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Steam generating heat pumps – Measuring results and market potential

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Abstract

Heat recovery becomes increasingly important for the decarbonization of industry. In addition to direct heat recovery, industrial heat pumps are increasingly used to valorize low-temperature waste heat for industrial processes. Increased utilization temperatures of heat pumps in recent years allow for generation of steam, serves as an efficient medium for heat transfer and as a process reactant in industry. For that, different types of heat pumps are available, but nearly no reference plants. In the H2020 project BAMBOO, different heat pump systems were investigated and a demonstrator consisting of a water-to-water heat pump and a flash tank system was built and tested to analyze steam production and efficiency in different operating conditions.
Furthermore, a market potential assessment for steam-generating heat pumps in European countries was done, considering production volumes, steam demand for selected products, and energy prices for different consumption bands (generally speaking different company sizes), showing the influence of different boundary conditions on the economic potential of integrating heat pumps in specific sectors.
This paper describes the measurement results of the demonstrator and the results of the market study.

Keywords: Steam generating heat pump; measurement results; market potential; heat recovery; industrial processes; decarbonization;

1. Introduction

The growing interest in industrial heat pumps already shows their great potential for decarbonizing process heat. On the one hand, by increasing energy efficiency through the use and recovery of waste heat, and on the other hand, by using electricity from renewable resources to power heat pumps, it is possible to completely decarbonize process heat. [1] For low and medium temperature levels in industrial processes, heat pump applications are projected to cover 30% of total heat demand by 2050. Thus, to achieve the International Energy Agency's "Net-Zero Emissions by 2050" scenario, heat pump capacities of about 500 MW need to be installed each month over the next 30 years. [2]

As far as European industry is concerned, low-temperature process heat forms a significant proportion of energy consumption. About 30% of the process heat is in a temperature range below 200°C. In many cases, steam is used as efficient heat transfer medium for production processes (e.g. drying, sterilization and cooking) and as a reactant. The use of steam is not only well proven in practice but steam itself can also be classified as environmentally safe. [3]

Due to the attractive market potential, there are already some developments in the European market for industrial high-temperature heat pumps that offer the provision of saturated steam up to 5 bar_a for industrial processes. [4], [5], [6] Nevertheless, there is still a lack of reference and demonstration plants to prove and

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visualize the functionality of these novel steam supply systems - especially under real operating conditions. Apart from the European market, steam-generating heat pump systems at high TRL with several 100 kW_{th} to a few MW_{th} heating capacity for saturated steam generation up to 9 bar_a can only be found in Japan. [7], [8] In this context, the system studied by Kaida et al [7] is comparable to the one analyzed in this publication, but has a higher heating capacity and a lower level of utilization temperature. In the publications of Bless et al [9] and Wilk et al [10], different cycle and technical approaches to heat pump-based steam generation have already been theoretically investigated. Marina et al. presented experimental results of a steam generating heat pump system for up to 4.8 bar_a saturated steam. [11]

Within this publication, results and findings of initial experimental investigations of a heat pump-based steam generation system using flash tanks are shown, which are based on the previous work of Helminger et al [12], Wilk et al [10], and mainly on Riedl et al. [13], among others. Extending these works within this publication the heat pump of the steam generating system is focused on.

Results from market potential analyses already carried out [14] [15] indicate potentials for high-temperature heat pumps in selected production areas (food, paper industry, wood-based materials industry, etc.). The market potential assessment for steam-generating heat pumps (< 150 °C) presented in this paper, which takes into account country-specific production volumes from statistics databases [16] and process-specific steam demand volumes for the production of selected products, and current energy prices of European countries, extends the works of Windholz et al. [17] by analyses with prices for different consumption bands (generally speaking different company sizes).

The paper is organized as follows: After this introduction, the steam-generating heat pump system is described, followed by measurement results and findings. After the market potential study is presented, the paper concludes with a summary.

2. Description of the steam-generating heat pump system, [13]

As stated in [13], Figure 1 shows the complete steam-generating heat pump system (SGHP) in the laboratory of EDF LAB Les Renardières. It is composed of the high-temperature heat pump (HTHP) HeatBooster HBS4 of the no longer existing manufacturer Viking Heat Engines (VHE), and a flash tank unit (FT) for steam generation from hot pressurized water.

The water-to-water HTHP is equipped with four oil-cooled reciprocating compressors and is capable of providing a maximum useful temperature of 160 °C by using HFO-R1336mzz(Z) refrigerant. It has a nominal heating capacity of 200 kW_{th}.

The FT was designed and manufactured specifically for the HTHP (i.e., 200 kW_{th}) and for test operation in the laboratory and subsequent demonstration operation in a semi-industrial environment. With this FT it is possible to generate saturated steam up to about 5 bar_a (~152 °C).

According to the schematic representation of the SGHP in Figure 2 the idealized steam generation of the SGHP works as follows [13]:

The refrigerant circulating in the heat pump (HP) extracts heat from the heat source by its evaporation, and after compression is in compressed form with higher temperature. By liquefying the refrigerant in the condenser, it adds heat to the circulating pressurized water on the secondary side, increasing the water temperature (ideally isobaric) to a still subcooled state.

