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DryFiciency

Waste Heat Recovery in Industrial Drying Processes

H2020-EE-2016-2017-PPP
Valorisation of waste heat in industrial systems (SPIRE PPP)

Final report on the heat pump technologies developed

D5.4

This Deliverable is a summary of WP4 and WP5.

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INDEX

Statement of originality:

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NOTES: For comments / suggestions / contributions to this document, contact: Coordinator of DryFiciency project at Veronika.Wilk@ait.ac.at. For more information on the project DryFiciency, link to www.dryficiency.eu

List of abbreviations

AT	Austria
AGA	Agrana
COP	Coefficient of Performance
EVI	Enhanced Vapor Injection
GWP	Global Warming Potential
HEX	Heat exchanger
IHX	Internal Heat Exchanger
MVR	Mechanical Vapor Recompression
SCS	Scanship
SHS	Superheated steam
VHE	Viking Heat Engines
WBG	Wienerberger

EXECUTIVE SUMMARY

Deliverable D5.4 *Final Report on the heat pump technologies developed* reports on the work conducted, and selected results achieved during integration, commissioning and demonstration of the heat pump systems developed and demonstrated for the first time in an industrial setting. Information on the design and configuration of the three novel heat pump prototypes and the research and development work undertaken on component and heat pump unit level in the first phase of the project are included in D4.5 *“Interim report on the heat pump technologies developed”*. The heat pump demonstrators and their integration infrastructure are described in detail in D4.3 *Integrated Heat Pump System.* More information on key performance indicators achieved is included in D5.2 *Report on the validation of the energy savings for each demo site*.

1 INTRODUCTION

Industrial drying and dehydration processes require vast amounts of energy. Estimates show that in developed countries, 12 to 25% of the industrial energy consumption is attributable to industrial drying. Currently, most of this energy is derived from fossil fuel use, with little-to-no utilization of waste heat streams. Hence, there is great potential for more efficient and environmentally-friendly technologies within industrial drying processes.

In the DryFiciency project, **three novel high temperature heat pump systems** were developed and demonstrated, thereby **utilizing waste heat streams** from three **drying processes and applications**:

In the **agricultural raw material application**, heat pump technology is used for **starch drying**. The technology demonstration takes place at Agrana Stärke GmbH (www.agrana.com) in Pischelsdorf, Austria.

The application in the **ceramic sector** is focused on integrating a novel heat pump technology for **green brick drying**. The technology is implemented by Wienerberger AG (www.wienerberger.com) in Uttendorf, Austria.

The application for the **waste management industry** is geared at **sludge drying**. The technology is integrated at a biomass plant in Lindum in Drammen, Norway.

The **three advanced high temperature heat pump systems** are composed of **two closed loop heat pump systems** based on the novel refrigerant Opteon™ MZ (R-1336mzz(Z)) and **one open loop heat pump system** that uses water (R-718) as a refrigerant.

The **main innovations** of the **closed loop heat pump systems** include:

Two advanced compressor technologies, modified screw compressors by Bitzer Kühlmaschinenbau GmbH (www.bitzer.de) and novel piston compressors by Viking Heat Engines (www.vikingheatengines.com) enable discharge temperatures of up to 160°C. Two screw compressors are integrated in the heat pump application at Agrana for starch drying; the one for brick drying at Wienerberger uses eight piston compressors. Details on the development work are included in *D4.5 "Interim report on the heat pump technologies developed",* specifically in sections 2.1.1 and2.1.2.

A **unique synthetic lubricant** for high temperature applications, which was developed by FUCHS (www.fuchs.com) for both compressors and which is sufficiently viscous and chemically stable with the refrigerant selected (Opteon™ MZ from Chemours) at elevated temperature levels. Details on the development work are included in *D4.5 "Interim report on the heat pump technologies developed",* section 2.3

Opteon™ MZ from Chemours (www.chemours.com), a synthetic refrigerant based on HFO (hydrofluoro-olefin), was developed, prior to the project, for high temperature applications with heat supply temperatures of up to 160°C.

It has a low GWP (Global Warming Potential) of 2 and demonstrates a number of favourable characteristics, such as non-flammability and non-toxicity. It is also not subject to the EU legislation to control F-gases (so called F-gas regulation).

The **design** of the **closed loop refrigeration cycle,** which was developed by AIT, is based on **numerical simulations.** It is described in more detail in *D4.5 "Interim report on the heat pump technologies developed",* section 2.4. This deliverable contains information on an appropriate process control for the two air drying processes.

The **main innovations** of the **open loop heat pump system**, commonly referred to as MVR (Mechanical Vapour Re-compression), includes:

Advanced, **low-cost**, **oil-free turbo-compressor technology** from ROTREX AS (www.rotrex.com), which originates from the automotive sector and has been further developed to reach condensation temperatures of up to 155°C. Details on the development work are included in *D4.5 "Interim report on the heat pump technologies developed",* section 3.4

Novel, highly efficient MVR dryer technology, which has achieved efficiency and capacity gains of more than 75%, while reducing energy consumption by 70%. The technology's main achievements are outlined in section 3.1.1 of this deliverable.

The **design** of the **MVR system,** which was elaborated and implemented by EPCON (www.epcon.no) and SINTEF (www.sintef.no). The boundary conditions of the drying application at Drammen are described in more detail in D4.5 *"Interim report on the heat pump technologies developed",* section 4. SINTEF and EPCON were also responsible for the integration and commissioning of the MVR heat pump at the demo-site, which is described in section 3 of this deliverable.

2 CLOSED LOOP HEAT PUMP SYSTEM

In the following section, the work undertaken, and selected results achieved during commissioning and demonstration of the two closed loop heat pump demonstrators are outlined.

The boundary conditions of the two **water-to-water compression heat pumps**, as well as work performed and results achieved on **component** (compressors, lubricant) and **heat pump unit level** (configuration of refrigeration cycle, sizing and positioning of heat pump prototypes) are presented in *D4.5 “Interim report on the heat pump technologies developed”*, section 2.1 to 2.4. The two heat pump demonstrators and their integration infrastructure are described in detail in D4.3 *Integrated Heat Pump System.*

2.1 Commissioning phase

The commissioning of the heat pumps was undertaken in two phases:

- In the first phase, also referred to as the **start-up** phase, all relevant equipment, and components, including the heat pump control functions, were thoroughly assessed for their functionality.
- In the second phase, a **trial operation** of the heat pump system was carried out, the aim of which was to provide its proof of operational safety and functional capability. The quality of the heat pump system was also assessed against functional tests according to predefined operating conditions to test the control algorithms, compressor lubrication, oil separation, operating temperatures of the compressors, the suction gas super heating, and part load conditions. The successful completion of the trial operation was the end of the commissioning phase and an important prerequisite for the subsequent long-term monitoring and improvement of the heat pumps’ performance.

2.1.1 Heat pump demonstrator for brick drying at WIENERBERGER

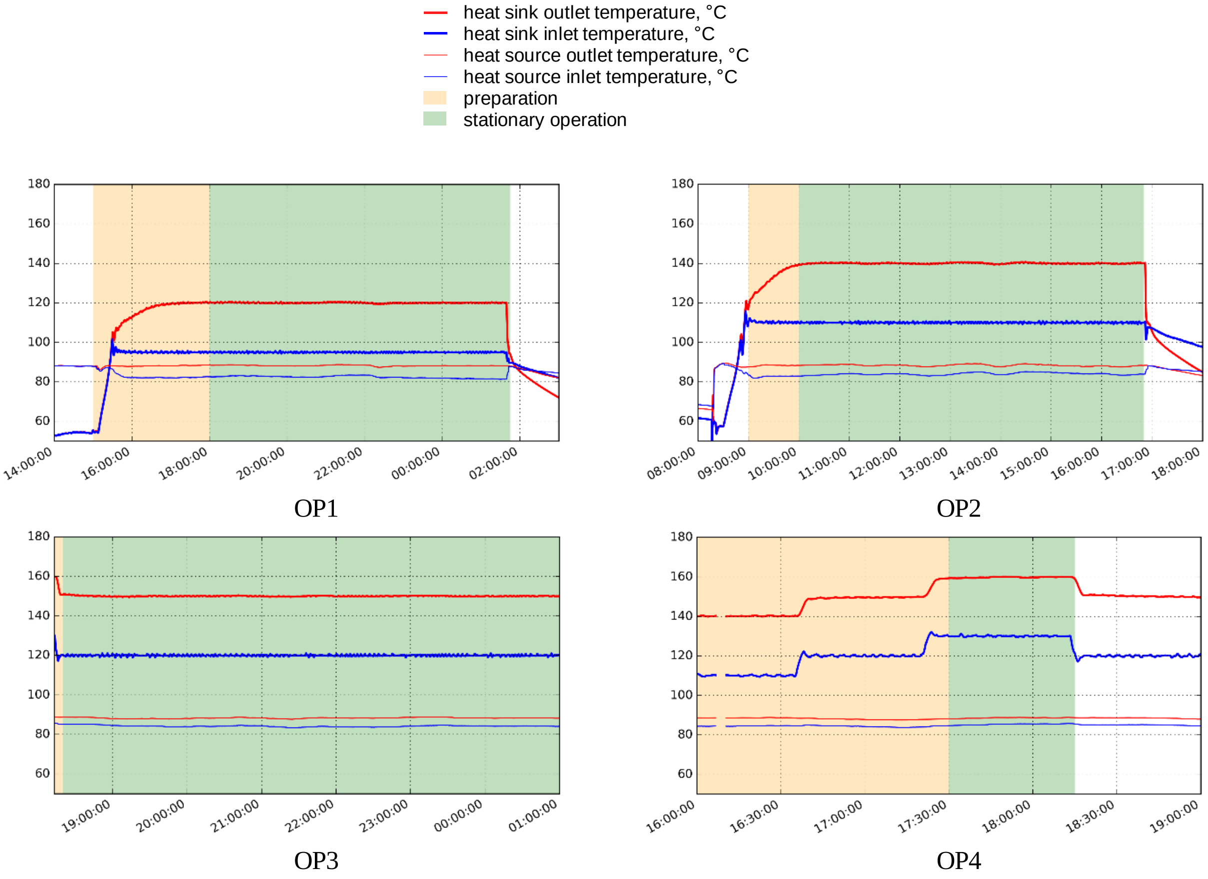
The commissioning of the closed loop heat pump demonstrator for brick drying at the demo-site of Wienerberger Österreich GmbH in Uttendorf, Austria, took place in November/December 2019.

Four different operation conditions were assessed at the trial operation. They are characterized by different heat supply temperatures; namely, 120, 140, 150 and 160 °C (see Table 1). Operation at 120°C is the design point of the heat pump demonstrator (marked in grey in Table 1).

Table 1:Operation points during trial operation

Operation point (OP)	Heat sink inlet temp., °C	Heat sink outlet temp., °C
1	95	120
2	110	140
3	120	150
4	130	160

Figure 1 illustrates the heat source and heat sink inlet and outlet temperatures for the four defined operation points for the trial operation. The yellow area indicates the preparation phase, the green area the stationary operation of the heat pump demonstrator. For OP 1, 2 and 3, the stationary operation lasted more than three hours and did not show any fluctuations in the heat source and heat sink. For OP4, the operation was shorter and lasted around one hour. The heat source inlet temperature was 88 °C for all operation points. The complete heat source mass flow was used for the heat pump without flow regulation, as a result, the heat source was cooled by 3 to 6 K.



