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Decarbonization of industrial processes with heat pumps

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ABSTRACT

To counteract climate change the efficient use of energy in industry becomes increasingly important. Heat pumps enable decarbonized industrial processes by replacing fossil fuels with electricity. DryFiciency develops and demonstrates high temperature heat pumps using OpteonMZ as refrigerant to supply hot water up to 160°C. Heat pumps will be installed in drying processes for starch and bricks in two Austrian companies in spring 2019. We present design considerations for high temperature heat pumps, as well as the expected CO_2 reductions and primary energy savings. Calculations are based on numerical process simulation. At the two demo-sites CO_2 emission reductions up to 40-90% and primary energy reduction from 20-80% can be achieved compared to natural gas. If the heat pump technology is spread out to 50% of all drying processes in the EU, they would contribute 3-7% of the CO_2 emission reduction necessary to achieve the EU climate targets. Heat pumps improve the energy efficiency of industrial processes significantly. The demonstrators are an important step in the development of viable industrial solutions.

Keywords: CO_2 Emission, Design, Drying, Energy Efficiency, R1336mzz(Z), Simulation.

1. INTRODUCTION

Recently, the International Panel on Climate Change published a special report pointing out the importance to drastically reduce the CO_2 emissions to stabilize global warming at 1.5°C. This implies changes in behaviour and lifestyle worldwide. Concerning the impact of industry, pathways limiting global warming to 1.5°C project CO_2 emissions from industry to be about 65–90% lower in 2050 relative to 2010. Such large reductions require substantial efforts and combinations of new and existing technologies and practices, including increasing energy and process efficiency, electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (IPCC 2018). Almost nine out of ten of all national contributions submitted to the 2015 climate summit in Paris mention energy efficiency (IEA 2016). The European Union (EU) set itself the target of reducing greenhouse gas emission by 40% below 1990 level, increasing energy efficiency by 32.5% and raising the share of renewable energy to 32% of total energy consumption by 2030 (European Parliament 2018a, European Parliament 2018b).

Heat pumps for industrial applications can make an important contribution to increasing the efficiency of industrial processes and reducing CO_2 emissions and enable decarbonized industrial processes by replacing fossil fuels with electricity. In this paper, the CO_2 emission and primary reduction potential of high temperature heat pumps for industry is presented based on the development of two prototypes for drying processes.

2. HIGH TEMPERATURE HEAT PUMPS FOR DRYING

The focus of the H2020 project DryFiciency is the development and demonstration of high temperature heat pumps for industrial drying and dehydration processes. The heat pumps use industrial waste heat as the heat source and supply hot water up to 160°C. Two heat pumps prototypes will be installed in drying processes for starch and brick in the first quarter of 2019.

The heat pumps are designed as closed compression heat pumps with a heating capacity of around 400 kW. R-1336-mzz(Z) is used as refrigerant, that was already successfully been tested at AIT in a lab-scale heat pump prototype (Fleckl et al. 2015). It is marketed by Chemours under the trade name OpteonMZ and is a synthetic refrigerant based on HFO (hydrofluoro-olefin) developed for high-temperature applications up to 160°C. It has a low GWP value of 2 (Global Warming Potential). Two different kinds of compressors are used for the heat pump prototypes, screw and piston compressors. Fuchs Schmierstoffe GmbH develops a suitable lubricant for both compressors, which fulfils all necessary requirements with regard to lubrication and viscosity. Furthermore the challenge is to find a lubricant which is chemically and thermally stable at high temperatures with the refrigerant. Bitzer Kühlmaschinen GmbH adapted their HS screw compressor for high temperature applications. The HS screws are suitable for multiple refrigerants, such as R134a, R404A, R507A, R407C and R22 and others. Most commonly, the compressors are used in refrigeration plants and heat pumps with evaporation temperatures from -50 to 12°C and condensation temperatures in the range of 45 to 70°C. The maximum suction gas temperature is 30°C and the maximum discharge gas temperature amounts to 100°C. The adapted version of the HS compressor can be applied for suction gas temperatures up to 100°C and discharge temperature of 160°C. It has a swept volume of 300 m^3/h at 60 Hz. Two screw compressors are used to supply about 400 kW of process heat. The piston compressors integrated in the second demonstrator are developed and supplied by Viking Heat Engines AS. The compressor design is based on an ORC (Organic Rankine Cycle) expander used for heat recovery applications with an overall design temperature of 215°C. The expander has already been extensively tested at high temperatures and achieves high efficiencies. The compressor designed is 90% the same as the ORC and built on the same piston bottom-end, only the cylinder head is different. Over the past five years, the piston expander has undergone a comprehensive development program to achieve a long service life and high durability at very high temperatures. Today, this piston machine technology is equally capable of operating in organic Rankine cycles (ORCs) as well as vapour compression heat pump systems. The compressor is designed for use with OpteonMZ, but have also been used with commonly applied HFC e.g. R135a, R245fa and several HFO e.g. R1336mzz-E, R1234ze, R1233zd. One piston compressor has a swept volume of 55 m^3/h at 60 Hz. A total of eight compressors arranged in two modules of four are used to supply 400 kW of process heat.

