years. For the full scale (one site), the payback period is slightly lower at 7.9 years. Substantial savings can also be achieved in relation to the other reference cases. Significant lower payback periods can be achieved compared to the biogas reference case.

4.4.3 Heat pump integration

The required integration infrastructure is very application specific. Also, the design of the heat pump components themselves can also be application specific. In the following, some of the aspects to be considered when integrating a heat pump are described. The overview is not comprehensive. Additional aspects may need to be considered depending on the application while other aspects that are presented in this work may not be relevant. Depending on the necessary infrastructure or requirements for the heat pump component, integration costs may be higher (or lower).

An essential aspect for the integration of a heat pump is that sufficient electrical grid connection power is available for operation. The extension of the electrical connection power in particular can cause high additional costs. It may also be necessary to invest in a feed water treatment system, especially if, for example, the steam supply has previously been provided externally.

Special requirements for the heat pump system in terms of safety and lifetime must also be addressed.

When selecting the material for the heat exchanger, for example, the medium on the source or sink side should be considered. It could be contaminated or contain substances that make a special heat exchanger material necessary for a long lifetime of the heat pump. It can also be beneficial to include an intermediate cycle due to contamination of the media or as a safety measure. In principle, the company standards must be applied during planning and execution.

The place where the heat pump is installed can also influence the requirements for the heat pump system, such as weight and size, as well as the necessary equipment. The costs for the integration infrastructure are influenced by the distance between the heat source and the heat pump as well as between the heat pump and the heat sink. Moreover, it must be considered that heat losses occur when operating a heat pump. Care must be taken to ensure that there is sufficient ventilation and needed conditioning of the environment (cooling and heating) so that the ambient temperature does not exceed or fall below the limit values required for the heat pump and switch cabinets.

In general, the heat pump should be operated as constantly as possible with the highest possible number of operating hours. Therefore, depending on fluctuations on the source or sink side, it may make sense to provide a storage tank on the corresponding side. The implementation of a new control strategy may be necessary to achieve the most efficient operation of the heat pump without affecting the production process itself.

4.5 Economic analysis of steam-generating heat pumps

The investigation results presented in the previous chapters have shown that high CO_2 emission savings are possible using steam-generating heat pumps. However, depending on the application and boundary conditions (e.g., energy carrier costs), long payback periods can occur. The payback period is an important key performance indicator, as the survey results have also shown (see Chapter 4.1). In many industrial companies, the payback period must be less than five years for a technology to be implemented or a measure to be taken.

4.5.1 Impact factors on the economy

The following subsection discusses the impact of various parameters (operating hours, natural gas price, electricity price, CO_2 price, specific heat pump cost) on the payback period of heat pump systems. For this purpose, steam generation with a heat pump (heat capacity 1 MW) was compared with a natural gas boiler with an efficiency of 90%. No investment costs and no maintenance costs were considered for the natural gas boiler. For the heat pump, integration costs amounting to 1.5 times the heat pump costs and 1% of the heat pump investment as annual maintenance costs were considered.

The investigations were carried out for two different COPs (2.7 and 4.1) of the heat pump. According to performance data from Siemens Energy [2], a COP of 4.1 can be achieved with a source inlet temperature of 115°C and a generated steam temperature of 150°C (feed water temperature 105°C), whereby the source is cooled down to 105°C. This results in a temperature lift of 45K (temperature difference between sink and source outlet temperature). Furthermore, a COP of 2.7 is achieved at a temperature range of 90K. Moreover, it was assumed that the heat pump's electricity consumption is green electricity and a CO_2 emission factor of 201 g/kWh [9] was assumed for natural gas. The payback period was calculated for an initial assumption as shown in Table 5 and then the individual parameters were varied, whereby only one parameter was varied at a time and the others were kept constant.