OP1 OP2

OP3 OP4

Figure 1: Time series diagrams for four different operation points (120, 140, 150 and 160 °C)

As described in more detail in *D4.5 “Interim report on the heat pump technologies developed”*, and shown in Figure 2, the DryFiciency heat pump for brick drying is designed as a twin cycle system consisting of two refrigerant cycles. The condensers of the two cycles are connected in series, therefore the condensation temperature of cycle 1 (yellow) is lower than the condensation temperature of cycle 2 (orange). The evaporators can be either operated in series or in parallel.

For the trial operation at Wienerberger, they were operated in parallel. Figure 3 shows the log(p)-h diagram of both cycles for OP1 (120 °C). Sections 1-2 takes place in the compressor; 2-3 in the condenser; 3-4 in the sub-cooler; 4-5 at the hot side of the internal heat exchanger (IHX); 5-6 in the expansion valve; 6-7 in the evaporator; and 7-1 at the cold side of the internal heat exchanger. Due to the sub-cooler, more heat can be supplied to the industrial process. The sub-cooler is integrated between the condenser and the internal heat exchanger (not illustrated in Figure 2). In cycle 2, more heat is provided in the sub-cooler than in cycle 1. For both cycles, the evaporation temperature amounted to 78 °C. As indicated by point 7, the refrigerant leaves the evaporator with super heat. The internal heat exchanger increases the efficiency by transferring heat from the high-pressure side to the low pressure side of the heat pump. Point 1 and 2 indicate the satisfying function of the super heat control to ensure dry compression. The difference in condensation temperature between cycle 1 and cycle 2 was 10 K.

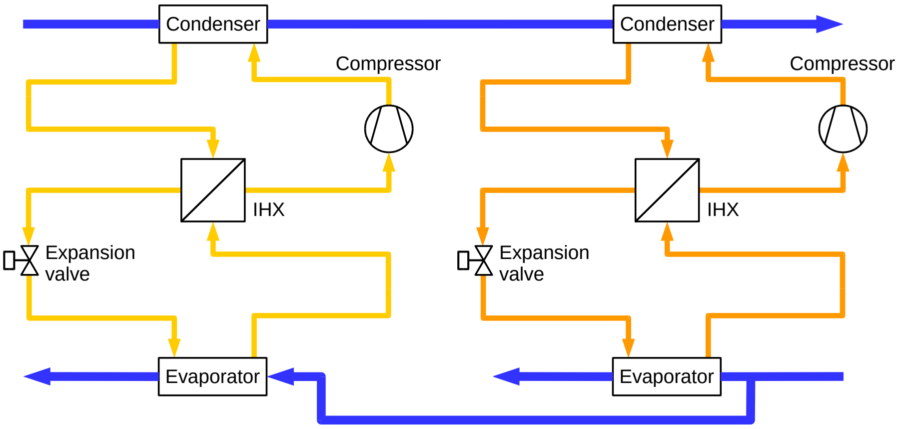


Figure 2: Layout of the DryFiciency heat pump (yellow = cycle 1, orange = cycle 2)

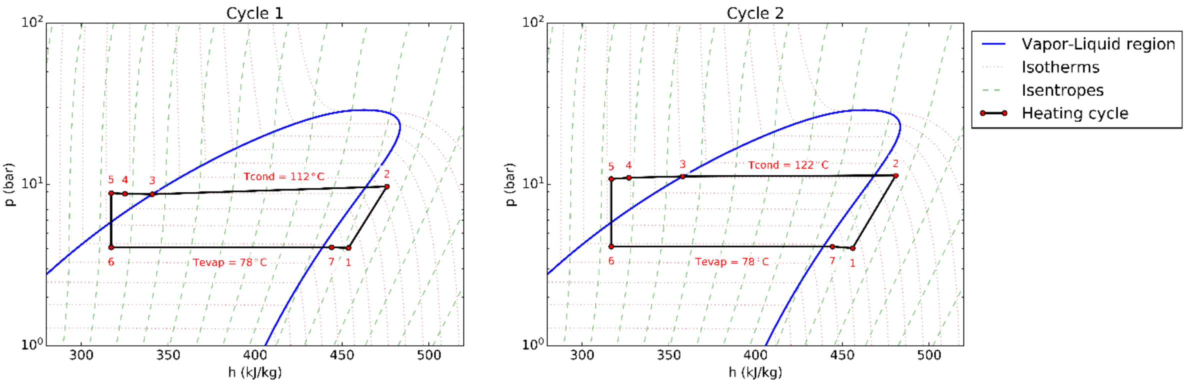


Figure 3: Log(p)-h diagram for cycle 1 and 2 of the heat pump, OP1 (120 °C)

OP2, OP3 and OP4 show similar behavior as illustrated in Figure 4, Figure 5, and Figure 6. With increasing temperature lift, more compressor work is needed to achieve higher discharge pressures. At a heat supply temperature of 160 °C, condensation takes place at the upper end of the vapor dome close to the critical point. With increase in supply temperature, the beneficial effect of the internal heat exchanger becomes more apparent. More superheat is needed at higher temperatures due to the shape of the vapor dome of R-1336mzz(Z).

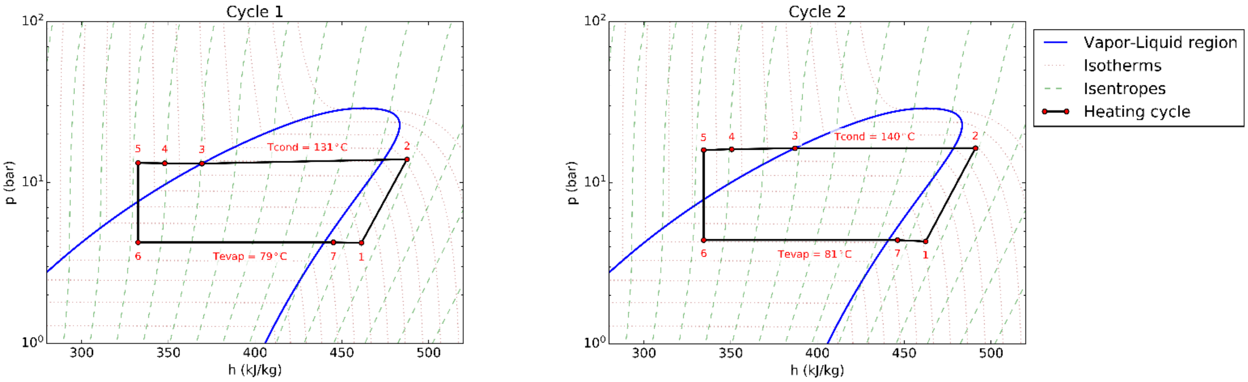


Figure 4: Log(p)-h diagram for cycles 1 and 2 of the heat pump, OP2 (140 °C)

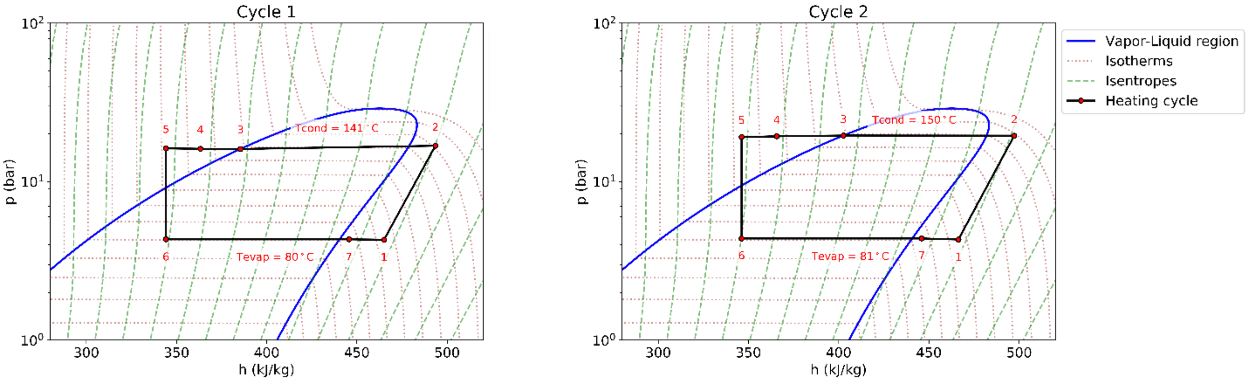


Figure 5: Log(p)-h diagram for cycles 1 and 2 of the heat pump, OP3 (150 °C)

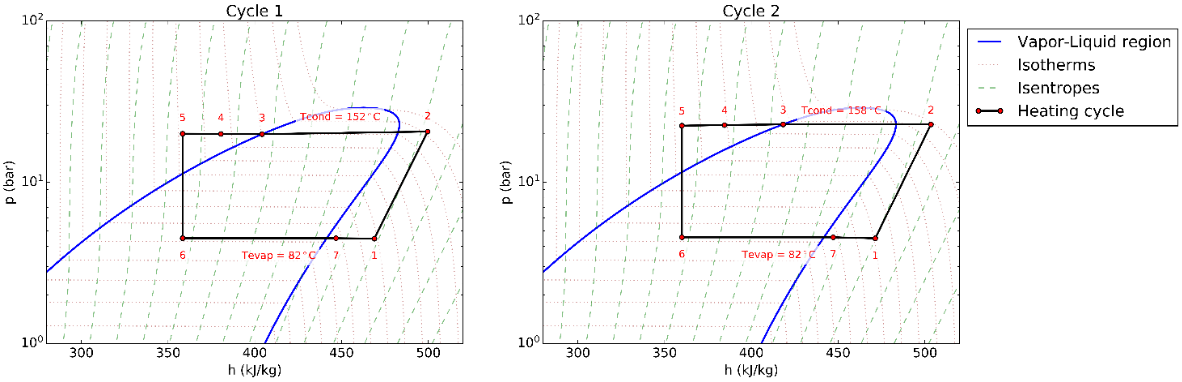


Figure 6: Log(p)-h diagram for cycle 1 and 2 of the heat pump, OP3 (160 °C)

Table 2 outlines the energy flows, mass flows and temperatures measured during trial operation. The compressors were operated at 1500 rpm. Q_{heat} is the sum of the heat transferred to the industrial process in the condenser and in the sub-cooler, ranging from 200 – 300 kW for the trial operation. Q_{cool} is the heat extracted from the heat source in the evaporator, ranging from 150 – 240 kW. The COP is calculated as the ratio of heat provided for the industrial process and the electricity consumption P_{el}. For OP1 (design point), the COP is the highest due to the smallest temperature lift of 40 K. It amounted to 4.65. At OP4 (heat sink outlet temperature of 160°C), the COP was 2.66.