- The speed of the water circulation pump and the use of its bypass together with the opening degree of the flash valve mainly define the circulation flow and the pressure drop of the pressurized water along the flash valve. The (ideally isenthalpic) expansion (exergy loss) of the subcooled water flow causes partial evaporation of the water, resulting in a certain steam quality after the flash valve. The higher the pressure drop, the higher are steam quality but also the exergy loss.
- In the flash tank, saturated steam is subsequently separated from the saturated liquid and discharged in a usable manner (ideally isobaric).
- The mass predominant saturated water collects in the flash tank and is pumped back to the condenser by the circulation pump (ideally isentropic), increasing its pressure.
- To keep the water level in the flash tank constant or to refill the flash tank, the evaporated water is replenished via the feedwater pump.

Since the studied object is a heat pump-based energy system, in addition to the COP of the heat pump COP_{HP}, the COP of the SGHP COP_{system} was also calculated, also considering the performance of the circulation pump.

Figure 1: HTHP in the lab of EDF, adapted from [13]

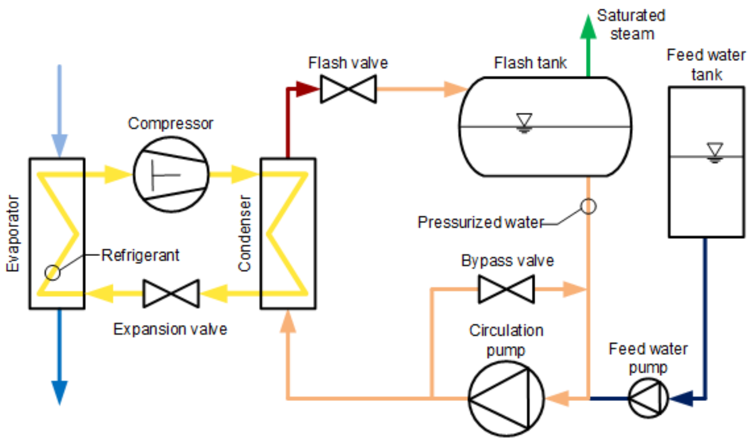

Figure 2: Scheme of the SGHP, adapted from [13]

3. Measurement results and findings

To the knowledge of the authors, the data of the measurement campaign are the first ones of a steam generating heat pump system like this, i.e., a saturated steam pressure of up to 5.5 bar_a with a high-temperature heat pump using a low GWP refrigerant and a flash tank.

As partly stated in [13], a maximum steam pressure of 5.5 bar_a (~155 °C) was reached, and a maximum saturated steam mass flow rate of 218 kg/h was achieved. Relevant system conditions at these two maximum operating points are listed in Table 1.

In [13], results of stationary operating points were presented by COP_{system} and corresponding steam mass flow, see Figure 3. The COP_{system} was broken down by saturated steam pressure (2/3.5/5 bar_a), source-side inlet temperature of the heat pump source (65/80 °C), and whether the circulation pump bypass valve was open or closed (cmp. scheme in Figure 2).

Table 1. System conditions at maximum values of steam pressure and steam mass flow reached during the test campaign

Steam pressure / temperature (bar_a / °C)	**Steam mass flow (kg/h)**	COP_{system} (-)	Sink-side water inlet/outlet temperatures of the heat pump (°C)	Source-side water inlet/outlet temperatures of the heat pump (°C)
5.5 / ~155	56	~1.7	154/157	80/77
2.0 / ~120	**218**	~4.2	121/129	80/74

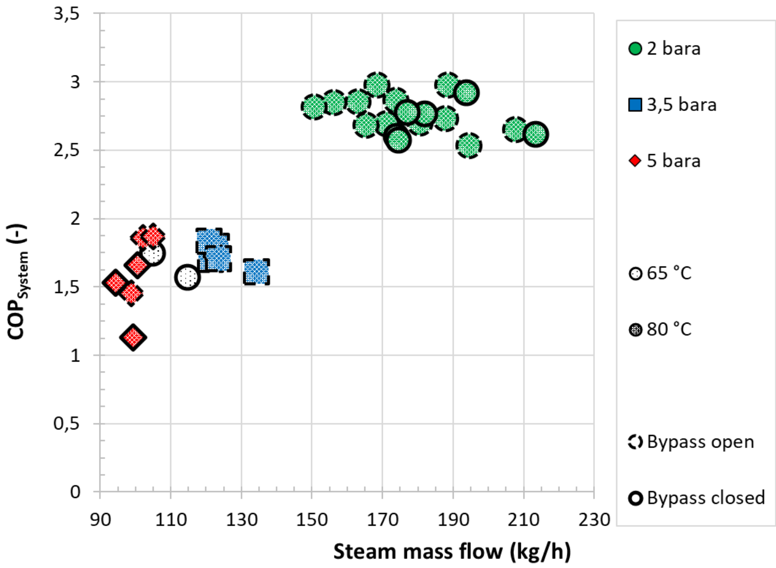

Figure 3: COP_{system} and different steam mass flows, broken down by saturated steam pressure (2/3.5/5 bar_a), source-side heat pump inlet temperature (65/80 °C), and whether the circulation pump bypass valve was open or closed. Adapted from [13]