Drying processes are among the most important process steps in the food industry, pulp and paper and chemical industry and require intensive use of energy. Estimates show that 12-25% of the national industrial energy consumption in developed countries is attributable to industrial drying (Mujumdar (2006), Kemp (2012), Minea (2011)). Currently, most of this energy is supplied by fossil fuels with no or only limited recovery of waste heat streams. The energy saving opportunities by the use of more efficient low grade waste heat recovery technologies was estimated to 12% savings for the chemical industry and 4% for petroleum refineries in energy consumption by 2030 according to Chan and Kantamaneni (2015). Hence, there is a great potential for more efficient and environment-friendly technologies for industrial drying processes. In the following, the starch drying process and the drying of bricks in which the high temperature heat pumps will be integrated are described in more detail.

2.1. Starch Drying

Agrana Starch GmbH operates many dryers in its 54 sugar and starch factories for product and by-product drying. In Pischelsdorf in Austria, at their integrated bioethanol and wheat starch production site, the starch dryer will be equipped with a high temperature heat pump. The starch drying process is a continuous process with an entrained flow dryer. Drying air is preheated in a water-air heat exchanger using heat from a heat recovery cycle, which is fed from other drying processes. In the original set up without heat pump, the drying air is heated to around 160°C in a second heat exchanger with steam. Steam is provided in a natural gas-fired power plant. Figure 1 shows the integration of the heat pump. After preheating the drying air, the heat recovery circuit is also used as the source for the evaporator of the heat pump system. The inlet temperature is about 70°C. In the condenser heat is transferred to the drying air via an intermediate water circuit and a water-air heat exchanger. The heat supply temperature of the heat pump is up to 160°C. With the heat pump, the use of steam in the third heat exchanger can be reduced or completely eliminated depending on the selected heat supply temperature of the heat pump. Thereby, the heat recovery cycle can be used to a larger extent and the use of natural gas is reduced.