Table 2: Operation points during trial operation

OP	Qheat, kW	Qcool, kW	Pel, kW	COP	Vsink, m³/h	Vsource, m³/h	Tsink_in, °C	Tsink_out, °C	Tsource_in, °C	dTsource, K
1	281.7	239.0	60.6	4.65	9.9	33.3	95.8	120.9	88.3	6.5
2	254.0	208.5	68.5	3.71	7.5	45.5	110.7	140.9	88.4	4.2
3	221.2	174.3	69.6	3.18	6.5	37.6	120.7	150.9	88.4	4.3
4	195.9	148.4	73.8	2.66	5.9	42.3	130.7	160.7	88.6	3.3

2.1.2 Heat pump demonstrator for starch drying at AGRANA

Due to COVID-19, the commissioning of the closed loop heat pump demonstrator for starch drying at the demo-site of Agrana Stärke GmbH in Pischelsdorf, Austria, took place in various phases: February/March 2020; April/May 2020; and June/July 2020.

Three different operating conditions were assessed in more detail in the trial operation. They are characterized by different heat supply temperatures: 100, 115, and 135 °C[1] (see Table 3).

Table 3:Operation points during trial operation

Operation point (OP)	Heat sink inlet temp., °C	Heat sink outlet temp., °C
1	90	100
2	95	115
3	115	135

Figure 7 illustrates the heat source and heat sink inlet and outlet temperatures for the three operation points at the Agrana demonstrator. The yellow area indicates the preparation phase, the green area the stationary operation. For OP 1 and OP 2 the stationary operation lasted about 4 hours and showed hardly any fluctuations of the heat source and the heat sink. For OP 3, the operation was shorter and lasted around 3.5 hours. The heat source inlet temperature was 67°C to 75°C for all

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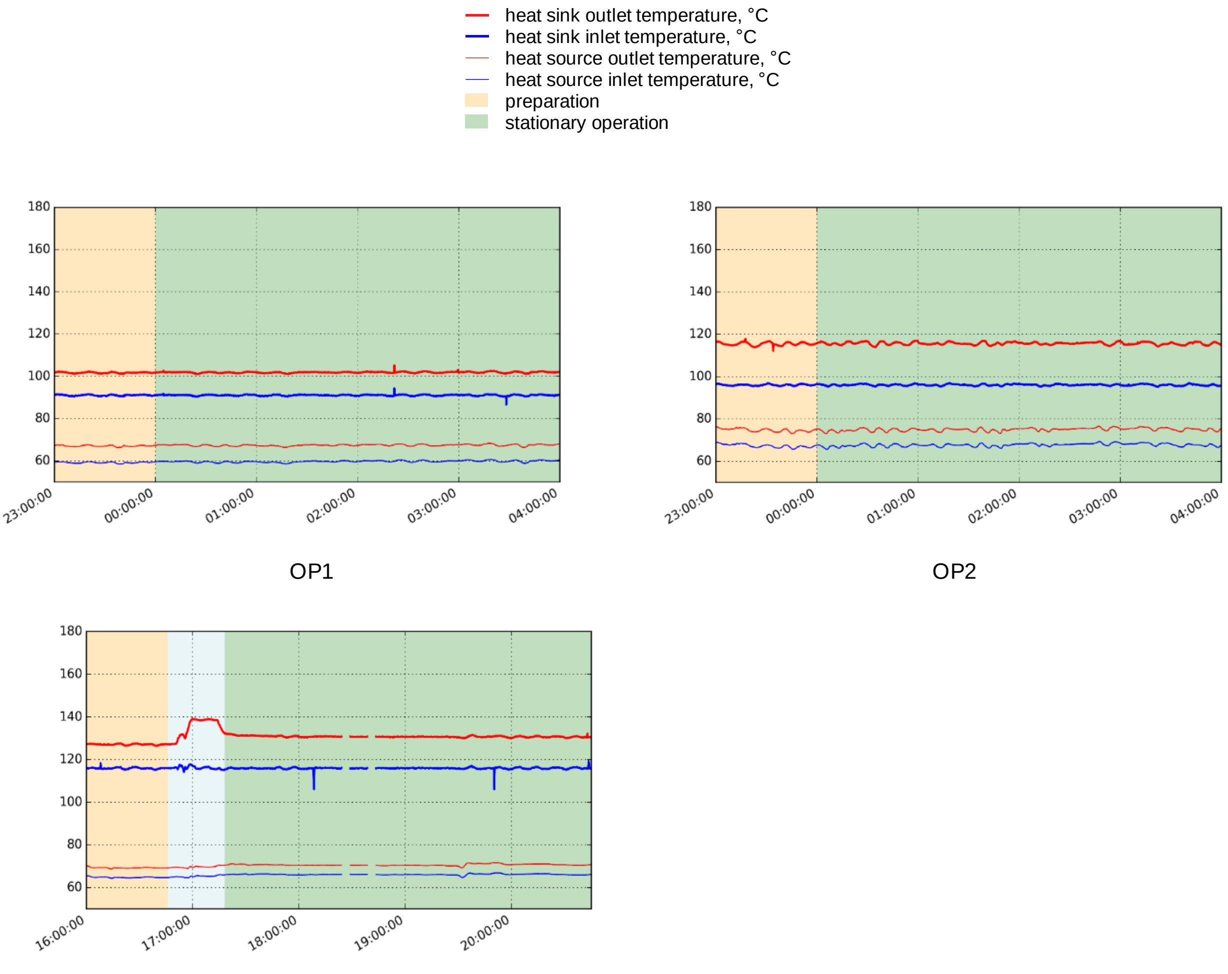
[1] During trial operation, maximum heat sink outlet temperatures of 135°C were reached. Further increases to 140°C (design point for the AGA demonstrator) and to 160°C (maximum temperature to be reached) was omitted at this stage, as problems with the oil cooler occurred and it could not be ensured to keep the oil temperature within the allowed operation range at this time.

operation points. The entire heat source mass flow was used for the heat pump without flow control, so that the heat source was cooled by 3 to 7 K.



OP1

OP2

OP3

Figure 7: Time series diagrams for three different operation points (100, 115, and 135 °C)

As described above for Wienerberger and shown in Figure 2, the DryFiciency heat pump for starch drying is also designed as a twin cycle system consisting of two refrigerant cycles. The evaporators can be either operated in series or in parallel but were operated in parallel for the trial operation.

Figure 8 shows the log(p)-h diagram for both cycles for OP1 (100 °C). Section 1-2 takes place in the compressor; 2-3 in the condenser; 3-4 in the sub-cooler; 4-5 at the hot side of the internal heat exchanger (IHX); 5-6 in the expansion valve; 6-7 in the evaporator; and 7-1 at the cold side of the internal heat exchanger. Due to the sub-cooler, more heat can be supplied to the industrial process. The sub-cooler is integrated between the condenser and the internal heat exchanger (not illustrated in Figure 8). In cycle 2, more heat is provided in the sub-cooler than in cycle 1. For both cycles, the evaporation temperature was around 53°C. As indicated by point 7, the refrigerant leaves the evaporator with super heat. The internal heat exchanger increases the efficiency by transferring heat from the high-pressure side to the low pressure side of the heat pump. Point 1 and 2 outline the transfer of the super heat control to ensure dry compression. The difference in condensation temperature between cycle 1 and cycle 2 was 5 K.

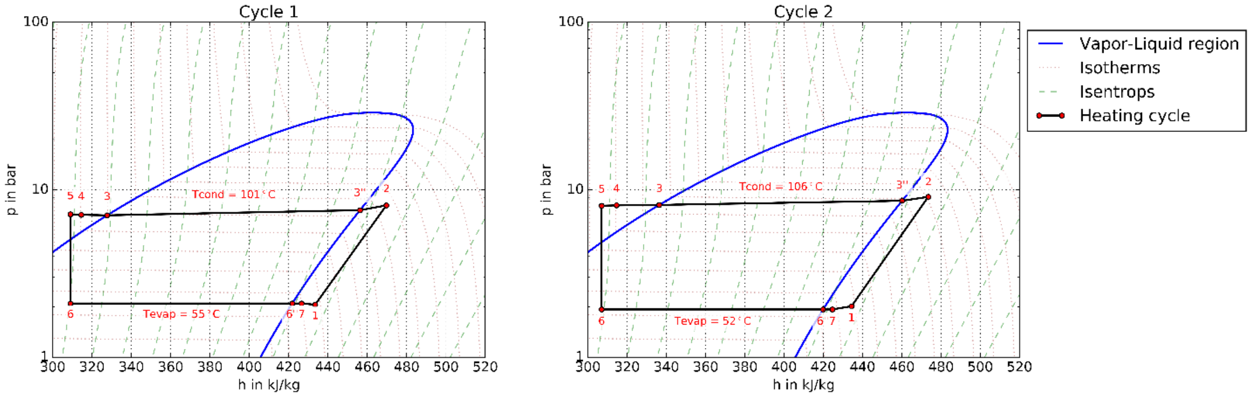


Figure 8: Log(p)-h diagram for cycle 1 and 2 of the heat pump, OP1 (100 °C)

OP2 and OP3 show similar behavior as OP1, as depicted in Figure 9. The difference between the two condensation temperatures increases with higher temperature difference between the inlet and outlet of the heat sink. For example, in OP 2, the difference between the condensation temperatures is the highest, and amounts to 8 K. Both condensation and evaporation temperatures are calculated from measured condensation and evaporation pressures.

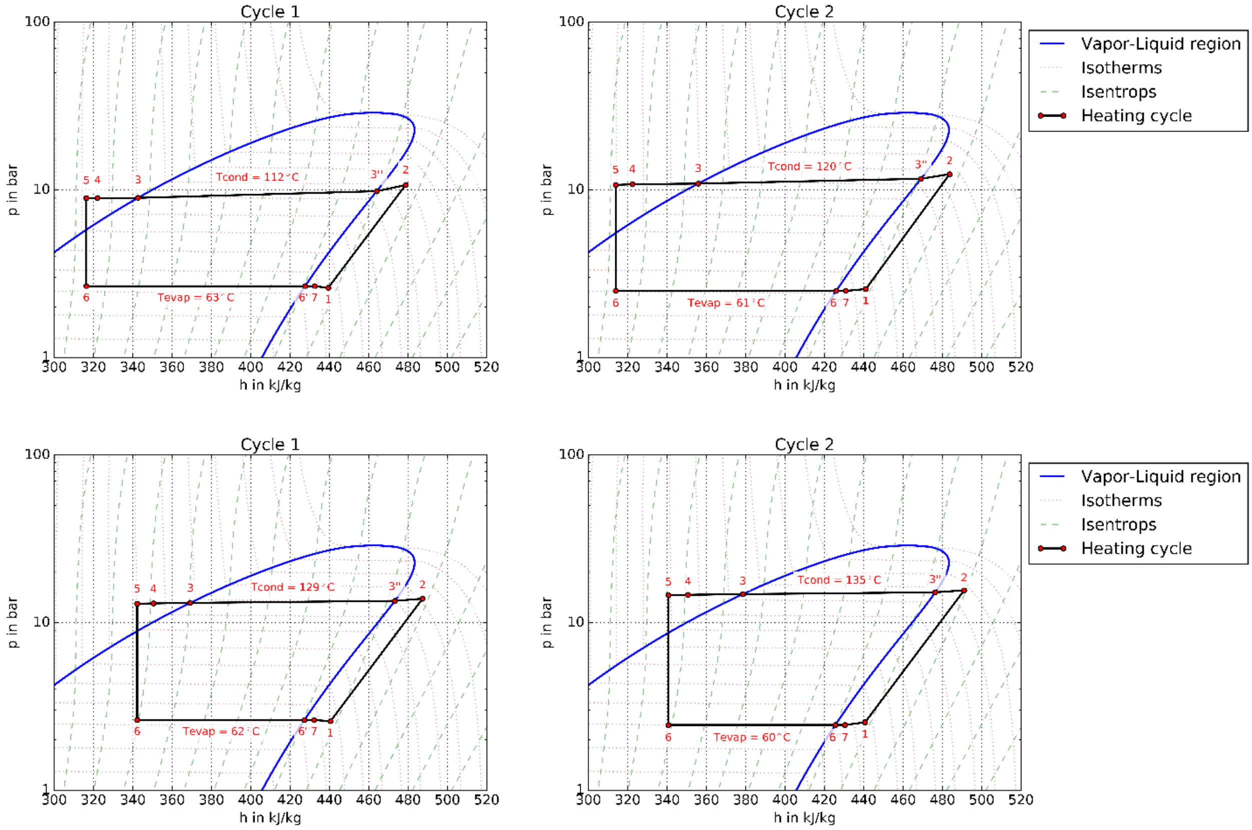


Figure 9: Log(p)-h diagram for cycle 1 and 2 of the trial operation of OP 2 and OP 3