Extending the earlier work of the authors, a deeper analysis of the heat pump's COP_{HP} (without flash tank system) is carried out within this paper to gain knowledge about the demonstrator and improve the design of future SGHPs. During the measurement campaign, the boundary conditions and setpoints of the SGHP were changed systematically, e.g., inlet/outlet temperatures and mass flows. Due to different issues (i.e., operation at operating limits, controls of the components and the test rig) not all combinations of boundary conditions and setpoints delivered stationary operation of the SGHP. The boundary conditions of the resulting 31 stationary operating points are shown in Figure 4. The diagram shows the volume flows on the sink and the source side of the heat pump, as well as the resulting temperature lift between sink outlet and source outlet at 100% rotational speed of the compressor. While the flow rate on the sink side had a range of 8.5 to 38.0 m³/h (ratio 1:4.5), the volume flow rate on the source side had only 2 concrete values 9.9 and 12.0 m³/h (ratio 1:1.2). The allowed volume flow range is 5 to 50 m³/h on both sides of the heat pump. The resulting temperature lift ranged from 49.2 to 79.2 K (ratio 1:1.6), distinguished within the diagram by 5 K groups (color and marker).

Given these boundary conditions, Figure 5 shows the resulting COP_{HP} of the heat pump at different temperature lifts between sink outlet and source outlet, broken down by the temperature difference (spread) of the pressurized water (sink). The authors focused on lift and spread since the lift is known to have a strong influence on the COP_{HP} of a compression heat pump (rising lift generally decreases COP_{HP}), and the spread on the sink side is also expected to play a role (at constant lift, rising spread reduces condensation pressure thereby increasing the COP). Analyzing the available measurement data, the expected trends are not fully confirmed, lift and spread are apparently not the only relevant parameters for the COP_{HP}, as can be seen especially at the operating points having a lift of about 78 K but different COP_{HP} values from 1.6 to 2.1 for different spreads, and on the other hand having nearly the same COP_{HP} values of around 3.5 (lift around 50 K) at spreads from 2 to 7 K. Unambiguous influences of other parameters could not be obtained with the available data.

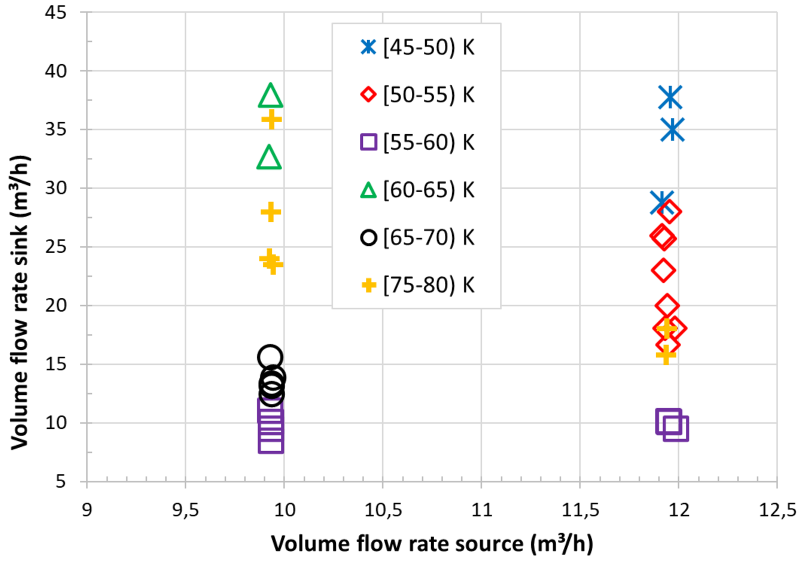

Figure 4: Boundary conditions at available operation points of the measurement campaign: Volume flow rates at heat source and heat sink (axes) and resulting temperature lift between sink outlet and source outlet

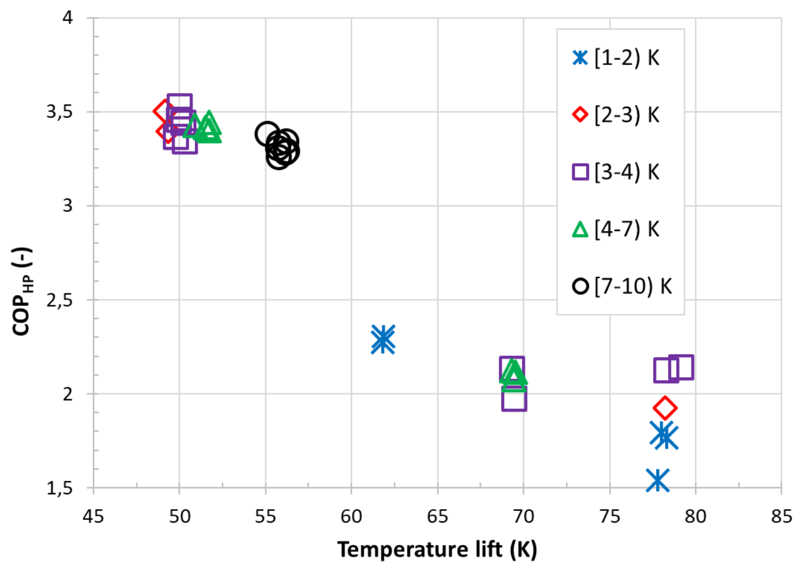

Figure 5: COP_{HP} at different temperature lifts between sink outlet and source outlet, broken down by the temperature difference (spread) of the pressurized water (sink)