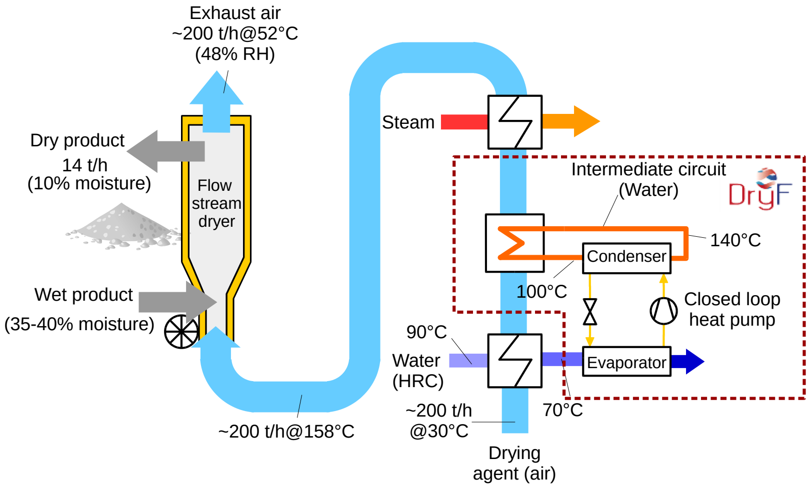

Figure 1: Starch drying process with high temperature heat pump

2.2. Brick Drying

Wienerberger AG, the world's largest brick producer, operates about 200 brick dryers. In the brick factory in Uttendorf in Austria, a high temperature heat pump will be integrated to supply heat for the drying process. In brick production, the bricks are first formed, dried and then fired. The drying process takes place in a continuous tunnel dryer shown in Figure 2. Air is used as the drying agent, which moves in a counter-current flow through the dryer. The bricks enter the dryer with 28% moisture and are dried to 2%. The drying air in the tunnel is heated by internal heat exchanger surfaces, which are supplied with 90°C hot water provided by a heat recovery circuit. The heat pump also uses this circuit as the heat source, the evaporator is placed in front of the heat exchangers. The heat pump supplies hot air via an intermediate water circuit, where heat supply temperatures of up to 160°C can be achieved. The hot air is fed into the outlet zone of the tunnel dryer, where the highest temperatures are required for drying.

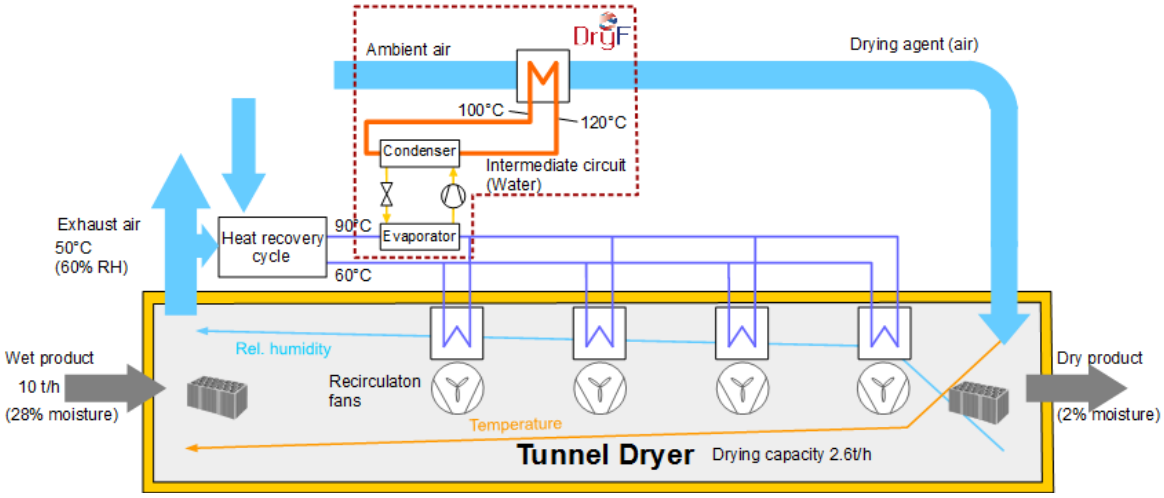

Figure 2: Brick drying process with high temperature heat pump

3. METHODOLOGY

3.1. Numerical Simulation of Heat Pump and Drying Process

A simulation model of two heat pump demo plants was created in the simulation package Dymola/Modelica. For the thermal modelling of the heat pump components the TIL library was used, which is widely used in refrigeration (Richter, 2008).

The modelling of the screw compressor and the piston compressor was based on measured data with an efficiency-based approach. The compressor is described by the isentropic and volumetric efficiency, which are a function of the pressure ratio and the condensation or evaporation temperature. The isentropic efficiency is based on the ideal isentropic compression and also considers the suction and pressure side pressure losses, internal leakage, re-expansion of the compressed fluid and mechanical friction. The volumetric efficiency describes the ratio between the geometrically possible mass flow and the actual mass flow through the compressor. For the screw compressor no measurement curves with R-1336mzz(Z) are available yet, therefore measurement data with R134a have been used, since both refrigerants have a similar isentropic exponent. For the description of the piston compressor, measurement data from Viking Heat Engines AG with R-1336mzz(Z) for volumetric and isentropic efficiency are available and were implemented in the model. The heat exchangers are modelled using the Number of Transfer Units method (NTU) and the pinch point as an input parameter enabling a reliable and robust calculation of the exchanged heat.