Table 4 outlines the energy flows, mass flows and temperatures for the trial operation. Q_{heat} is the sum of the heat transferred to the industrial process in the condenser and in the sub-cooler, ranging from 230 – 340 kW for the trial operation. Q_{cool} is the heat extracted from the heat source in the evaporator, ranging from 165 – 250 kW. For OP1, the COP is the highest due to the smallest temperature lift of 42 K. It amounted to 3.73. At OP3 (heat sink outlet temperature of 135°C), the

COP was 2.17. Compared to the trial operation of Wienerberger, the heat source temperature of Agrana was considerably lower, requiring higher temperature lifts and more compressor work. Therefore, the COP is lower when comparing the results for the same heat supply temperature.

Table 4: Operation points during trial operation

OP	Qheat, kW	Qcool, kW	Pel, kW	COP	Vsink, m³/h	Vsource, m³/h	Tsink_in, °C	Tsink_ out, °C	Tsource _in, °C	dTsourc e, K
1	230.5	186.3	61.7	3.73	18.8	20.1	91.0	101.9	67.4	7.7
2	336.6	249.0	96.1	3.50	15.2	30.0	96.1	115.7	75.0	7.3
3	271.6	163.4	125.1	2.17	13.9	31.7	116.1	134.8	69.6	4.4

2.2 Demonstration phase

2.2.1 Heat pump demonstrator for brick drying at WIENERBERGER

The demonstration phase covers the period from December 2019 till August 2021. In total, the heat pump demonstrator for brick drying has collected **4.020 hours in operation,** covering heat supply temperatures from 100°C up to 160°C. Figure 10 depicts the distribution of operating hours in terms of heat sink outlet temperature. Most operational experience was gathered at heat sink temperatures of 140°C and 120°C, which represents the required site conditions. However, **572 hours** have been collected at elevated temperature levels from 150°C up to 160°C.

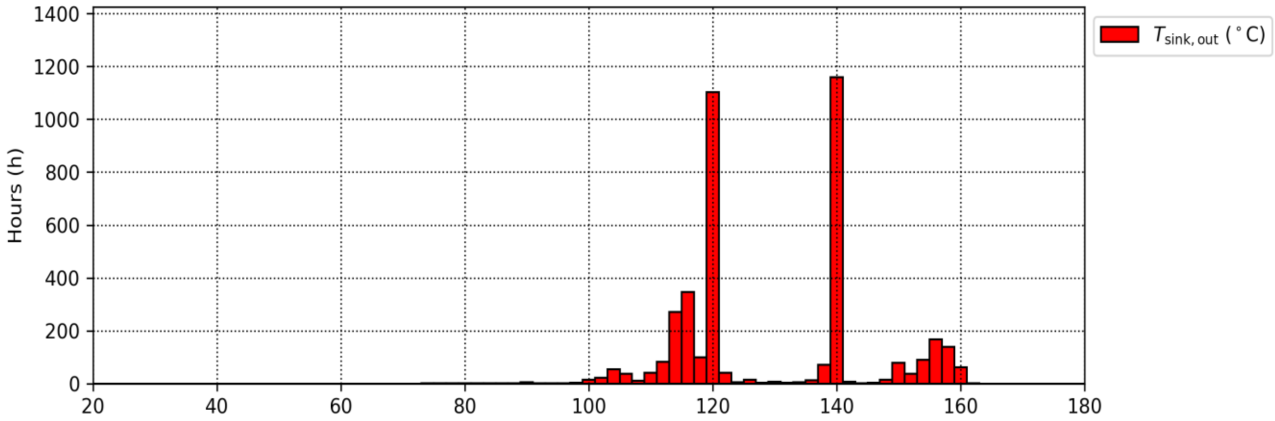


Figure 10: Distribution of operating hours collected from the heat pump demonstrator for brick drying

The following figure shows snapshots of heat sink and source inlet and outlet temperatures from the HP operation at two selected points in time. On the left, a period of about 3 weeks of operation is shown shortly after the trial operation. The fluctuations in the heat sink inlet temperature are created by the industrial process and show changing operation conditions at the beginning of the week. However, the heat source outlet temperature remains constant, illustrating the successful implementation of the heat pump control algorithm.

On the right, a period after approx. six months of the, demonstration phase, illustrates the reaction of the control algorithm to the change in the set point of the heat sink outlet temperature that was increased from 120°C to 140°C and to 160°C. The reaction of which were found to be quite satisfactory. There were also fluctuations in the heat source that were levelled out smoothly by the control algorithm. The implemented control approach proved to be favorable.

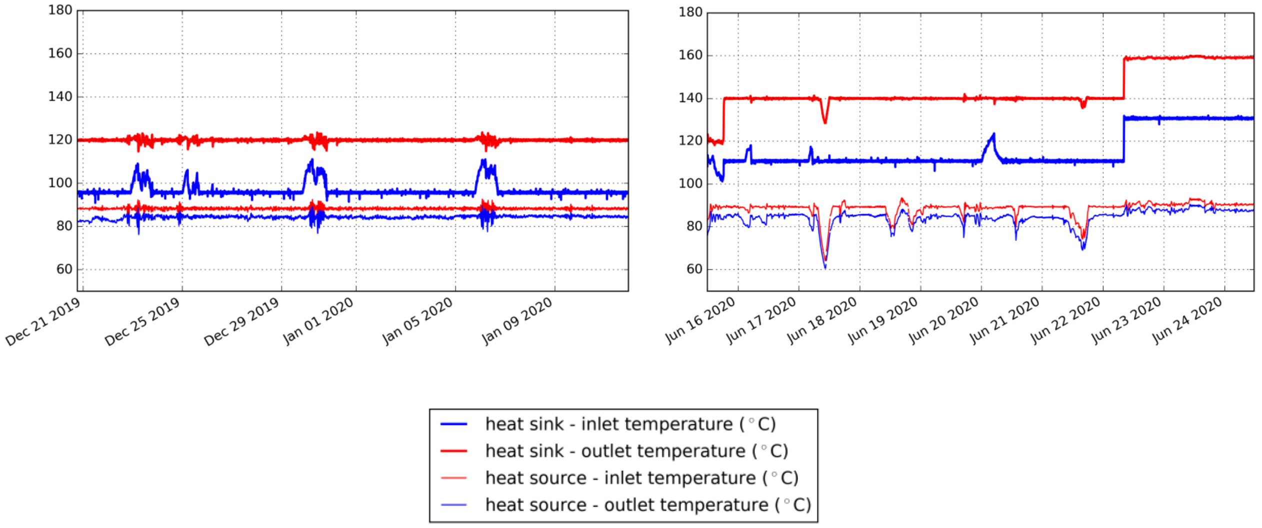


Figure 11: Selected operation data of the heat pump demonstrator for brick drying

2.2.2 Heat pump demonstrator for starch drying at AGRANA

The demonstration phase covers the period from August 2020 till August 2021. In total, the heat pump demonstrator for starch drying has collected **4.008 hours in operation,** covering heat supply temperatures ranging from 90°C to 160°C and reaching a maximum heat output of 370kW. Figure 12depicts the distribution of collected operation hours in terms of heat sink outlet temperature. As evident, most operational experience was gathered at heat sink temperatures of 134°C, 155°C and 130°C, which represent the required site conditions. However, **897 hours** were collected at supply temperatures from 150° to max. 160°C.

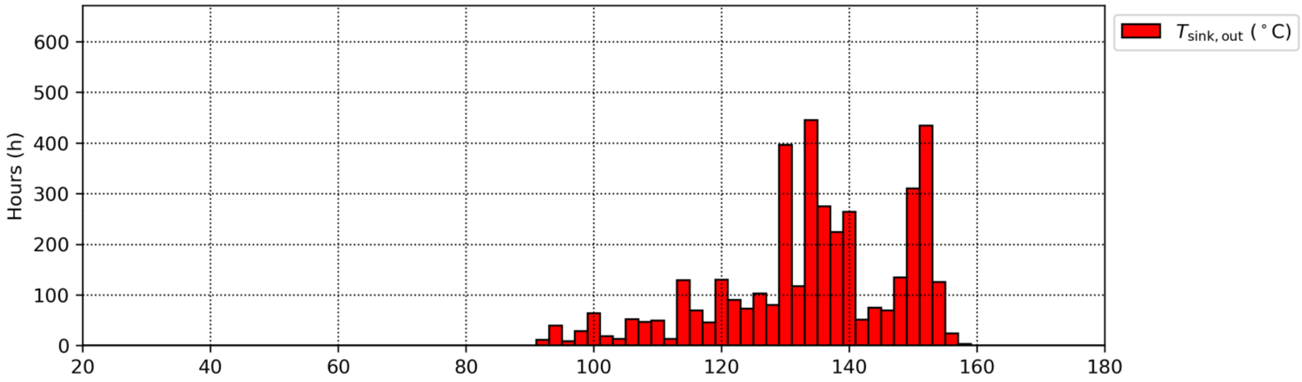


Figure 12: Distribution of operation hours collected of the heat pump demonstrator for starch drying

The following figure shows snapshots of heat sink and source inlet and outlet temperatures from the HP operation at two selected points in time. A week of operation after approximately seven months of the demonstration phase, is presented on the left. The heat source temperature is considerably lower compared to the Wienerberger plant and shows much more fluctuation. The heat sink temperatures, however, were constant at 110°C and 135°C respectively. This demonstrates a very satisfactory reaction from the heat pump control algorithm, which leveled out the variations of the heat source. A period after ten months of operation is shown on the right. Here, the set point of the heat sink inlet and outlet temperatures were varied to test different conditions. The heat sink outlet temperature was in the range of 150 to 155°C, the heat sink inlet temperature was varied to test the influence of different temperature differences in the condenser. The reaction of the control algorithm was found to be very satisfactory. During that period, the heat source temperatures varied in the range of 60-80 K, only a sudden temperature increase of 20 K translated into a small peak in the heat sink outlet temperature (June 24th). The control proved to be favorable.

