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Heat Pumping Technologies MAGAZINE

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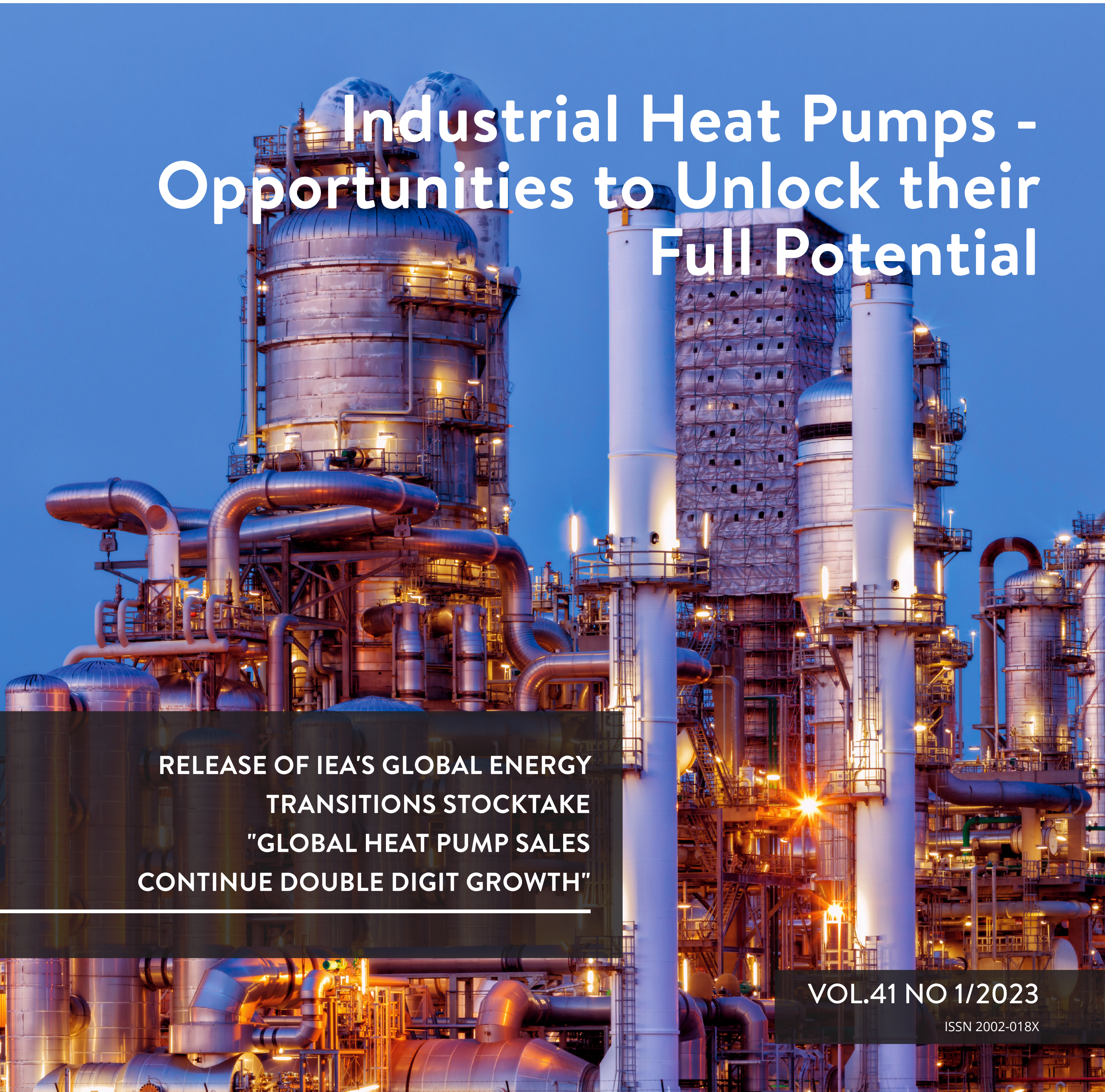