Table 5: Initial assumptions for the variations in influencing factors on the payback period

Operating hours, h	4700	assumption
Specific investment costs, €/kW	800	[2]
CO_2 certificate price, €/t_{CO2}	78	[10]
Electricity price, €/MWh (without grid fees)	120	[10]
Gas price in €/MWh	49.5	[10]

Figure 24 presents the variation results for the heat pump with a COP of 2.7. This shows that even with a moderate increase in the variation value (x-axis) in relation to the base value 1, the electricity costs cause the payback period (y-axis) to rise very quickly. The initial payback period is 15 years. If the electricity price is increased by 30%, the payback period rises to around 29 years. If the electricity price falls to 24 €/MWh, this results in a payback period of approx. 7 years. In contrast, the influence of the gas price has the opposite effect. If the gas price is doubled, the payback period for the heat pump system is reduced to 5 years. In contrast, a 20% reduction in the gas price results in a payback period of 25 years.

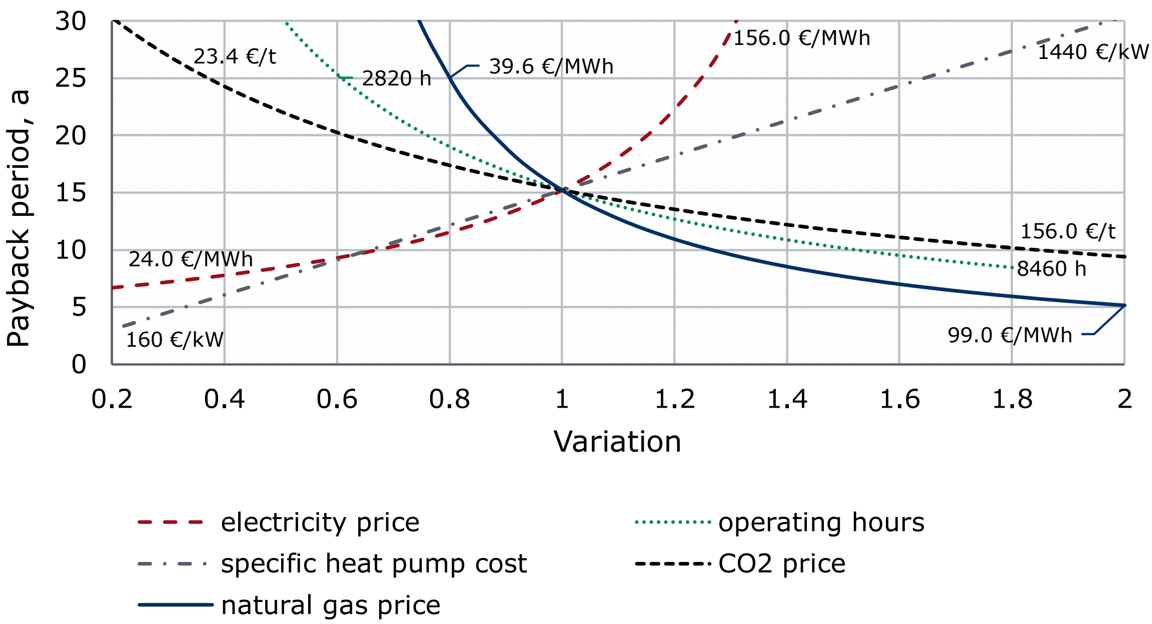


Figure 24: Impact on payback period for the heat pump system (COP 2.7) compared to the reference natural gas combustion by variation of different parameters.

The influence of the specific investment costs is also clearly recognizable (Figure 24). If the specific investment costs increase by 80%, the payback period also increases (27 years). A reduction of the specific investment costs to 160 €/kW results in a payback period of 3 years. If the CO_2 price is doubled, a payback period of 9 years can be achieved, whereas the payback period corresponds to 27 years if the CO_2 price is reduced by 70%. If the operating hours are reduced by 40%, the payback period increases to 25 years and if it increases by 80%, it decreases to approx. 9 years.