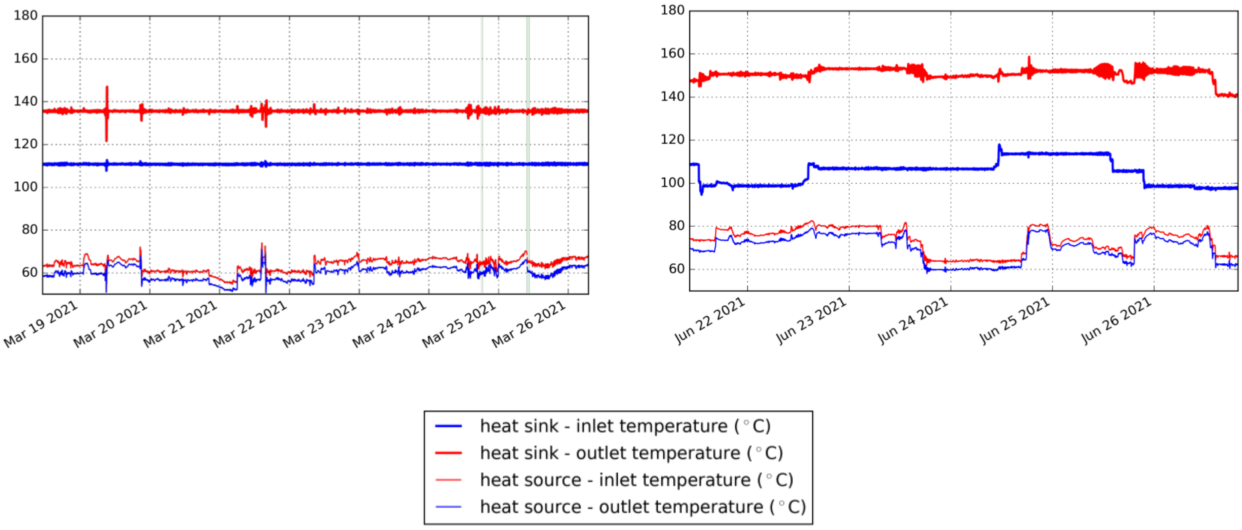


Figure 13: Selected performance data of the heat pump demonstrator for starch drying

2.3 Performance assessment of the two closed loop heat pumps

Figure 14 provides an overview of the heat pump (COP) efficiency as a function of the temperature lift, which is the temperature difference between heat source outlet and heat sink outlet. The COP is the ratio of heat supplied to the process and electricity consumed by the heat pump. This analysis is based on a statistical approach considering all data collected during demonstration. Each data point shown in the diagram represents at least 10 h of stationary operation with constant temperatures and compressor speed. Crosses are used for data of the WBG demonstrator and rings for the AGA demonstrator. The error bars illustrated for each data point show how much variation was found in operation data that is presented as a single data point. In the diagram, the COP for an ideal heat pump with a second law efficiency of 50% and a heat supply temperature of 120°C is also included.

As evident, the COP ranges from 5.0 at 120°C (heat sink outlet) and 84°C (heat source outlet) to 2.2 at 160°C (heat sink outlet) and 89°C (heat source outlet) for the Wienerberger demonstrator. The variations for the COP are on average 3%, the variations of the temperature lift are lightly higher with ca. 4%. Design point: At a heat supply temperature of 120.9°C and a heat source outlet temperature of 84°C, the heating capacity amounted to 297 kW and the electricity consumption to 59 kW. The COP was 5.0.

The Agrana demonstrator was operated at higher temperature lifts due to the lower sink temperature. The COP of the Agrana demonstrator ranges from 3.1 at 121°C (heat sink outlet) and 62°C (heat source outlet) to 2.7 at 153°C (heat sink outlet) and 73°C (heat source outlet). The variations of COP and temperature lift were on average 3%. Design point: At a heat supply temperature of 138°C and a heat source outlet temperature of 71°C, the heating capacity amounted to 373 kW and the electricity consumption to 117 kW. The COP was 3.17.

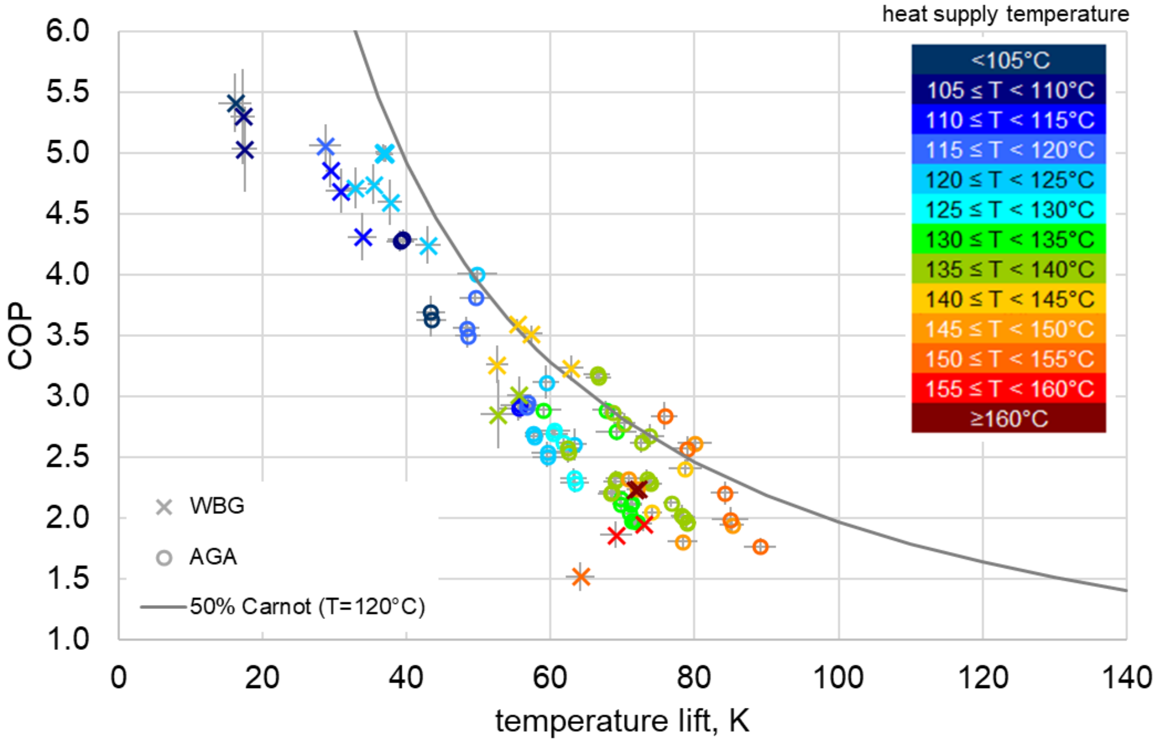


Figure 14: Performance data of the heat pump demonstrators with ranges of variation

Figure 15 and Figure 16 compare the measured efficiency data of the two demonstrators with data from other industrial heat pumps[2] collected by Arpagaus[3] (and depicted in the figures as small grey dots labelled "other IHP"). The DryFiciency heat pumps range among the devices with high efficiency.

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[2] From heat pump manufacturers such as e.g., Kobelco, Viking Heat Engines, Ochsner, Friotherm, Combitherm, GEA, Star Refrigeration, etc.

[3] Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch S, High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials, Energy (152), p.985-1010, 2018.