The second law efficiency presented in the following compares the actual COP_{HP} with the maximum possible COP of a Lorenz cycle. For the correct calculation of this efficiency value, the difference of the logarithmic mean sink and source temperatures takes the place of the above used simple temperature lift between sink outlet and source outlet. But again, temperature difference between sink and source (though calculated differently) and spread was focused on since they are expected to have influence on the second law efficiency. The results for the available operating points are shown in Figure 6 with the corresponding volume flows on the heat source and the heat sink shown in Figure 7 over the resulting temperature difference between sink and source, broken down by the temperature difference (spread) of the pressurized water (sink). The diagrams indicate a lower second law efficiency at a higher difference between sink and source temperature (esp. spread group [1-2) K, having occasional comparable volume flows). Considering the spread on the heat sink (different colors and marker symbols) at comparable temperature differences between sink and source temperature (esp. 75 K), the second law efficiency tends to rise with rising spread.

Another observation at a temperature difference between sink and source of around 75 K and a constant source volume flow (spread groups [1-2) K and [3-4) K) is a decrease of second law efficiency with rising sink volume flow. This effect is not that strong at lower temperature differences between sink and source.

The current findings within this paper are that the second law efficiency (Lorenz cycle) of the heat pump is far from being constant, it increases when the temperature difference between sink and source is decreased, and with a rising temperature difference between sink and source the second law efficiency increases with rising spread of the pressurized water (respectively a lower sink volume flow). Even though unambiguous influences of all the parameters could not be obtained with the available data, the so far derived trends can help to operate the SGHP more efficient.

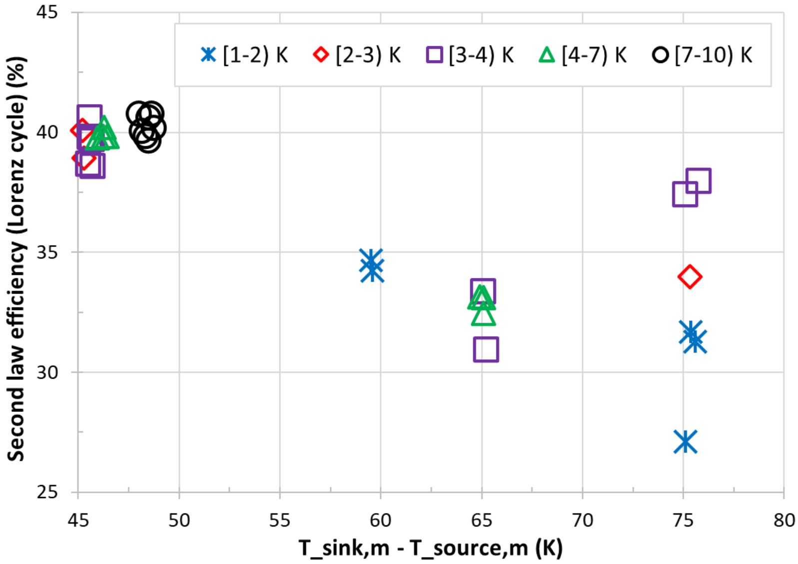

Figure 6: Second law efficiency (Lorenz cycle) over the difference between logarithmic mean sink and source temperature, broken down by the temperature difference (spread) of the pressurized water (sink)

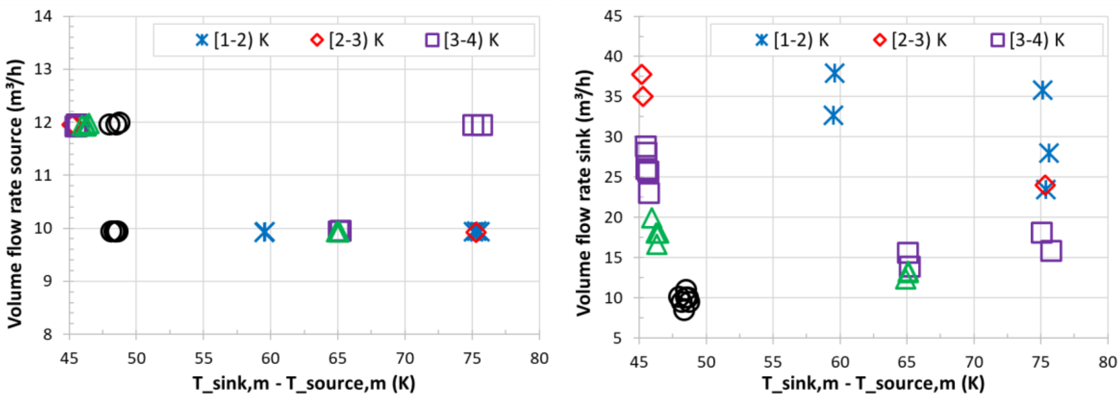

Figure 7: Boundary conditions at available operation points of the measurement campaign: Volume flow rates at heat source (left) and heat sink (right) over the resulting temperature difference between sink and source, broken down by the temperature difference (spread) of the pressurized water (sink)

4. Market potential

Within this paper, the market potential assessment of steam-generating high-temperature heat pumps up to 150 °C by Windholz et al. [17] is extended by analyses with prices for different consumption bands. Prices for different annual consumption bands of electricity and gas were extracted from the eurostat database [16] for the year 2021, see Table 2. Figure 8 shows the calculated effective ratios of electricity to gas prices in various European countries.