Figure 25 presents the variation results for a heat pump with a COP of 4.1. With a higher COP of the heat pump, the impacts are less strong than for a heat pump with a COP of 2.7. The initial payback period is approx. 10 years. If the electricity price is increased by 30%, the payback period rises to around 12 years. If the electricity price falls to 24 €/MWh, this results in a payback period of approx. 6 years. If the gas price is doubled, the payback period for the heat pump system is reduced to 4 years. In contrast, a 20% reduction in the gas price results in a payback period of 13 years. If the specific investment costs increase by 80%, the payback period also increases (18 years). A reduction of the specific investment costs to 160 €/kW results in a payback period of 2 years. If the CO_2 price is doubled, a payback period of 7 years can be achieved, whereas the payback period corresponds to 14 years if the CO_2 price is reduced by 70%. If the operating hours are reduced by 40%, the payback period increases to 16 years and if it increases by 80%, it decreases to approx. 6 years.
When reducing the assumed parameters, the reduction in the gas price causes the greatest increase in payback time. Also, the reduction in operating hours also shows a significant increase in the payback period. If the assumed parameters are increased, the increase in electricity prices or the specific heat pump cost cause the greatest increase in payback period. From an increase in these two parameters of around 50%, the increase in the electricity price causes the greatest increase in the payback period.

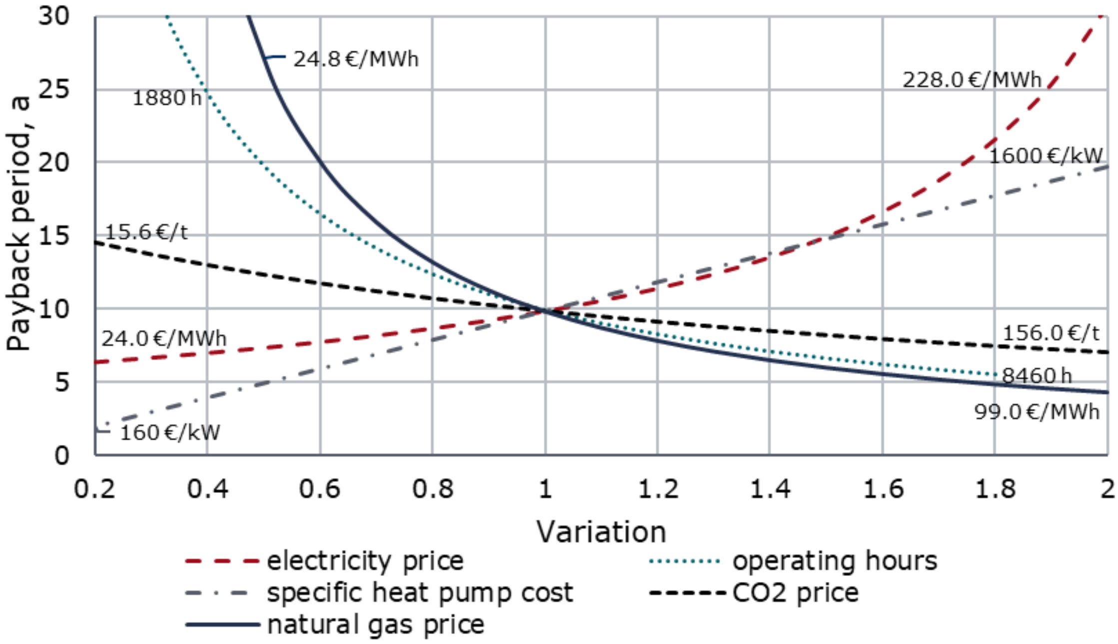


Figure 25: Impact on payback period for the heat pump system (COP 4.1) compared to the reference natural gas combustion by variation of different parameters.

Steam generation with electric boilers or the combustion of biomass or renewable gases can be considered as decarbonized alternatives to heat pumps for steam generation. If the heat pump is considered in comparison to an electric boiler reference case with an efficiency of 100% and investment costs of 160 €/kW, the heat pump achieves payback periods of approx. 5 years (COP = 2.7) and approx. 4 years (COP = 4.1). These payback periods are significantly lower than for the *natural gas combustion* reference case. Integration and maintenance costs were here not considered for the electric boiler. If the combustion of biogas with an efficiency of 90% is considered as a reference case, even lower payback periods of 2.39 and 2.21 years are achieved with the basic assumptions. Here, a biogas price of 200 €/MWh [7] was assumed. Investment, integration, and maintenance costs were not considered for the biogas boiler.