Industrial Heat Pumps - Opportunities to Unlock their Full Potential

RELEASE OF IEA'S GLOBAL ENERGY TRANSITIONS STOCKTAKE "GLOBAL HEAT PUMP SALES CONTINUE DOUBLE DIGIT GROWTH"

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Heat Pumping Technologies
MAGAZINE

VOL.41 NO 1/2023

In this issue

According to the IEA's World Energy Outlook special report - The Future of Heat Pumps, decarbonization of industrial heat through electrification is key to tackling the climate crisis, and there is considerable potential for electric heat pumps to provide process heat for industry. The comprehensive and interdisciplinary efforts needed from the various stakeholders to unlock the full potential of industrial heat pumps have been inferred in the foreword of this issue.

Under the title "High-temperature heat pumps are on the rise – Why is their market uptake slow?" the column addresses how to create the framework conditions for implementing industrial heat pumps, including (i) creating guidelines and training qualified personnel, and (ii) support fast implementation to avoid investments into less optimal energy solutions that block industrial heat pump adoption in future years.

In the HPT news in focus section, you can read a summary of the IEA report on Energy Technology Perspectives 2023 report, an excerpt of an IEA commentary about global heat pumps sales, which continues to show strong growth and about important Policy Acts in Europe and US which supports deployments of heat pumps.

The topical articles of this issue provide a strategic focus on the challenges and opportunities of industrial Heat Pumps, and the topics covered include (i) Opportunities for high-temperature heat pumps as grid flexibility providers, (ii) Conceptualization of wet and dry steam compression with liquid water injection for high-temperature heat pumps (iii) Developing a high-temperature heat pump technology concept using natural refrigerants and (iv) Storing Electricity with Industrial Heat Pumps.

Enjoy your reading!

Metkel Yebiyo, Editor
Heat Pump Centre
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Unlocking the game changer for decarbonizing industries

Most of the total energy demand of industries is used for process heating and is typically based on fossil fuels. Decarbonization of industrial process heating is accordingly one of the focus areas for reducing greenhouse gas emissions, where energy efficiency and electrification are the most effective measures.

Industrial heat pumps are combining energy efficiency and electrification and are, accordingly, one of the most promising technologies for decarbonizing industrial process heating. Already today, they are the optimal solution for a variety of applications, while fuel prices and carbon taxes are becoming more favorable for heat pumps, extending the range of applications even more. The IEA underlines the tremendous potential of industrial heat pumps, estimating that around 500 MW of heat pumps have to be installed per month over the next 30 years in light industries to keep on track towards net zero emissions by 2050.

Most of the systems applied in the industry operate at supply temperatures below 100 °C, where various technologies are readily available, and good performances can be achieved. For higher temperatures, where most of the current process heating is required, only a few technologies are currently available. It may, however, be noted that a considerable number of developments are ongoing, aiming to develop and demonstrate heat pump-based process heating. Considering the huge potential in contrast to the technology status, it may be questioned how the full potential of industrial heat pumps can be fully exploited?

In my opinion, it requires a comprehensive and interdisciplinary effort involving various stakeholders to unlock the full potential for industrial heat pumps, including:

- The development of advanced heat pump technologies for both retrofit of existing process equipment and integration of industrial heat pumps into new process equipment with a focus on bringing solutions up to 160 °C into application and advancing the state of the art for even higher temperatures.
- A dedicated and immediate effort from process industries to initiate the transition towards heat pump-based process heating typically starts with strategy development, process modifications, and, finally, the testing and integration of industrial heat pumps.
- Clear and long-term political frameworks supporting the implementation of energy efficiency measures and electricity-based process heating solutions.

Partnerships are key to realize these developments at the needed speed – heat pump technology suppliers, end-users, process equipment suppliers, consultants, R&D organizations, policy makers, and more are required to team up and make a common effort for the green transition.

In order to support these urgently needed developments and to create a solid knowledge base to inform the various stakeholders, we have facilitated HPT Annex 58 about high-temperature heat pumps. In this Annex, we are providing a technology overview, integration concepts, and guidelines for the transition process. Stay tuned for the various results of the Annex to be published during 2023! Furthermore, you will find various good examples of relevant developments within this issue. I hope you will enjoy reading it and get inspired by the great examples being presented!