As stated in [17] for consumption bands IF/I4 (centre): Countries with relatively cheap electricity - above all Finland and Sweden - are particularly suitable for the substitution of gas by electricity, for example with heat pumps. In contrast, the implementation of heat pump projects in countries with relatively expensive electricity - especially Slovakia, Ireland and Germany - is only economically viable over longer periods of time, if at all.

In comparison with the maps in the left (consumption bands IA/I1) and the right diagram (consumption bands IG/I5), price ratios – against first expectations – do not decrease with higher consumption bands in each country. In Bulgaria, Netherlands, Portugal, and Sweden, price ratios increase strictly monotonically from IA/I1 over IF/I4 to IG/I5. In Ireland, Hungary, Austria, Romania and Finland, price ratios only increase from IF/I4 to IG/I5.

Table 2. Energy consumption bands of non-household consumers for electricity and gas according to eurostat database [16]

Name of consumption band	Energy carrier	Band of annual consumption
IA	Electricity	Less than 20 MWh
IF	Electricity	70,000 MWh – 149,999 MWh
IG	Electricity	150,000 MWh or over
I1	Gas	Less than 1,000 GJ
I4	Gas	100,000 GJ – 999,999 GJ
I5	Gas	1,000,000 GJ – 3,999,999 GJ

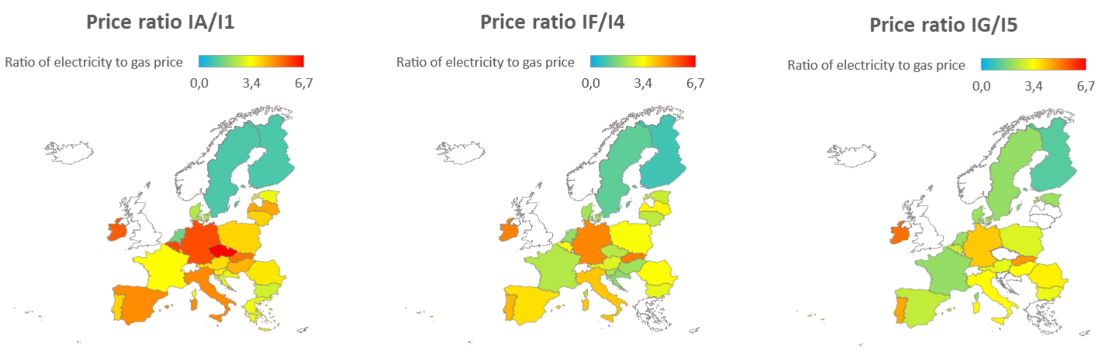

Figure 8: Ratio of electricity to gas prices in various European countries in 2021 according to *[16]*.
Left: Electricity consumption band IA, gas consumption band I1. Center: Electr. cons. band IG, gas cons. band I4 - adapted from *[17]*.
Right: Electr. cons. band IF, gas cons. band I5.
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4.1. Pulp and paper sector

Windholz et al. [17] found a total installed heating capacity in the paper industry in the European countries considered of around 12.6 GW_{th}. Germany achieves the highest individual value in this respect with 3.0 GW_{th}, followed by Finland and Sweden with 1.3 GW_{th} each. The technical potential for the use of steam-generating high-temperature heat pumps (< 150 °C) in the paper industry in various European countries was found to be around 6.1 GW_{th} or, at 48%, almost half of the installed heating capacity that could be provided by heat pumps - a heat recovery measure that saves primary energy.

The economic viability of heat pump systems is strongly dependent on the energy price ratio (electricity to natural gas) and the pricing of greenhouse gas emissions. Under the assumption that the use of heat pump systems must be financially worthwhile for the operator in addition to the primary energy savings, at a certificate price of 60 €/t and the three different price ratios of consumption bands a heating capacity of 1.3, 1.7 or 1.9 GW_{th} of HT heat pumps can be installed, i.e., only around 22, 28 or 31% of the technical potential in the paper industry.

As can be seen in the upper three images in Figure 9, Finland and Sweden as well as the Netherlands, Hungary and Croatia can leverage 100% of their technical potential with financial gain already with price ratio IA/I1. In Estonia and France this goal can only be reached with price ratio IG/I5. Note: Relevant information for the evaluation is missing for the countries shown in white.

An increase of the emission pricing (certificates) to e.g., 200 €/t increases the economic efficiency of heat pump systems, so that with the three different price ratios a total of about 1.4, 3.4, or 3.6 GW_{th}, or a share of 24, 55, or 58% of the technical potential can be raised in an economically profitable way, see in the lower three images in Figure 9. While with price ratio IA/I1 6 countries could possibly leverage 100% of their technical potential, this number increases to 15 or 14 with price ratios IF/I4 or IG/I5, respectively (As before: Relevant information for the evaluation is missing for the countries shown in white).