Compared to the alternative decarbonized options for steam generation, the heat pump has the additional advantage that the final energy demand is reduced and thus the operating costs can be also lower (depending on the COP of the heat pump and the energy carrier costs). The here cases considered result in final energy savings of 63-78%. Furthermore, the availability of biomass and renewable gases must be assessed in advance, as they are not always available at a location, or not in sufficient quantities. Further analysis results (see Figure 26) show how high the CapEx (heat pump incl. integration) for a heat pump system should be based on the initial assumptions so that a payback period of 5 years could be achieved. The results are shown for different COPs of the heat pump and operating hours.

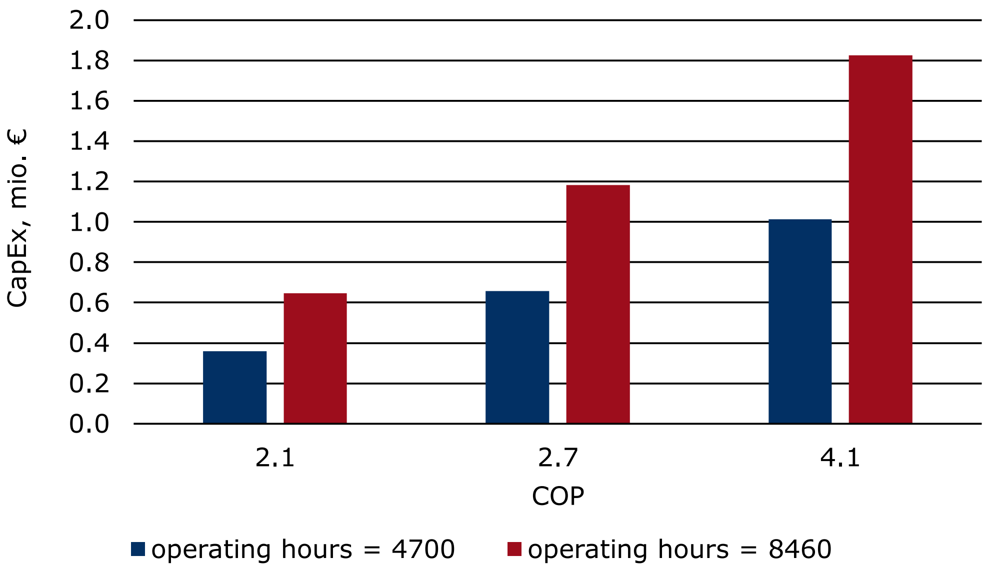


Figure 26: Maximum CapEx for different COPs of the heat pump and operating hours to reach a payback period of 5 years.

A significantly higher investment (1.8 million €) is possible for a heat pump with a COP of 4.1 and operating hours of 8460 h than for a heat pump with the same COP and only 4700 operating hours (approx. 1 million €). Different COPs represent here different applications. For applications with a low COP, the investment costs must be significantly lower to achieve a payback period of 5 years.

If it is assumed that the CapEx is made up of integration costs and heat pump costs, with specific heat pump costs of 800 €/kW, the integration costs may only account for 0.45 (COP=2.1, operating hours = 4700) to 2.28 (COP=4.1, operating hours =8460) of the absolute heat pump costs.
If, on the other hand, it is assumed that the integration costs are 1.5 times the absolute heat pump costs, the specific heat pump costs may only be between 144 and 730 €/kW, depending on the operating hours and COP. It is recognizable that the investment costs of steam-generating heat pump applications with

low COP, as they often occur in industry due to the high temperature lifts and low operating hours, must be greatly reduced to bring them into implementation. Funding can beneficially influence here.

In summary, it can be said that, apart from the economic influencing factors, the highest possible COP and the highest possible operating hours are advantageous for the economic presentation of the steam-generating heat pump. This must be considered during integration.