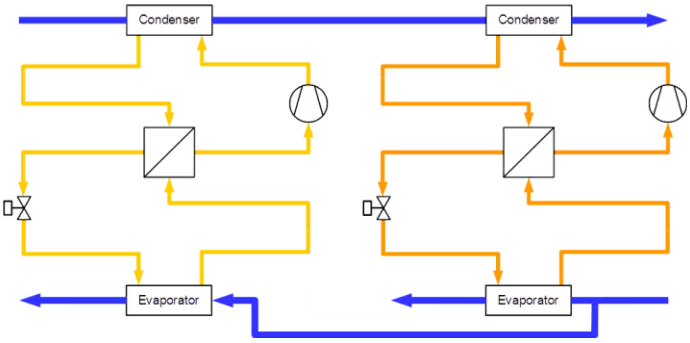

Figure 3: Schematic view of a twin cycle heat pump with parallel source

Figure 3 shows the configuration of the heat pump. It is a twin cycle set up, where each compressor module is located in a single refrigerant cycle. The condensers are arranged in series, the evaporators in parallel. Thus, the temperature lift is reduced somewhat for one of the two cycles and about one half of the heating capacity is provided at a higher COP. The twin cycle layout is also beneficial in terms of safety, start up procedure and official permits because of the smaller amount of refrigerant in the cycles. One cycle is equipped with a single Bitzer compressor or four Viking Heat Engines compressors. Due to the thermodynamic properties of the refrigerant, an internal suction gas heat exchanger is used to ensure dry compression.

The following boundary conditions were applied for the simulation based on the two heat pump demo plants: The source inlet temperature is 70°C for the Agrana heat pump, two screw compressors with the Bitzer characteristic and a constant speed of 60 Hz were used in this simulation. For the Wienerberger heat pump, the inlet temperature of the heat source is 90°C, eight piston compressors with the Viking Heat Engines characteristic and a constant speed of 60 Hz were used. For both demo plants, the condenser outlet temperatures were varied (110, 120, 140, 160°C). The spread at the condenser is set to 40 K. The pinch of the heat exchangers (evaporator and condenser) was assumed to be constant at 3 K. The suction gas superheat in the evaporator is 5 K, the hot gas superheat is 10 K.

3.2. CO_2 emission and primary energy calculation

Potential reduction in CO_2 emissions and primary energy consumption are calculated by comparing the original process to the process with the heat pump. In the original process at Agrana, heat is supplied by steam boilers fired by natural gas. At Wienerberger, a natural gas burner is used to heat the drying air. With the use of the heat pump, natural gas consumption is reduced but electricity is needed for the compressor. The CO_2 emission factor relates the amount of CO_2 emitted into the atmosphere to the end energy available as process heat. In case of the CO_2 equivalent, also other greenhouse gases such as methane are considered. According to GEMIS 2013, the CO_2 equivalent factor is 7-10% higher than the CO_2 factor for CO_2 emissions only. The primary energy factor shows how much energy is needed for extraction, processing, storage, transport, conversion, transmission, and distribution to provide end energy. The primary energy factor can be split in the renewable primary energy factor and the non-renewable factor. Here the total primary energy factor is used.

CO_2 emissions and primary energy consumption for electricity mainly depend on the energy carriers used for electricity generation. In Table 1, the CO_2 factors and in Table 2 the primary energy factors are compiled that are used for this calculation. They differ in their regional scope and reference year. If the reference year was not indicated in the publication, the publication year was given and marked with “p”. The CO_2 factor for natural gas is in the range of 236 to 290 g/kWh, values calculated for Austria are slightly lower than those for EU. The CO_2 factor for electricity in Austria is 248 – 300 g/kWh. Austrian electricity production is mainly based on hydropower (60% in 2017), wind and photovoltaics amount to about 10%. Therefore the CO_2 emissions are lower than those for electricity generation in the EU. The primary energy factors show similar dependencies. Fritsche and Greß (2015) assessed that the EU-28 electricity primary energy factor was rather stable in the years 2010-2013 and was dominated by the non-renewable primary energy use. Recently the European Parliament amended the primary energy factor to be used for the calculation of the energy efficiency targets to 2.1 kWh/kWh for electricity (European Parliament, 2018c).