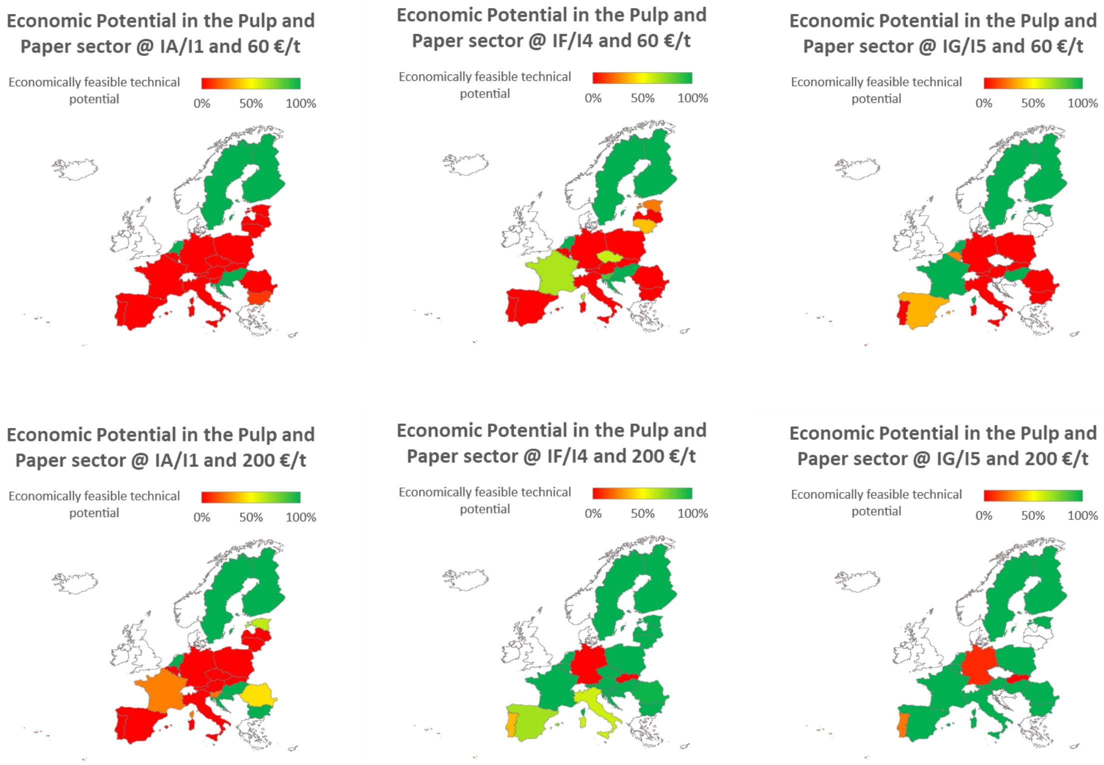

Figure 9: Economically feasible technical potential for steam-generating heat pumps (< 150 °C) in the paper industry in various European countries with a certificate price of 60 €/t.
Left: Price ratio IA/I1. Center: IG/I4. Right: IF/I5
Top: 60 €/t. Bottom: 200 €/t.
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4.2. Dairies, breweries, and meat processing

Windholz et al. [17] found a total installed heating capacity in subsectors (Dairies, breweries, and meat processing) of the food & beverage sector in the European countries considered of around 5.1 GW_{th}. Ireland achieves the highest individual value in this respect with 1.1 GW_{th}, followed by France with 875 MW_{th} and United Kingdom with 558 MW_{th}. The technical potential for the use of steam-generating high-temperature heat pumps (< 150 °C) in these subsectors of the food & beverage sector in various European countries was found to be around 2.2 GW_{th} or, at 44%, almost half of the installed heating capacity that could be provided by heat pumps - a heat recovery measure that saves primary energy.

The economic viability of heat pump systems is strongly dependent on the energy price ratio (electricity to natural gas) and the pricing of greenhouse gas emissions. Under the assumption that the use of heat pump systems must be financially worthwhile for the operator in addition to the primary energy savings, at a certificate price of 0 €/t and the three different price ratios of consumption bands a heating capacity of 136, 106 or 134 MW_{th} of HT heat pumps can be installed, i.e., only around 6, 5 or 6% of the technical potential in the considered subsectors of the food & beverage sector, see upper three images in Figure 10. These not really rising but partly even decreasing numbers are a direct consequence of the increasing price ratios with increasing consumption bands in some countries as explained above. While with price ratio IA/I1 three countries (Finland, Sweden, Netherlands) could possibly leverage 100% of their technical potential, this number decreases to two or one with price ratios IF/I4 or IG/I5, respectively.