The following scenarios were made based on the results shown in Figure 24 to lower the payback period for a steam-generating heat pump to 5 years, which is often a decisive criteria for companies:

- The CO_2 price increases from the assumed 78 €/t to approx. 330 €/t. With the assumed ratio of electricity to gas price of approx. 2.4 (01/24 the electricity to gas price ratio was 2.6 according to EEX Futures [13]), the CO_2 price must therefore be significantly increased to incentivizing the conversion from fossil fuel systems to heat pumps through this factor alone. Other effects that such an increase could have are not discussed in this document.
- CapEx (incl. integration) subsidies of 70% could also reduce the payback period to less than 5 years (in this case from 2 million € to 0.6 million €). If Austrian companies were commissioned, this would stimulate the heat pump industry on the one hand and, on the other hand, increased market demand would also promote innovation in the technology sector. This in turn can lead to more efficient, more powerful, and more favorable systems. Industrial heat pumps would also contribute to a massive increase in energy efficiency in industrial companies.
- A key factor influencing the operating costs of heat pumps is the ratio between electricity and gas prices. Despite falling energy prices, this ratio has deteriorated from 2.2 in 2022 to 2.6 (EEX Future [13] in 01/2024). The solutions developed during other NEFI projects, such as the InduGrid platform for operational energy communities or the energy communities planning tool, would be possible starting points for realizing cost savings in the electricity sector. Electricity price reductions for heat pump operators with high CO_2 savings potential or tax incentives would also be an option.

4.5.2 Economies of scale

Economies of scale in the field of steam-generating heat pumps are currently still very difficult to quantify. Due to the complexity of retrofitting steam-generating heat pumps in existing industrial plants, which are usually built individually and over long periods of time, standardization and the associated economies of scale are difficult to achieve. As described in Agora Energiewende [14], economies of scale can be considered from two points of view: firstly, the occurrence of economies of scale in production through increased quantities and, secondly, through larger heat pump sizes. According to Agora Energiewende [14], lower specific costs can occur with heat pumps in higher heat capacity classes. It is mentioned that for heat capacity above 10 MW, the costs per installed MW of heat capacity are only around half as high as for heat pumps with 2-5 MW heat capacity.

The closer to the process a heat pump is integrated, the more complex the integration is expected to be and the more application-specific the heat pumps must be designed. The opposite is the case for example, when heat pumps are integrated at supply level. It can also be assumed that the heat pumps at process level have a lower heat capacity than heat pumps that are integrated at supply level. Furthermore, integration at supply level could also increase the operating hours of the heat pump component. Nevertheless, it should be noted that in general the efficiency of the heat pump component is higher the closer to the process it is integrated.

One way to realize high operating hours and a larger heating capacity could be a sharing platform. Thus, not only use of a heat pump is shared but also costs are split up between several companies. This concept is also discussed again in the next chapter.

It is difficult to standardize heat pumps, especially when it comes to integration at process level. A higher number of steam-generating heat pumps integrated into industrial processes could support standardization and thus lead to economies of scale in production. Comprehensive funding would also lead to an accelerated adaptation of heat pumps in other industrial sectors, which can also lead to economies of scale if the amount is appropriate. It would be fundamentally important to consider steam-generating heat pumps as early as the planning stage for new industrial plants.

4.5.3 Business models

The topic of contracting and sharing platforms is discussed in this chapter. Such business models can help to increase the number of integrated steam-generating heat pumps in industrial processes.
The “Bundesamt für Wirtschaft und Ausfuhrkontrolle” [15], describes four different contracting models for general applications. In relation to steam-generating heat pumps, the models can be described as follows:

- Energy saving contracting: Financing, planning, implementation, and support of heat pump by contractor. Contractor guarantees steam-generating cost savings and receives a share of these savings as remuneration.
- Energy supply contracting: Financing, planning, implementation, and support of heat pump by contractor. Contractor supplies steam at a fixed price.
- Operating management contracting: Contractor optimizes existing steam-generating heat pump. The rest is the same as for energy supply contracting.
- Financial contracting: Financing, planning and implementation of the steam-generating heat pump by contractor. Contracting client operates the heat pump and pays back system costs over the duration of the contract.

In principle, all four contracting models are conceivable, but the operating management contracting model implies that a steam-generating heat pump is already integrated in the industrial operation and therefore does not support the implementation of steam-generating heat pumps in industry.
With the first two contracting models, however, it depends on what is used as the heat source for the heat pump. If waste heat from the industrial site is used, it is essential that an agreement is made as to how the waste heat source must be available (temperature, humidity, mass flow) to achieve the corresponding savings or a corresponding COP. Furthermore, it must be regulated what happens if the heat pump does not have the appropriate waste heat available or the agreed operating hours cannot be achieved.
For manufacturers acting as contractors, such models can be particularly interesting as they can bring their newer products into application more quickly and collect operating hours, thus creating trust in the

product. However, here too the framework conditions must be designed, or subsidies offered in such a way that an economic advantage is created for the contractor and the end user.