Table 1. CO_2 emission factors for natural gas and electricity

CO_2 emissions		Natural gas			Electricity		
data set	g/kWh	factor	source	year	factor	source	year
Austria 2011	CO_{2eq}	249	GEMIS 2013	2011	300	GEMIS 2013	2011
Austria 2015	CO_2	236	OIB 2015	2015 p	276	OIB 2015	2015 p
Austria 2018	CO_{2eq}	271	Umweltbundesamt 2018	2018	248	Umweltbundesamt 2018	2018
EU 2014	CO_2	277	EN15603	2008 p	363	EControl 2014	2014 p
EU 2018	CO_{2eq}	290	EN ISO 52000	2018 p	420	ENISO 52000	2018 p

Table 2. Primary energy factors for natural gas and electricity

Primary energy		Natural gas			Electricity		
data set		factor	source	year	factor	source	year
Austria 2011	kWh/kWh	1.18	GEMIS 2013	2011	1.79	GEMIS 2013	2011
Austria 2015	kWh/kWh	1.17	OIB 2015	2015 p	1.91	OIB 2015	2015 p
EU 2013	kWh/kWh	1.36	Fritsche and Greß 2015	2010	2.46	Fritsche and Greß 2015	2013
EU 2018	kWh/kWh	1.1	EN ISO 52000	2018 p	2.1	European Parliament 2018c	2018 p

Relative savings Δx in CO_2 emissions and primary energy are calculated according equation 1 using the respective factors for natural gas (g) and electricity (el). η_{ref} is the efficiency of the fossil energy supply system used for the calculation (Agrana = 0.93, Wienerberger 0.9), the COP is the coefficient of performance of the heat pump (ratio of supplied heat and electricity).

$$\Delta x = \frac{\eta_{ref}}{f_g}\left(\frac{f_g}{\eta_{ref}} - \frac{f_{el}}{COP}\right) \qquad \text{Eq. (1)}$$

4. RESULTS

4.1. Reductions on Prototype level

Figure 4 show the results on prototype level. Heat pump assisted drying allows for substantial CO_2 emission and primary energy reductions for all kinds of factors that were discussed in chapter 3. In the brick drying process, the reductions are higher, because the temperature of the heat source is 90°C compared to 70°C for starch drying. All reductions are strongly dependant on the heat supply temperature that was varied between 110 and 160°C because the prototypes will be operated in a broad range of operation conditions. For the highest heat supply temperatures the most electricity is required resulting in lower reductions. The results are calculated with the isentropic efficiency curves that are expected for the prototypes. The maximum isentropic efficiency for the Bitzer compressor is reached at the pressure ratio of 3 corresponding to a heat supply temperature of 110°C. The maximum for the Viking compressors is reached at a heat supply temperature of 140°C (pressure ratio of 6). In other operation conditions the efficiency is lower. For high temperature heat pumps that should be operated in a specific operation point e.g. a heat supply temperature of 160°C, both types of compressors can be adjusted to have the highest efficiency at the required pressure ratio of the application (screw compressor: geometry and location of the discharge port, piston compressor: valves and dead volume adjustment). Therefore it can be assumed that even higher emission reductions can be achieved.