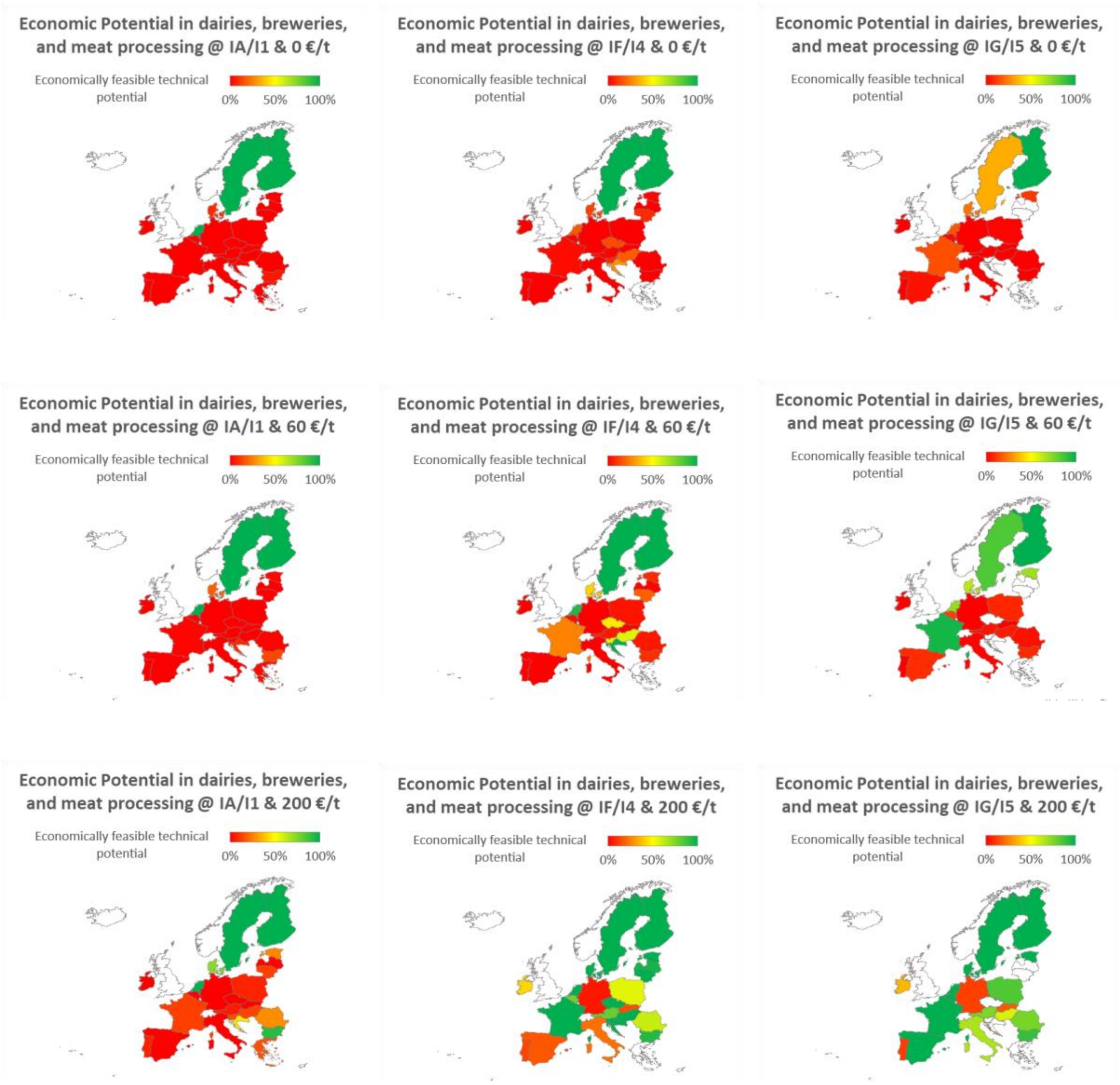

Figure 10: Economically feasible technical potential for steam-generating heat pumps (< 150 °C)
in dairies, breweries, and meat processing in various European countries with a certificate price of 0 €/t.
Left: Price ratio IA/I1. Center: IG/I4. Right: IF/I5
Top: 0 €/t. Middle: 60 €/t. Bottom: 200 €/t.
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An increase of the emission pricing (certificates) to e.g., 60 €/t increases the economic efficiency of heat pump systems, so that with the three different price ratios a total of about 151, 300, or 545 MW_{th}, or a share of 7, 13, or 24% of the technical potential can be raised in an economically profitable way, see middle three images in Figure 10. While with price ratio IA/I1 three countries could possibly leverage 100% of their technical potential, this number stays three or decreases to one with price ratios IF/I4 or IG/I5, respectively. On the other hands, in countries with decreasing price ratios (with rising consumption bands), e.g. France and Denmark, the economic potential rises from IA/I1 to IG/I5.

An increase of the emission pricing (certificates) to e.g., 200 €/t increases the economic efficiency of heat pump systems, so that with the three different price ratios a total of about 284, 1084, or 1318 MW_{th}, or a share of 13, 48, or 59% of the technical potential can be raised in an economically profitable way, see lower three images in Figure 10. While with price ratio IA/I1 three countries could possibly leverage 100% of their technical potential, this number increases to eleven or eight with price ratios IF/I4 or IG/I5, respectively. On the other hands, in countries with decreasing price ratios (with rising consumption bands), e.g. Poland and Spain, the economic potential rises from IA/I1 to IG/I5.

The current findings add a new aspect to the results of Windholz et al. [17], namely that in some countries the price ratio of electricity to gas is not strictly monotonically decreasing with rising consumption bands, but even increasing. This means, that in the countries concerned, smaller companies in the considered subsectors of the food & beverage sector, due to their better price ratio, have more economic potential to integrate heat pumps than larger companies (generally speaking having price ratios of higher consumption bands). However, despite the same price ratios, this effect was not found in the results of the pulp and paper sector, mainly due to different annual operating hours (8000 h/a in pulp & paper, 6000 h/a in the food & beverage sector) as boundary conditions.

Nevertheless, the influence of certificate prices on the economic potential of heat pump integration is clear, higher prices increase the economic potential.