Benjamin Zühlsdorf, PhD
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High-temperature heat pumps are on the rise – Why is their market uptake slow?

The current unprecedented surge in energy prices and the risk of natural gas supply shortages poses an existential threat to many industrial companies, especially small and medium-sized enterprises. Industrial heat pumps are one of the most promising technologies for tackling climate and energy crises.

They are, therefore, indispensable in reducing energy demand and natural gas dependency. According to the IEA , nearly 30% of the heat demand of the chemical, paper, and food industries could be covered by commercially available industrial heat pumps. In Europe alone, 15 GW of heat pumps could be installed in 3,000 facilities in these three sectors.

Moreover, recent gas price increases have made industrial heat pumps the cheapest solution for process heat generation, even in countries with a high electricity-to-gas price ratio (e.g., Germany, Italy, UK) . As a result, a wide range of industrial high-temperature heat pumps (HTHP) is now available on the market. In addition, there is great interest from many industrial partners and multiple applications where integrating an industrial heat pump is economical. Nevertheless, there are still only a few implementations. What are the reasons?

Despite the promising facts, the market adoption of industrial heat pumps is challenged by a low level of standardization resulting in few practical implementation examples. One of the key reasons is that industrial heat pumps are usually products tailored to the specific industrial process, which requires specialized planning, design, manufacturing, and installation. This situation poses a high market barrier that adds too much risk, time, cost, and complexity for many potential customers who demand a timely and predictable solution. On the other hand, manufacturers and designers still lack a critical mass of customers to develop standardized solutions that could reduce costs and planning efforts.

Accelerating market development requires concerted action by all relevant stakeholders. To give companies a head start in realizing the economic and environmental potential of industrial heat pumps. It is necessary to create a competitive business ecosystem that accelerates market development. This should be the goal and mission of the heat pump industry.

Over the last few years, many research projects have started on the topic of HTHP and industrial heat pumps on the national and international levels. Some of these projects add value through technology improvements, others by analyzing individual case studies from a technical or economic point of view. However, it is about creating the framework conditions for implementing industrial heat pumps.

The following topics need to be addressed:

- Creating guidelines and training of qualified personnel able to implement industrial heat pumps optimally.
- Pilot projects to learn from experience, reduce implementation risks, and multiply application potential.
- Support fast implementation to avoid investments into less optimal energy solutions that block industrial heat pump adoption in future years.

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[1] International Energy Agency (IEA), The Future of Heat Pumps – World Energy Outlook Special Report, Paris, November 2022, https://www.iea.org/reports/the-future-of-heat-pumps
[2] White paper: Strengthening Industrial Heat Pump Innovation - Decarbonizing Industrial Heat, https://hthp-symposium.org/media/1379/strengthening-industrial-heat-pump-innovation-decarbonizing-industrial-heat.pdf
[3] IEA HPT Annex 58 on HTHP, Task 1: Technologies – State of the art and ongoing developments for systems and components, https://heatpumpingtechnologies.org/annex58/task1

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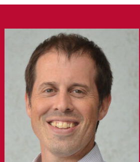

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Release of IEA's Energy Technology Perspectives 2023 – heat pumps one of six highlighted and analyzed clean energy technologies in the report

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Heat pumps are one of the most important clean energy technologies. This is established in the world's first global guidebook for the clean technology industries of the future and the latest of IEA's flagship reports Energy Technology Perspectives 2023.

Heat pumps are one of the most important clean energy technologies. This is established in the world's first global guidebook for the clean technology industries of the future and the latest of IEA's flagship reports Energy Technology Perspectives 2023.

On January 11 the Executive Director of IEA, Fatih Birol, introduced the launch of the report stating that a new global clean energy economy is developing, and that all clean energy technologies are flourishing around the world.

The report highlights major market- and employment opportunities. For example, related clean energy manufacturing jobs will more than double from 6 million today to nearly 14 million by 2030, with over half of these jobs tied to electric vehicles, solar PV, wind and heat pumps.
But there are potentially risky levels of concentration in clean energy supply chains. For mass manufactured technologies like wind, batteries, electrolyzes, solar panels and heat pumps, the three largest producer countries account for at least 70% of manufacturing capacity for each technology.