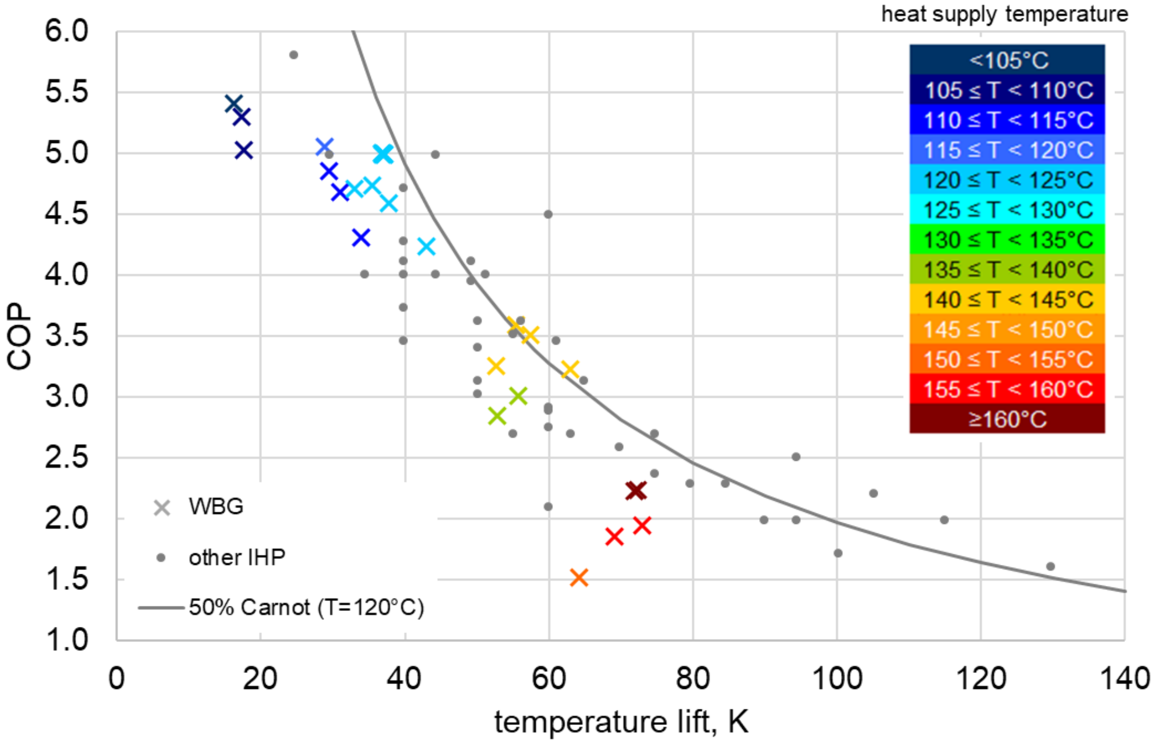

Figure 15: Performance data of the WBG demonstrator in comparison with other IHP

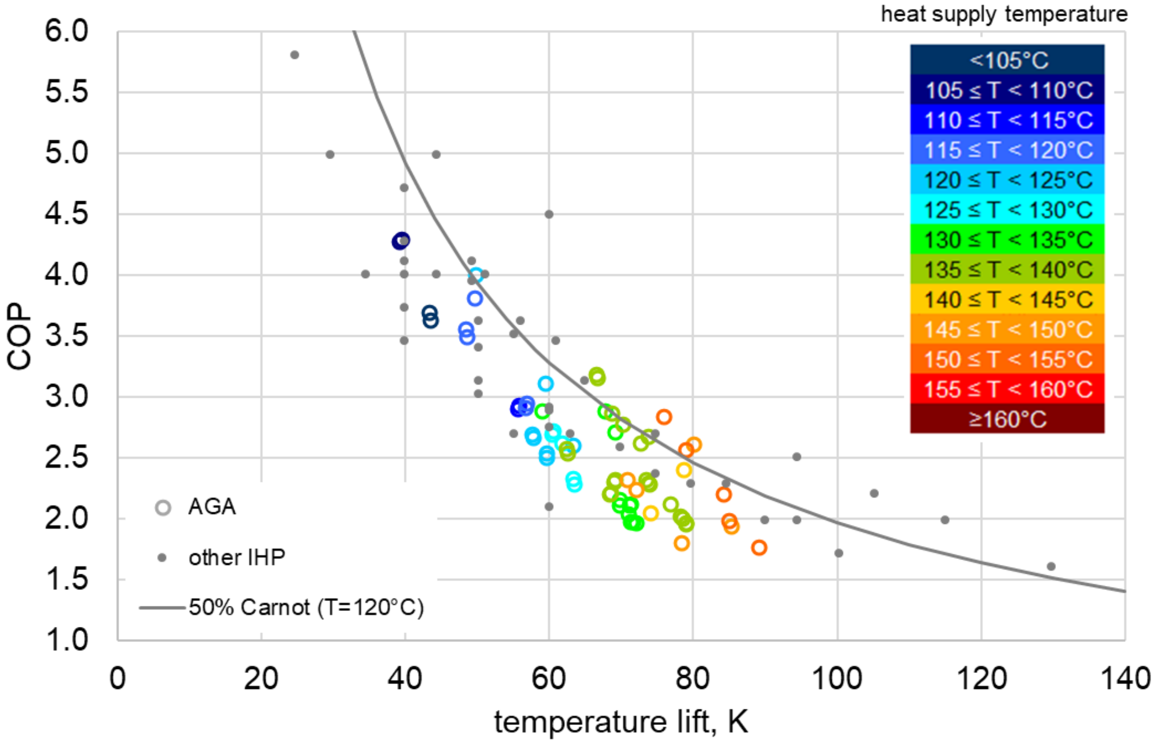

Figure 16: Performance data of the AGA demonstrator in comparison with other IHP

More information on the **key performance indicators** achieved by the two closed loop heat pump demonstrators is included in D5.2 [Report on validation of the energy savings for each demo site.]

2.4 Techno economic assessment of the two closed loop heat pumps

Based on the operating results of the DryFiciency heat pump, potential savings for drying processes are now calculated when heat pumps are used in place of gas burners. The most commonly available heat source in drying processes is moist exhaust air. Assuming dew points of the exhaust air between 40-60°C, the source outlet temperature will be around 40°C, thus considerably lower than the heat sources used by the DryFiciency demonstrators (Wienerberger: heat provided by a thermal driven heat pump, Agrana: heat provided by a waste heat recovery cycle). Using moist exhaust air instead will increase the temperature lift to about 120 K if the maximum heat supply temperature of 160 °C is maintained. At a second law efficiency of 50%, the COP decreases to 1.8. The following savings potentials are therefore calculated with a minimum COP of 1.8 and a maximum COP of 4.7. Natural gas burners with a thermal efficiency of 90 %, that provide the heat for the drying process, are the baseline. For the comparison, they are replaced by heat pumps providing the same amount heat recovery latent energy from the dryer exhaust gas.

2.4.1 Savings in CO_2 emissions

Currently, the use of electrical energy in Austria leads to 258 g CO_2eq /kWh and use of natural gas accounts for 271 g/kWh.[4] With a share of 75% in Austria's electricity generation in 2018, renewable energy sources, mostly hydropower[5], are already widely used.[6] For the future, renewable energy supply targets are even more ambitious with the target of covering 100% of the total national electricity consumption by renewable energy sources in 2030.[7] Therefore, the CO_2eq value for the ecolabel "Green Electricity" of 16 g/kWh is used for electrical energy in 2030.[4]

In the EU, on average 275 g/kWh are currently emitted by using electrical energy. To achieve a net reduction of 55% in greenhouse gases by 2030, emissions must fall to 75.49 g/kWh to 96.81 g CO2eq /kWh. Thus, 75.49 g/kWh is chosen for the CO_2eq emissions for electricity in 2030.[8]

Using a heat in a drying process reduces end energy consumption by 50 – 81%. The highest savings are achieved if the heat pump is operated at a low temperature lift and therefore a high COP. As the heat pump consumes less end energy than a gas burner and the use of electricity is related to fewer CO_2 emissions than natural gas, the CO_2 emissions of the drying process can be lowered considerably. Figure 17 illustrates the emission reduction potential of the heat pump as a function of the COP for Austria and the EU. Today, CO_2 emissions can be reduced by about 50 to 80% when using a heat pump. As the share of renewable energy for electricity generation will increase in the future, higher savings can be expected for 2030. With green electricity, industrial drying processes can be almost completely decarbonized (reduction of 99 % of CO_2 emissions for drying processes in Austria 2030).

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[4] Umweltbundesamt, Calculation of green house gas emissions for different energy carriers in Austria, updated in January 2020, https://secure.umweltbundesamt.at/co2mon/co2mon.html, accessed on 13.5.2021

[5] 60% of gross electricity generation

[6] E-Control 2019, Statistikbroschüre, Link, Accessed on 02.05.2020

[7] bmnt & bmvit, #mission2030, Bundesministerium für Nachhaltigkeit und Tourismus und Bundesministerium für Verkehr, Innovation und Technologie, Wien, 2018.

[8] European Environmental Agency, Link, Accessed on 13.5.2021

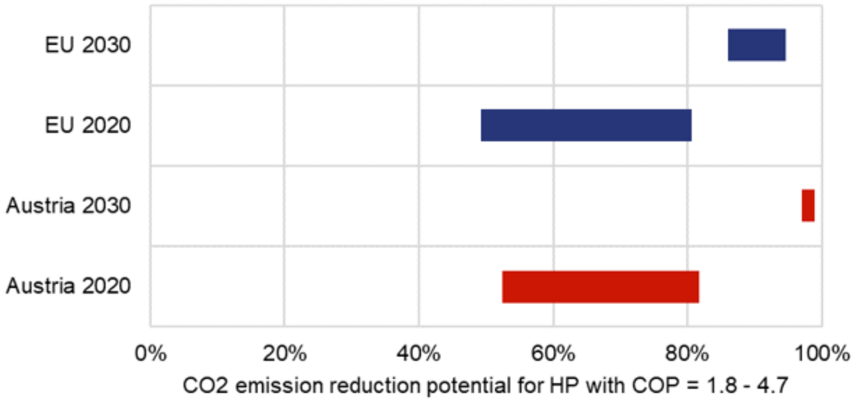

Figure 17: Potential CO_2eq savings in industrial drying processes

2.4.2 Savings in energy costs

To calculate the energy cost savings, mean values for the Austrian industry from the 2nd half year of 2020 are used, which are 9.86 ct/kWh for electricity for non-household customers, with a purchase of 70,000 MWh/a to 150,000 MWh/a[9] and 4.069 ct/kWh for natural gas for non-household customers with a purchase of 2,778 MWh/a to 5,595 MWh/a[10]. In the future, the CO_2 price will impact on energy costs. For this purpose, a CO_2 price of 54.74 €/t CO_2 is considered[11], as well as an estimated increase in CO_2 price to 110 €/t by 2030, which corresponds with the current CO_2 price in Sweden[12].

Figure 18 illustrates the saving potentials in energy costs, when using a heat pump instead of a natural gas burner for drying. Considering current Austrian energy prices without CO_2 pricing, heat pump applications with a COP >2.2 allow for energy cost savings. In the shaded area, the energy costs of the heat pump are higher that the gas burner. If higher temperature lifts are required, hybrid systems might be considered to keep the lift of the heat pump small and to further heat with a gas burner. If the current CO_2 price is added to the cost of natural gas, the gas price rises to 5.5 ct/kWh. Thereby, the entire operation range of the heat pump leads to lower energy costs than the gas burner (Austria 2020+CO_2 price in Figure 18). Cost savings range from 11 to 66%. The future scenario with the increased CO_2 price of 110 €/t increases savings to 39 – 77% (Austria 2030+CO2price).

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[9] eControl, electricity prices, Link, Accessed on 13.5.2021
[10] eControl, natural gas prices, Link, Accessed on 13.5.2021
[11] Ember Price Viewer, Link, Accessed on 13.5.2021
[12] Carbon pricing dashboard, Link, Accessed on 13.5.2021

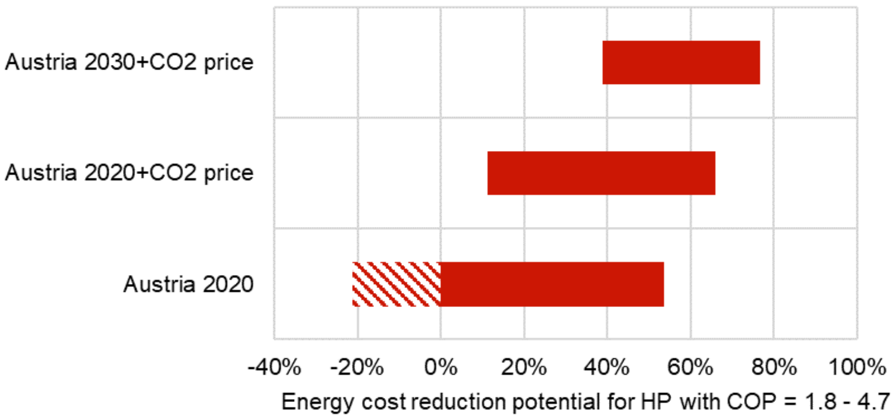

Figure 18: Potential energy cost savings in industrial drying processes

3 OPEN LOOP HEAT PUMP SYSTEM

In the following section, work and selected results achieved during the final testing of the MVR heat pump at the SINTEF laboratory, as well as during integration and commissioning on the demo-site in Lindum, are presented. In addition, the novel dryer system is described in terms of its main innovations and achievements.

The boundary conditions of the open loop heat pump demonstrator to be applied for sludge drying, as well as the work conducted and results achieved on **component** (turbo compressor) and **heat pump unit level** (configuration, sizing and positioning) are presented in *D4.5 "Interim report on the heat pump technologies developed"*, sections 3.1 to 3.5. Section 3.6 contains the first results from testing the open loop heat pump with the novel compressors.

3.1 Integration phase

The open loop heat pump demonstrator, its integration layout and integration infrastructure are described in detail in D4.3 *Integrated Heat Pump System.* Information on the novel dryer system and its infrastructure is provided in this section.