Aneo Industry AS supplies heat pumps that generate steam up to 5 bar_a, currently only in Norway. This supplier offers its product as an “energy as a service" solution with monthly fixed costs. Planning, engineering, installation, financing, and power consumption is included in the costs. The heat pump is operated by the end user, who is trained by the supplier and the system is monitored by the supplier. This means that the technical risk, performance, and investment remain with the supplier. [2, 16]

Moreover, a future contracting model could also include Power Purchase Agreements (PPA). This would include three contracting partners:

- Green electricity provider
- Heat pump operator
- Industrial company that uses the heat pump in production

To implement this contracting model, a detailed risk-sharing model is required. This must define the consequences of non-fulfilment or deviation from the guaranteed electricity and heat capacity and temperature level on source and sink side of the steam-generating heat pump. This also requires a comprehensive monitoring and reporting system that enables extensive monitoring of the performance parameters. Regular reports ensure compliance with the contract and enable a rapid response in the event of deviations. Adjustment mechanisms in the event of a significant change in electricity prices, for example, will also be part of this model.

A high number of operating hours leads to shorter payback periods. A sharing platform would be conceivable, which could be operated at large industrial cluster locations such as the Chemiepark Linz[3], Upper Austria. The companies located there could be supplied from a central location via a steam network (which already exists in Linz). For the heat pump operator, this could make it possible to increase the operating hours, provided that the companies agree on a time-adjusted steam supply. Furthermore, it could be possible that a heat pump with higher heating capacity (economy of scale) can be used than it would be the case for each individual industrial site. If several companies are involved, the endeavor is very complex. There are numerous challenges to consider. For example, a sufficiently large waste heat source must be available here and the corresponding quality must be ensured. The implementation of a waste heat network could be necessary. In addition, there is a comprehensive set of contracts that regulate the distribution of investment and operating costs, as well as liability and utilization agreements.

5 Outlook and recommendations

The variation of specific factors that influence the payback period, such as electricity and gas prices, operating hours, specific heat pump cost and CO_2 price, shows the complexity of interactions and the high

[3] https://www.chemiepark.at/en/location/contact.html, Accessed on 17.04.2024

number of factors influencing the economic performance and feasibility of steam-generating heat pumps or heat pumps in general.

The heat pump has the potential to be a key technology for the decarbonization of Austrian industry. Steam in particular will also play an important role in industrial processes in the future. Therefore, steam-generating heat pumps are an important technology for increasing efficiency, electrification and thus decarbonization of the process steam supply. It was shown that significant CO_2 emission savings and also final energy and primary energy savings are possible through the use of steam-generating heat pumps. However, due to the current price level of steam-generating heat pumps and the ratio of electricity to natural gas prices, it is currently difficult to realize projects economically. Also, the end user survey has shown that long payback periods, high investment costs, as well as risks for production safety and temperature level are obstacles for the integration of steam-generating heat pumps.

There are already steam-generating heat pump products available on the market, but their range of application is sometimes very limited and, depending on the product, the TRL can also be very low. A significant development of the steam-generating heat pump technologies on the market is to be expected in the next few years.
Incentives to minimize the economic risk (low TRL) are needed to promote the broad integration of this technology in the industrial environment. Also, stronger incentives for decarbonization must be created for the end user to accelerate the distribution of the technology. Compared to alternative decarbonization technologies in particular, the studies showed that the heat pump can offer significant economic advantages.

First-movers, such as the NEFI demonstration project AHEAD, which tackles the specific challenges and help the technology achieve a breakthrough, are important as examples of best practice. Close cooperation between industry, funding organizations and research institutes is essential if steam-generating heat pumps are to achieve a breakthrough in the near future. This breakthrough can make a significant contribution to achieving national and international decarbonization targets.

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