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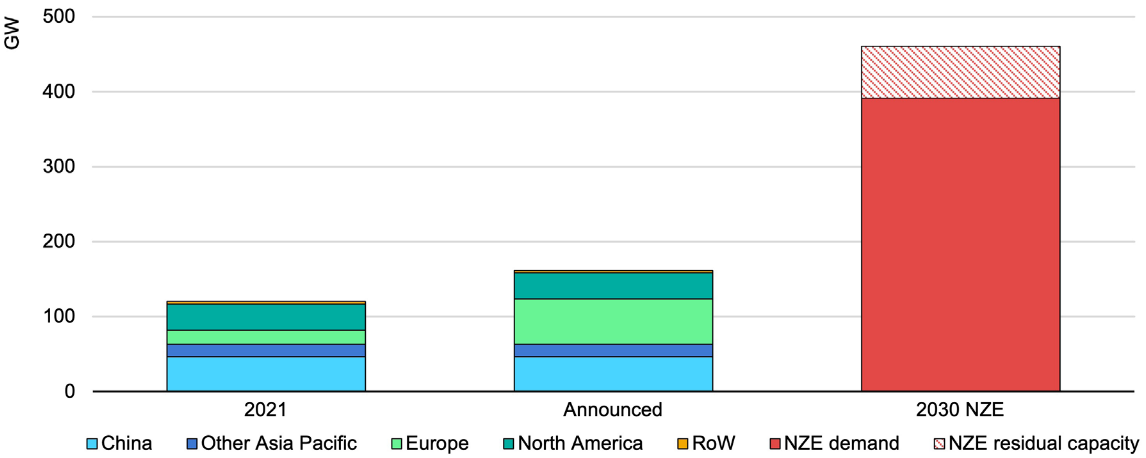
Need for a skilled workforce
According to the analysis an adequately skilled and sufficiently large workforce will be central to the energy transition. For clean energy technology supply chains like solar PV, wind and heat pump systems, about 800 000 additional workers that can install the technologies will be needed in order to reach IEA's Net Zero Emissions by 2050 (NZE) scenario.

Trade of heat pumps
IEA's analysis also shows that heat pumps are less traded than solar PV modules. In Europe, intra-regional trade of heat pumps is common, but the sudden surge in demand for the technology in 2021, combined with an open trade policy, led to a sharp increase in imports from outside the continent, almost exclusively from Asian countries.

Expansion plans and the gap with the net zero trajectory
Under the NZE Scenario, expanding the global manufacturing capacity of the six technologies reviewed in the report will require cumulative investments of around USD 640 billion (in real 2021 US dollars) over 2022-2030. Shortfalls in investment to 2030 amount to around USD 15 billion for heat pumps. According to IEA, this highlights the importance of clear and credible deployment targets from governments to limit demand uncertainty and to guide investment decisions.

Manufacturing capacity for heat pumps is set to grow in the next few years, but how quickly is very uncertain. Capacity expansion that would result from publicly announced or planned projects falls short of the goals of NZE, although in reality, expansion is likely to be much greater by 2030 according to IEA.



Notes: RoW = rest of world; NZE = Net Zero Emissions by 2050 Scenario. Announced capacity includes existing capacity.The manufacturing capacity needed to meet projected demand in the NZE Scenario (NZE demand) is estimated assuming a utilisation rate of 85%. NZE residual capacity, thus, represents the manufacturing capacity that would remain unused, on average, which provides some flexibility to accommodate demand fluctuations. Heat pump capacity (in GW) is expressed as thermal output capacity. By and large, Europe is the main region to have concrete public expansion plans from manufacturers in place.
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Heat pump manufacturing capacity by country/region according to announced projects and in the NZE Scenario Source: IEA Energy Technology Perspectives 2023, figure 4.10

US Inflation Reduction Act, EU Net Zero Industry Act, and Heat Pump Action Plan: Important Climate Policies for Heat Pumps

In an effort to address some of the most pressing issues facing the world today, governments and policymakers around the globe have been busy introducing a variety of legislative measures aimed at reducing inflation, transitioning towards net zero emissions and promoting sustainable and secure energy.