5. Summary

Within this publication, results and findings of initial experimental investigations of a heat pump-based steam generation system using flash tanks were shown, which are based on the previous work of Helminger et al [12], Wilk et al [10], and mainly on Riedl et al. [13], among others. Extending these works within this publication the heat pump of the steam generating system was focused on. The current findings within this paper are that the second law efficiency (Lorenz cycle) of the heat pump is far from being constant, it increases when the temperature difference between sink and source is decreased, and with a rising temperature difference between sink and source the second law efficiency increases with rising spread of the pressurized water (respectively a lower sink volume flow). Even though unambiguous influences of all the parameters could not be obtained with the available data, the so far derived trends can help to operate the SGHP more efficient.

Results from market potential analyses already carried out [14] [15] indicate potentials for high-temperature heat pumps in selected production areas (food, paper industry, wood-based materials industry, etc.). The market potential assessment for steam-generating heat pumps (< 150 °C) presented in this paper, which takes into account country-specific production volumes from statistics databases [16] and process-specific steam demand volumes for the production of selected products, and current energy prices of European countries, extends the works of Windholz et al. [17] by analyses with prices for different consumption bands (generally speaking different company sizes). The current findings add a new aspect to the results of Windholz et al. [17], especially for the considered subsectors of the food & beverage sector, namely that in some countries the price ratio of electricity to gas is not strictly monotonically decreasing with rising consumption bands, but even increasing. This means, that in the countries concerned, smaller companies in the considered subsectors of the food & beverage sector, due to their better price ratio, have more economic potential to integrate heat pumps than larger companies (generally speaking having price ratios of higher consumption bands). However, despite the same price ratios, this effect was not found in the results of the pulp and paper sector, mainly due to different annual operating hours (8000 h/a in pulp & paper, 6000 h/a in the food & beverage sector) as boundary conditions, increasing the economic potential.

Nevertheless, the influence of certificate prices on the economic potential of heat pump integration is clear, higher prices increase the economic potential.

Nomenclature

Abbreviation/symbol		Subscript	
COP	Coefficient of performance	a	absolute
FT	Flash tank	HP	Heat pump
HFO	Hydrofluoroolefin	m	mean
HP	Heat pump	th	thermal
HT	High-temperature		
HTHP	High-temperature heat pump		
SGHP	Steam-generating heat pump system		
TRL	Technology readiness level		

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References

[1] R. de Boer, A. Marina, B. Zühlsdorf, C. Arpagaus, M. Bantle, V. Wilk, B. Elmegaard, J. Corberán and J. Benson, "Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat," 2020.

[2] IEA, "Net Zero by 2050 - A Roadmap for the Global Energy Sector," 2021.

[3] IEA, "HEATING AND COOLING facts and figures: The transformation towards a low-carbon Heating & Cooling sector," 2017.

[4] SPH Sustainable Process Heat, "Die Wärmepumpe: Produktbeschreibung.," [Online]. Available: https://www.spheat.de/. [Accessed 11 2022].

[5] Heaten AS, "HeatBooster," [Online]. Available: https://www.heaten.com/product/. [Accessed 11 2022].

[6] Turboden, "Large Heat Pump," [Online]. Available: https://www.turboden.com/solutions/2602/large-heat-pump. [Accessed 11 2022].

[7] T. Kaida, I. Sakuraba, K. Hashimoto and H. Hasegawa, "Experimental performance evaluation of heat pump-based steam supply system," *IOP Conference Series: Materials Science and Engineering,* vol. 90, p. 12076, 2015.

[8] Fuji Electric, "Steam Generating Heat Pump," [Online]. Available: https://www.fujielectric.com/company/research_development/theme/heatpump.html. [Accessed 11 2022].

[9] F. Bless, C. Arpagaus and S. Bertsch, "Theoretical investigation of high-temperature heat pump cycles for steam generation," *13th IEA Heat Pump Conference,* p. 357–369, 2021.

[10] V. Wilk, F. Helminger, S. Dusek, M. Lauermann and T. Fleckl, "Steam generation from waste heat with heat pumps".*Proceedings of DKV Tagung 2019.*

[11] A. Marina, S. Smeding, A. Wemmers, S. Spoelstra and P. Kremers, "Design and Experimental Results of a Two-Stage Steam Producing Industrial Heat Pump," *13th IEA Heat Pump Conference,* p. 908–919.

[12] F. Helminger, "Steam generating heat pumps – Upcoming technology for heat recovery," [Online]. Available: https://www.hp-summit.de/de/events/vortrag/steam-generating-heat-pumps--upcoming-technology-for-heat-recovery-24/768038. [Accessed 11 2022].

[13] J. Riedl, F. Hubmann, B. Windholz, C. Gachot, F. de Carlan and Y. Beucher, "Messergebnisse einer dampferzeugenden Wärmepumpe mit Flash tank".*Proceedings of DKV-Tagung 2022.*

[14] G. Kosmadakis, "Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries," *Applied Thermal Engineering,* vol. 156, pp. 287-298, 2019.

[15] A. Marina, S. Spoelstra, H. Zondag and A. Wemmers, "An estimation of the European industrial heat pump market potential," *Renewable and Sustainable Energy Reviews,* vol. 139, p. 110545, 2021.

[16] "Database - Production - Eurostat," 2021. [Online]. Available: https://ec.europa.eu/eurostat/web/energy/data/database.

[17] B. Windholz, S. Knöttner, P. Schmidberger, F. Helminger and A. Schneeberger, "Marktpotentialabschätzung dampferzeugender Hochtemperatur-Wärmepumpen bis 150°C".*Proceedings of DKV-Tagung 2022.*