3.1.1 MVR Dryer

The open loop heat pump system is designed to be integrated into superheated steam drying processes. Superheated steam is, in many ways, a more superior drying agent than air due to its physical properties, heat, and mass transfer, as well as more efficient penetrability. The heat transfer coefficient of steam is twice of that of air. At the same time, the viscosity (penetrability) of steam is almost half of the viscosity of air. Superheated steam drying therefore has the potential to shorten drying time and energy demand by 20-30%, compared to air drying. The MVR dryer of DryFiciency was developed with this background and under the following considerations:

1. The construction of the dryer ensured that the SHS can be circulated through the dryer and a heating element. This is similar to an air dryer, but the ventilation and heating system were exchanged (steam-fans, steam-heater, etc.).
2. The excess steam must be condensed out by separate condenser. This condenser will substitute air filtration or air handling units.
3. The insulation of the dryer was increased since the drying temperature in SHS is normally higher than in air drying. It was also increased to avoid condensation. The insulation must be sufficient to ensure that no cold bridges cause condensation in the system.
4. The construction of the dryer ensured that as little as possible air or oxygen is present in the system in order to ensure an efficient drying process and to avoid air pockets in the system.
5. The dryer is operated at atmospheric pressure in order avoid expensive pressurized drying chambers and product lock/valves.

The overall layout of the dryer can be seen in Figure 19, while in Figure 20 the functional pilot at the demo-site is depicted.

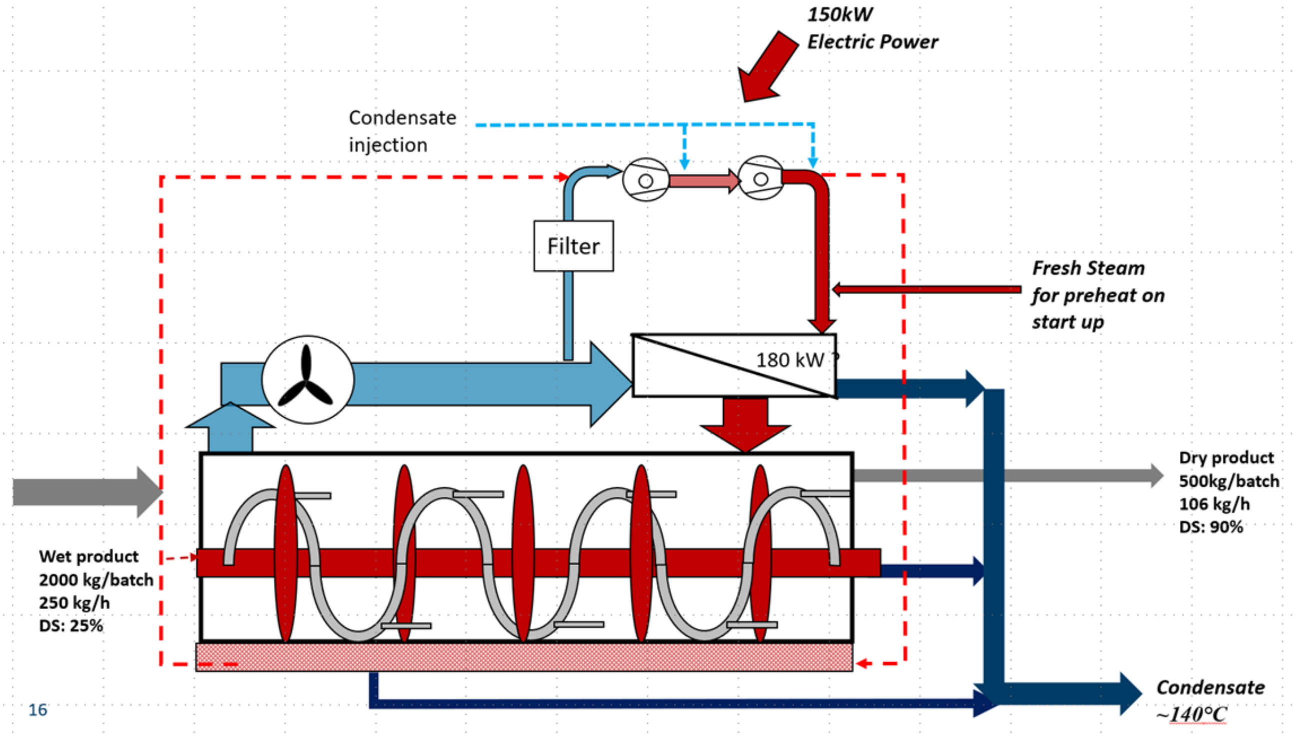

Figure 19: Principle layout of Scanship SHS-dryer as developed in DryFiciency.

Figure 20 Complete SHS-dryer pilot (to the left) installation at Lindum with the open loop heat pump (in the back to the right).

3.1.2 Open loop heat pump

The MVR drier is essentially the evaporator of the open loop heat pump system. It generates the steam, which is compressed and then re-used as drying energy for the pilot system. The open loop heat pump system was developed by EPCON Evaporation Technology AS (Trondheim, Norway) and is based on MVR technology. The turbo-compressors used by the open loop heat pump were developed by Rotrex A/S (Copenhagen, Denmark) and a further development of automotive superchargers. The design of the turbo-compressors enables a pressure ratio of 4.2 to 4.7 (depending on pressure losses in auxiliary systems), with a two stage compression system.

Conventional MVR technology will need more stages in series to achieve such higher pressure lift. The CAPEX for the capacity range demonstrated in DryFiciency (approximately 1000 kg/hour evaporated water) will be rather high versus the demonstrated Rotrex compressors.

Figure 21: The two turbo-compressors of the open loop heat pump.

During the verification of the open loop heat pump, the compressor maps and operational points for different impeller design were determined and analysed, as shown in Figure 22 and Figure 23:

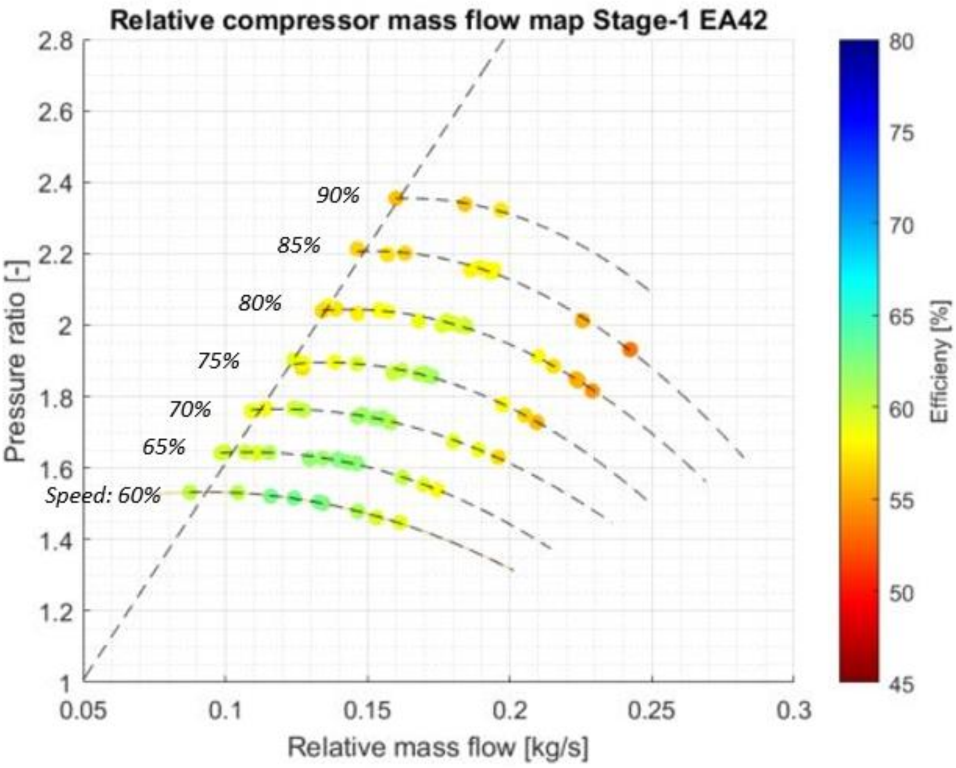

Figure 22: Compressor map and operational points for the turbo-compressor model EA42 in the first stage of open loop heat pump.

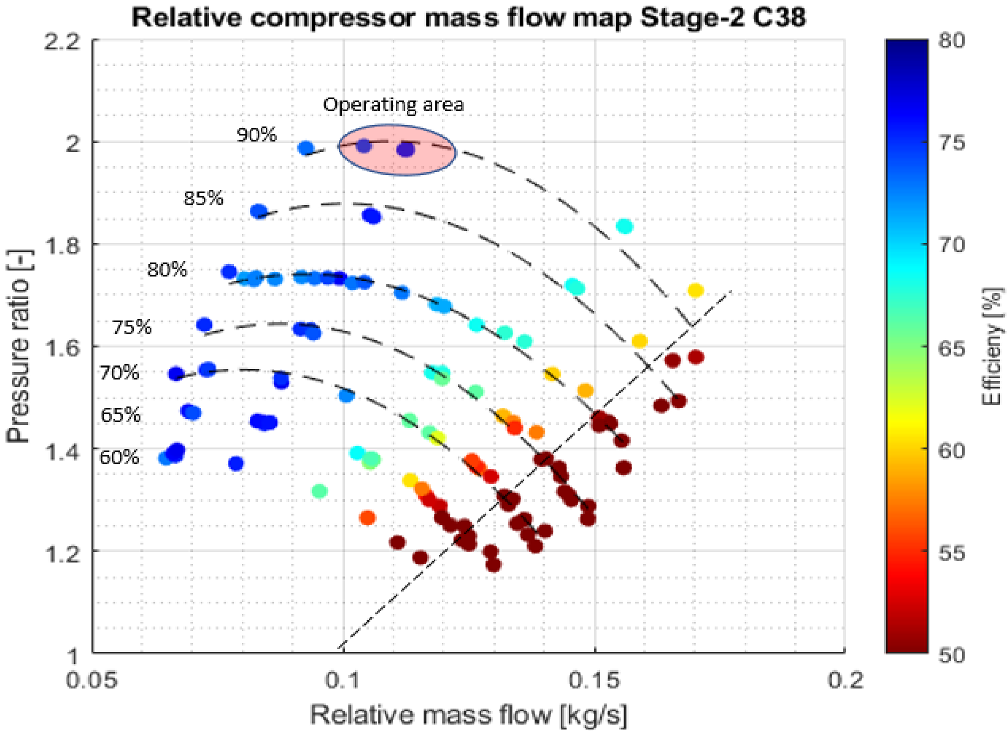

Figure 23: Compressor map and operational points for the turbo-compressor model C38 in the second stage of open loop heat pump.

3.2 Commissioning phase

3.2.1 Heat pump testing on-site

The heat pump operation on-site enables the demonstration of different operation points of the open loop heat pump, which will depend on the temperature requirements of the SHS-dryer. At the highest possible supply temperature of 146°C, the open loop system can provide 494 kW thermal energy at a COP of 4.5. At lower temperatures, the supplied heat will be reduced while the COP is increased up to 8.7 (see Table 5).

Table 5: Performance and COP of the open loop heat pump for different temperature ranges and heat supplies.