In the United States, the government has recently passed the Inflation Reduction Act, while in the European Union, lawmakers have introduced the Net Zero Industry Act. Additionally, the Heat Pump Action Plan has been launched to encourage the adoption of more efficient heating systems.

On August 16 the US Inflation Reduction Act, signed into law by President Biden (read more on page 23). Among other impacts, the wide-ranging law is designed to lower the cost of prescription drugs, reform the U.S. tax code including instituting a minimum corporate tax of 15%, and reduce greenhouse gas emissions by offering clean energy incentives to stimulate domestic production of clean energy technologies, such as for example heat pumps. At roughly US$ 370 billion, the law includes the largest investment the U.S. government has ever made to fight climate change and has the potential to transform clean energy industries in the United States.

As has been widely reported, the IRA is the most impactful and transformative climate legislation in U.S. history. The bill includes heat pumps as a central technology in the mission of building a clean economy. Including a $14,000 in direct consumer rebates for families to buy heat pumps or other energy efficient home appliances, saving families at least $350 per year.

Meanwhile, the European Union has introduced the Net Zero Industry Act, which aims to accelerate the transition towards a carbon-neutral economy and enables to scale up the clean energy transition quickly. The Act will strengthen the resilience and competitiveness of net-zero technologies manufacturing in the EU, and make our energy system more secure and sustainable. It will create better conditions to set up net-zero projects in Europe and attract investments, with the aim that the Union's overall strategic net-zero technologies manufacturing capacity approaches or reaches at least 40% of the Union's deployment needs by 2030.

The act includes a range of measures aimed at promoting the use of renewable energy, increasing energy efficiency, and supporting the development of new technologies including solar, wind, batteries and storage, heat pumps and geothermal energy, electrolysers and fuel cells, biogas/biomethane, carbon capture, utilisation and storage, and grid technologies.

Finally, the the action plan to accelerate the roll-out of heat pumps accross EU has been launched to encourage the adoption of more efficient heating systems. The use of efficient heat pumps in buildings, industry and local heat networks is key for cutting greenhouse gases and achieving the Green Deal and REPowerEU targets.

The action plan on accelerating the heat pump market and deployment sets out four strands of action:

- partnership between the Commission, EU countries and the sector (including R&I)
- communication to all interest groups and a skills partnership for rolling out heat pumps
- legislation (ecodesign & energy labelling)
- accessible financing

These three initiatives represent a major step forward in the fight against climate change and to improved energy security. By addressing key issues such as inflation, industrial emissions, and heating and cooling, governments around the world are taking decisive action to reduce their carbon footprint and promote a more sustainable and secure future. With continued effort and investment in these areas, we can build a more resilient and sustainable world for future generations.

Global Heat Pump Sales Continue Strong Growth Driven by Policy Support, Incentives and Climate Goals

According to the latest analysis by the IEA, a commentary published on March 31, global sales of heat pumps grew by 11% in 2022, marking a second year of double-digit growth for the technology. Increased policy support and incentives for heat pumps drove strong uptake, with Europe enjoying a record year, and sales of air-to-water models jumping almost 50%. Heat pump purchases exceeded those of gas furnaces in the US. However, sales remained stable in China amidst a general economic slowdown.

To align with all existing national energy and climate pledges worldwide, heat pumps will have to meet nearly 20% of global heating needs in buildings by 2030. According to this report, the world is almost on track to reach this milestone if new installations continue to grow at a similar rate globally as they did the last two years. However, analysis performed by IEA shows that annual sales growth needs to be well over 15% this decade to achieve net zero emissions by 2050. Installations of heat pumps remain concentrated in new buildings and existing single-family homes, and multistorey apartment buildings and commercial spaces need to become a priority area if solid growth is to continue. Energy efficiency retrofits also need to accelerate to ensure new heat pumps installed in existing buildings are as efficient as possible.