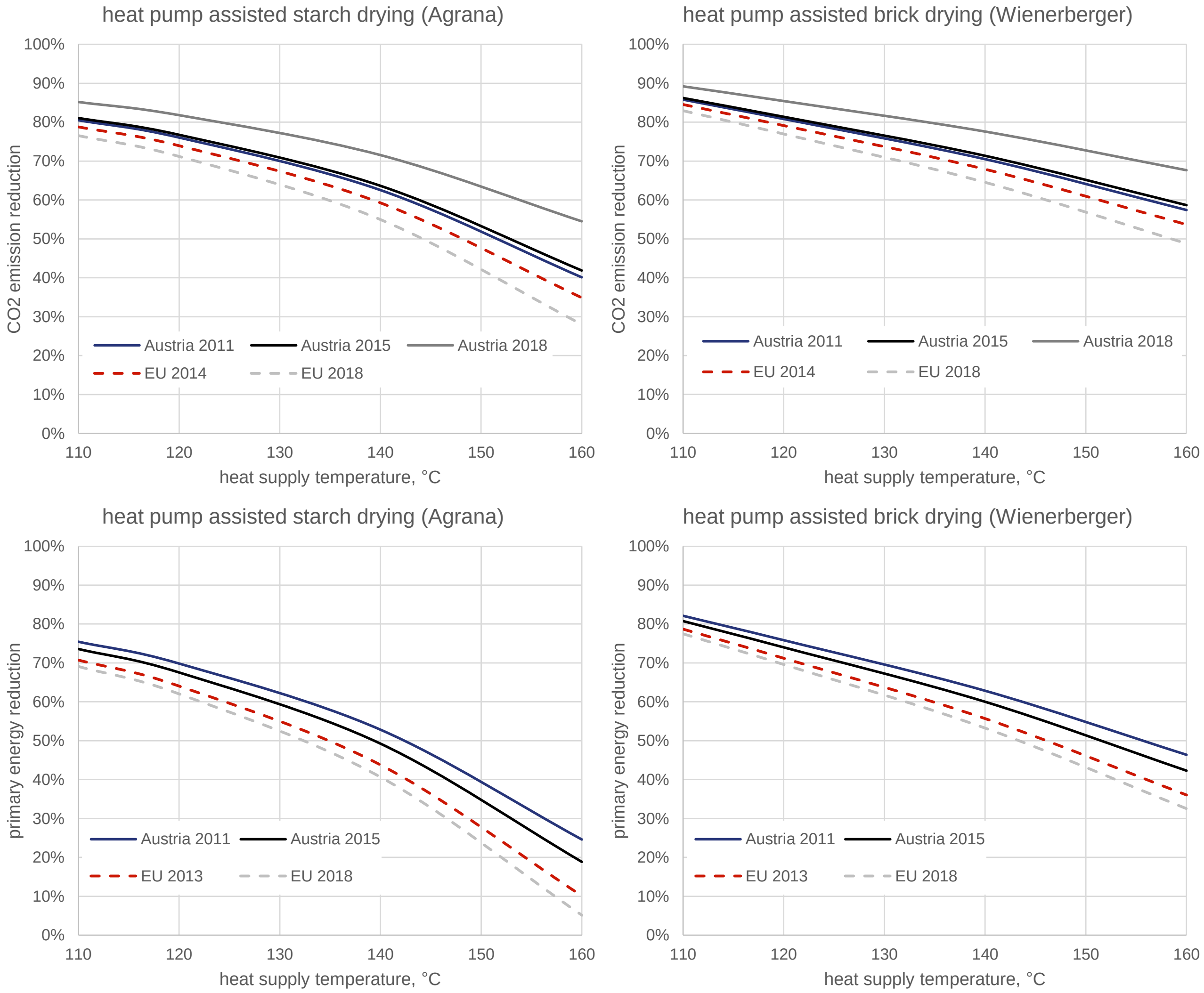

Figure 4: CO_2 and primary energy reduction on prototype level

4.2. Reductions on EU level

In the following, the savings of the prototypes are extrapolated to their potential contribution to the EU climate goals, if heat pumps for drying are wide spread in industry. As mentioned before, drying accounts for 10-25% of the total industrial energy use in most developed countries (Mujumdar (2006), Kemp (2012), Minea (2011)). In 2015, 12630 TWh/a of final energy were consumed in EU28 (Eurostat 2018a). The share of industry amounts to 25% or 3211 TWh in 2015. If drying consumes 10% of the total industrial energy use, it results in 321 TWh. If the share is 25%, drying consumes 803 TWh in the EU28. 10% and 25% are used to describe the range of potential.