Speed	**Speed**	$\dot{m}$ **at 1bar**	**Pressure ratio**	**Tsat**	**Tlift**	**Heat delivery**	**COP**	COP_{Carnot}	η_{system}
RPM	%	kg/h	-	°C	K	kW	-	-	%
72000/ 81000	90/90	756	4.23	146	45.6	494	**4.54**	9.2	49.4 %
68000/ 81000	85/90	648	4.05	144	44.0	423	**4.8**	9.5	50.4 %
64000/ 81000	80/90	720	3.59	140	39.7	461	**5.2**	10.4	50.5 %
64000/ 76500	80/85	684	3.44	138	38.2	440	**5.1**	10.8	47.1 %
60000/ 76500	75/85	648	3.21	136	35.9	413	**5.8**	11.4	50.5 %
56000/ 72000	70/80	576	2.83	132	31.5	367	**6.4**	12.8	50.0 %
52000/ 67500	65/75	504	2.49	127	27.3	325	**6.5**	14.7	44.2 %
48000/ 63000	60/70	360	2.32	125	24.9	226	**8.7**	16.0	54.7 %

Figure 24 depicts the achieved COPs of the open loop heat pump with data from other industrial heat pumps[13] collected by Arpagaus[14], that are closed loop heat pumps (labelled "other IHP"). The open loop heat pump achieved an overall efficiency, which is around 50% of the Carnot efficiency (with an assumed heat sink temperature of 140°C). However, the temperature lift is limited to approximately 45 K.

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[13] From heat pump manufacturers such as e.g., Kobelco, Viking Heat Engines, Ochsner, Friotherm, Combitherm, GEA, Star Refrigeration, etc.

[14] Arpagaus C, Bless F, Uhlmann M, Schiffmann J, Bertsch S, High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials, Energy (152), p.985-1010, 2018.

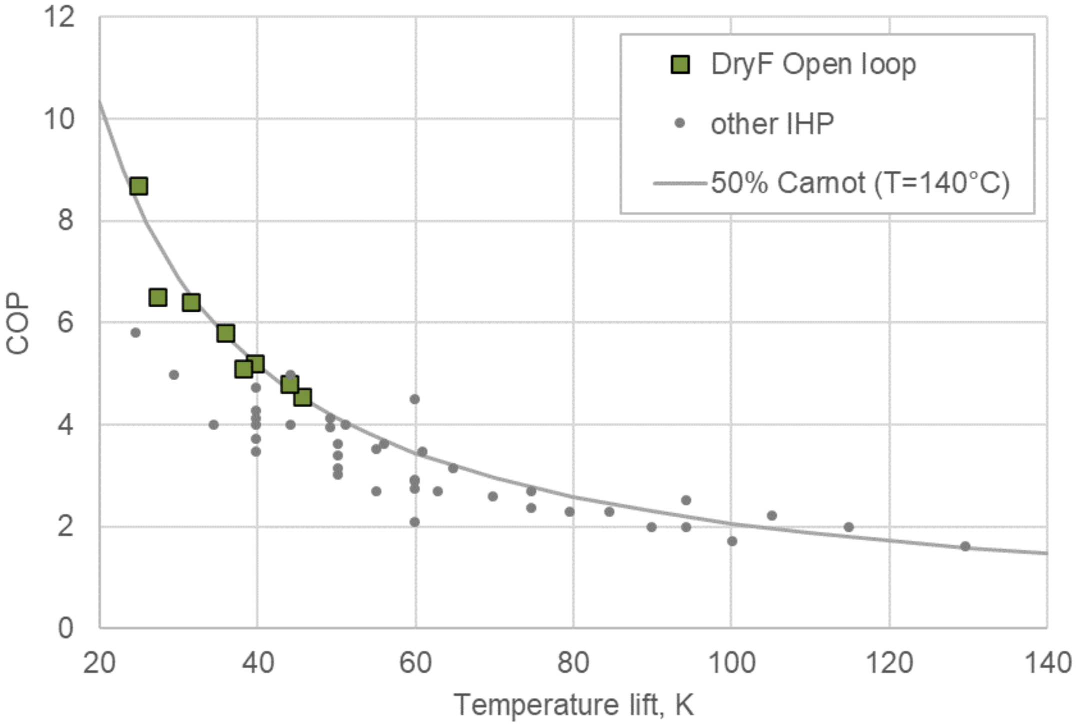

Figure 24: Achieved COP of the DryFiciency open loop heat pump.

3.2.2 Dryer testing

The test campaign confirmed that the SHS drier can be used to dry a large variety of feedstocks:

- dewatered raw sludges
- dewatered digested sludges
- garden waste
- compost
- wood chips from waste wood/demolition wood
- digestates from food waste biogas plants
- fibre reject from pre-treatment of food waste

Figure 25: Dried fiber reject from food waste biogas plant (to the left) and final pellets from compost (to the right); both dried and processed with the SHS-drier of the pilot plant.

3.3 Demonstration phase

When the SHS dryer was connected to the open loop heat pump system, the temperature from the dryer quickly reached the saturation point and the open loop heat pump operated with a wet steam atmosphere. This started a downward spiral, as the temperature in front of the compressors drops to 100°C, the compressor speed is reduced in order to avoid operating with wet steam. This in turn, reduces the pressure in the condenser, which is further reducing the temperature in the system.

The system as it was at this state, was unable to deliver steady superheated steam to the compressor, which is necessary in order to deliver heat to the dryer steam. Therefore, there was a need for additional components and adjustments made to the start-up procedure. The demand for an **external energy supply for the open loop heat pump** for the start-up procedure was identified as the main cause for the described challenges during system start-up.

The required external energy for the Start-Up in the laboratory (without dryer) can be provided by the compressors of the open loop heat pump. This is basically the electric energy of the motors which is transferred to the working media. Since the working media during Start-Up is re-circulated the system is heated well beyond the saturation point of steam.

For the onsite installation the system size which needs to be heated during Start-Up is increased by the heat exchanger, piping, parts of the dryer and the filter elements. With this additional mass it was not possible to heat the system by the electric energy of the motors. Hence additional energy supply is required, e.g. external boiler or electric heating elements.

This system re-construction was projected but not finalized by the end of the project period, and therefore it was not possible to report on the outcome of the full MVR heat pump drier. The delay was caused by the lead-times for the required new valves and pipes, as well as operational constraints onsite. The second phase of testing, "hot operation", meaning full scale drying using the heat pump as primary heat source, has not yet been successful.

However, the dryer is fully functional, provided that 2-5 bar pressure steam is delivered, which was proven by drying 50 tons (dry matter) of garden waste during the site acceptance tests using a 300 kW steam generator. In addition, the open loop heat pump was also able to deliver at least 4.5 bar, as demonstrated by full scale testing in the lab.

4 CONCLUSION

The core of the DryFiciency project was to develop **three prototype heat pump demonstrators** for industrial waste heat recovery and **demonstrate** them **on-site** at three drying applications at elevated heat sink temperature levels of up to 160°C (closed loop) respectively 155°C (open loop) at TL7.

4.1 Closed loop heat pumps

The following main results were gained from the two closed loop water-to-water compression heat pump prototypes installed and demonstrated in drying processes of Agrana and Wienerberger:

- Development of an adapted screw compressor technology allowing suction gas temperatures of up to 100°C and discharge temperatures of 160°C.
- Development of a fine-tuned, sufficiently viscous lubricant, acting chemically and thermally stable when exposed to Opteon^{TM} MZ, a non-toxic, non-flammable refrigerant with a GWP of 2, at elevated temperature levels.
- Development of two novel heat pump configurations, which best consider the given boundary conditions at the demo-sites, the operating points of the heat pump systems required, as well as the components available (two screw compressors, eight piston compressors) in technical and economic terms. Twin cycle configurations were found to be the best solution for both drying applications in terms of highest COP of all configurations possible at moderate temperature levels, and the highest energy cost savings per year.
- Development of successful control strategies for the heat pump demonstrators that prove level out fluctuations in heat source temperature and react appropriately and fast to set point changes.

At the Wienerberger demo-site for brick drying, ca. 4.000 operation hours were collected covering heat supply temperatures from 100°C up to 160°C. Most operational experience was gathered at heat sink temperatures of 140°C and 120°C, which represents the required site conditions. However, ca. 570 hours were collected at elevated temperature levels from 150°C up to 160°C. The heat output reached up to 297 kW. The COP ranged from 5.0 at 120°C (heat sink outlet) and 84°C (heat source outlet) to 2.2 at 160°C (heat sink outlet) and 89°C (heat source outlet). Compared to the use of natural gas, end energy savings of up to 83% were achieved resulting in carbon emission reductions of 600 tons per year.

The heat pump demonstrator at the AGRANA demo-site for starch drying was also operated for ca. 4.000 hours. There, the heat supply temperatures ranged from 90°C to 160°C, reaching a maximum heat output of 373 kW. Most operational experience was gathered at heat sink temperatures of 134°C, 155°C, and 130°C, which represent the required site conditions. Ca. 900 hours were collected at supply temperatures from 150° to max. 160°C. The Agrana demonstrator was operated at higher temperature lifts because of the lower heat sink temperature. The COP of the Agrana demonstrator ranges from 3.1 at 121°C (heat sink outlet) and 62°C (heat source outlet) to 2.7 at 153°C (heat sink outlet) and 73°C (heat source outlet). Replacing natural gas, end energy savings of ca. 2,400 MWh/a were achieved leading to a yearly reduction in carbon emissions of 660 tons.

Closed loop heat pumps can recover waste heat from liquid and gaseous streams. With heat supply temperatures of up to 160°C, they can be replicated in a large number of industries, such as e.g., chemicals, food, textiles, or paper industry. Calculations performed based on the operation results from the DryFiciency heat pumps have shown that CO_2 emission reductions of about 50 to 80% are already possible when applying heat pumps in drying applications. This figure will further increase, as the share of renewable energy sources for electricity generation rises. By making use of green electricity, industrial drying processes can be almost completely decarbonized in the future.

Also, with regard to future increasing CO_2 costs, the heat pump is a future-proof heat supply system for drying processes. Based on average Austrian energy prices, cost reductions of up to 54% can already be achieved now. If the CO_2 price rises up to 110 €/t, the savings potential may even increase up to 77 %.

4.2 Open loop heat pumps

The open loop heat pump system which was developed and installed at the Scanship demo site has achieved the following main results:

- Development of the two stage open loop heat pump for superheated steam compression, designed for pressure ratios of up to 3 per stage with subsequent demand for intercooling.
- Development of turbo-compressors for superheated steam compression for industrial steady state operation, with increased gearbox cooling and improved impeller design.
- Determination of the techno-economic balance for the integration of open loop heat with demands for high efficiency on the one side and the required temperature lift for drying processes on the other side.
- Evaluation of the required start-up procedure which integrates the SHS-dryer with an open loop heat pump.

The demonstrated COP of the open loop heat pump is approximately 50% of Carnot efficiency; the highest temperature lift is achieved with 45.6 Kelvin at a COP of 4.5 and 494 kW thermal energy supplied to the system.

The developed open loop heat pump system can be integrated into industrial processes like drying and evaporating with a steam demand of 0.5 to 2 MW. The system can be also used in general for steam producing heat pumps in the same capacity range, hereby substituting fossil boilers. The durability of the compressor technology must be increased and proven in order to match the industrial demand for service intervals.

The developed dryer is fully functional, provided that 2-5 bar pressure steam is delivered, which was proven by drying 50 tons (dry matter) of garden waste during the site acceptance tests, using the 300 kW steam generator.

The second phase of testing, "hot operation", which is full scale drying using the heat pump as a primary heat source, has not yet been successful.