It is assumed that 50% of all drying processes can be equipped with a heat pump similar to the heat pump prototypes developed in DryFiciency. The heat pumps for this consideration provide process heat and have an average COP of 3. This is the calculated value for the Agrana demonstrator at a heat source temperature of 70°C and a heat supply temperature of 140°C. This heat pump can be used for all kinds of applications requiring a similar lift, the heat supply temperature itself can be higher or lower resulting in the same COP. The heat pump replaces natural gas burners with an assumed efficiency of 95% and provide 161-401 TWh of process heat. Thus, heat pump assisted drying processes would consume 54-134 TWh of electricity, converting 107-268 TWh of waste heat into usable process heat.

Energy efficiency: The aim to increase energy efficiency is measured by the final energy and primary energy consumption in 2030, which should be as low as 956 Mtoe of final energy and 1273 Mtoe primary energy (European Parliament 2018b). Based on the final energy consumption 2015, 130 Mtoe (1512 TWh) of final energy have to be reduced by 2030 (Eurostat 2018a). The heat pump assisted drying processes allow for 107-268 TWh of energy consumption reduction, which corresponds to a contribution of 7-18% to the climate target. For the calculation the EU2018 dataset in Table 2 was used. In 2015, 17933 TWh primary energy were consumed, resulting in 269 Mtoe (3128 TWh) of primary energy reduction until 2030 (Eurostat 2018b). The heat pump assisted drying processes would reduce the primary energy consumption by 74-184 TWh, which is a contribution of 2-6% to this target.

CO_2 emissions: The EU target aims to reduce the CO_{2eq} emissions to 40% below the level of emissions in 1990 (European Parliament 2018a). In 2030, 3444 million t CO_{2eq} can be emitted. In 2015, 4461 million t CO_{2eq} were emitted resulting in 1017 million t CO_{2eq} that have to be reduced to reach the climate target. The manufacturing sector (NACE C) including manufacturing of food and other products where drying is a common process, emitted 843 million t CO_{2eq} in 2015, which is 19% of all CO_2 emissions (Eurostat 2018c). It is assumed the share of emissions among the sectors remains constant until 2030, therefore 19% of the emission reduction has to be contributed by the manufacturing sector, which are 192 million t CO_{2eq}. For the calculation the EU2018 dataset in Table 1 was used. With 50% of heat pump assisted dryers, the emissions would be reduced by 27-66 million t CO_{2eq}/a. The heat pump assisted drying processes contribute 14-35% to this target for the manufacturing sector or 3-7% of the total emission reduction that has to be achieved until 2030.

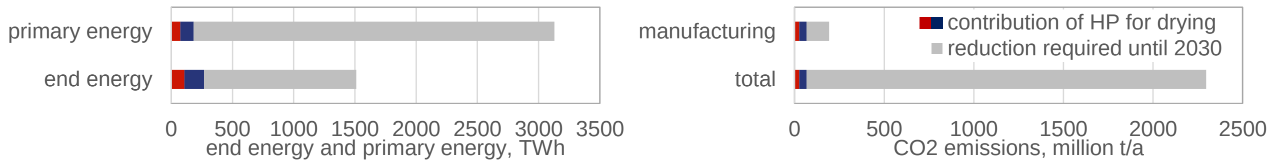

Figure 5: Contribution to EU climate targets

5. CONCLUSION

Heat pumps improve the energy efficiency of industrial processes significantly. At the two demo-sites of the DryFiciency project, CO_2 emission reductions up to 40-90% and primary energy reduction from 20-80% are expected for the drying processes compared to natural gas. If the heat pump technology is spread out to 50% of all drying processes in the EU, they would contribute 3-7% of the CO_2 emission reduction necessary to achieve the EU climate targets. The demonstrators are an important step in the development of viable industrial solutions. The heat pumps will be installed in drying processes for starch and bricks in two Austrian companies in spring 2019 and will be monitored and optimized for about one year. The high temperature heat pump solution can be multiplied not only for drying processes, but for all kinds of applications requiring hot media up to 160°C, such as the food industry (brewing, dairy, sugar, etc.), pulp and paper and the chemical industry (boiling processes, distillation, etc.).

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