The IEA commentary as well as heat pump market data published by the European Heat Pump Association reveal that heat pump sales in Europe continue to surge, with almost 3 million units sold in 2022, representing a 40% YoY increase. The surge in sales was partly driven by Russia's invasion of Ukraine, leading to a rise in natural gas and electricity prices and incentivising consumers to switch to more efficient heat pumps. Furthermore, the European Commission aims to double heat pump deployment rates in line with its decarbonisation goals, with most EU countries offering financial incentives to encourage their uptake. Italy, France and Germany are the largest markets in Europe, while in the Nordic countries, nearly five times as many units were sold per household than in the rest of Europe. Some more nascent markets such as Poland and Czechia doubled in size last year. Nordic and Baltic countries had the highest share of air-to-air units, which account for 50-80% of installations, while Germany and Poland preferred air-to-water heat pumps.

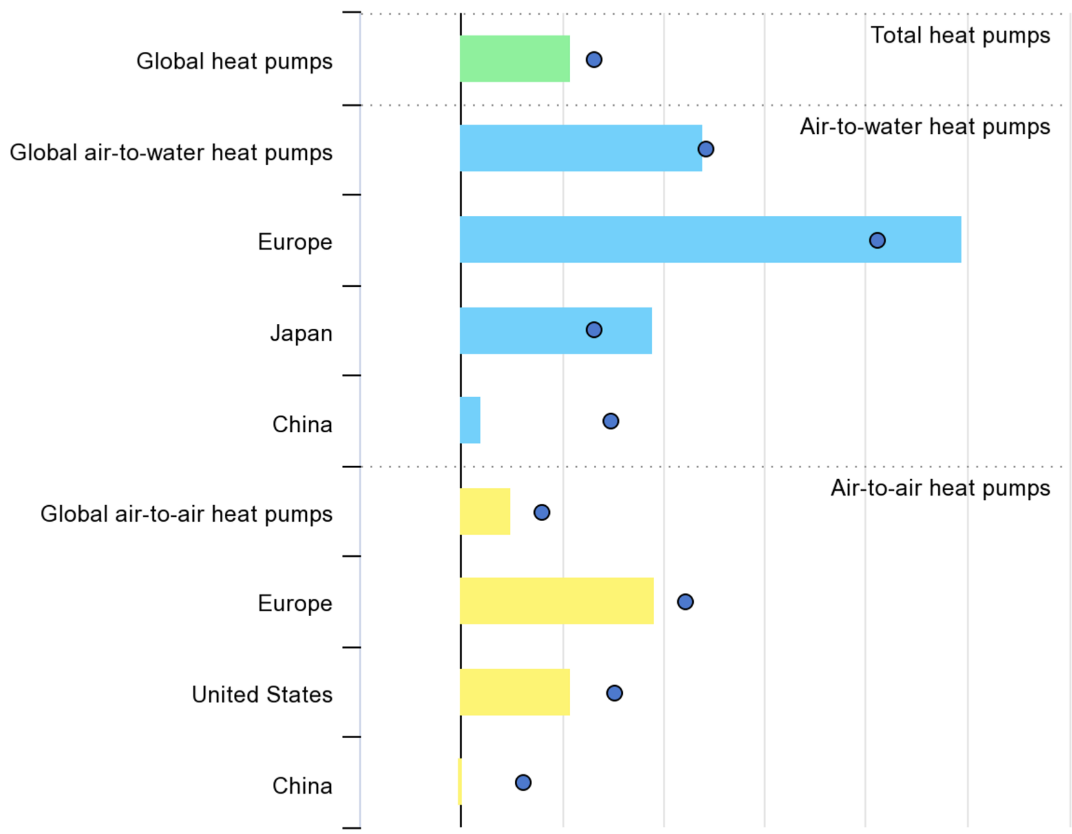

Figure 1: Annual growth in sales of heat pumps in buildings worldwide and in selected markets, 2021 and 2022. Sources: IEA (2023), Global heat pump sales continue double-digit growth, IEA, Paris https://www.iea.org/commentaries/global-heat-pump-sales-continue-double-digit-growth , License: CC BY 4.0

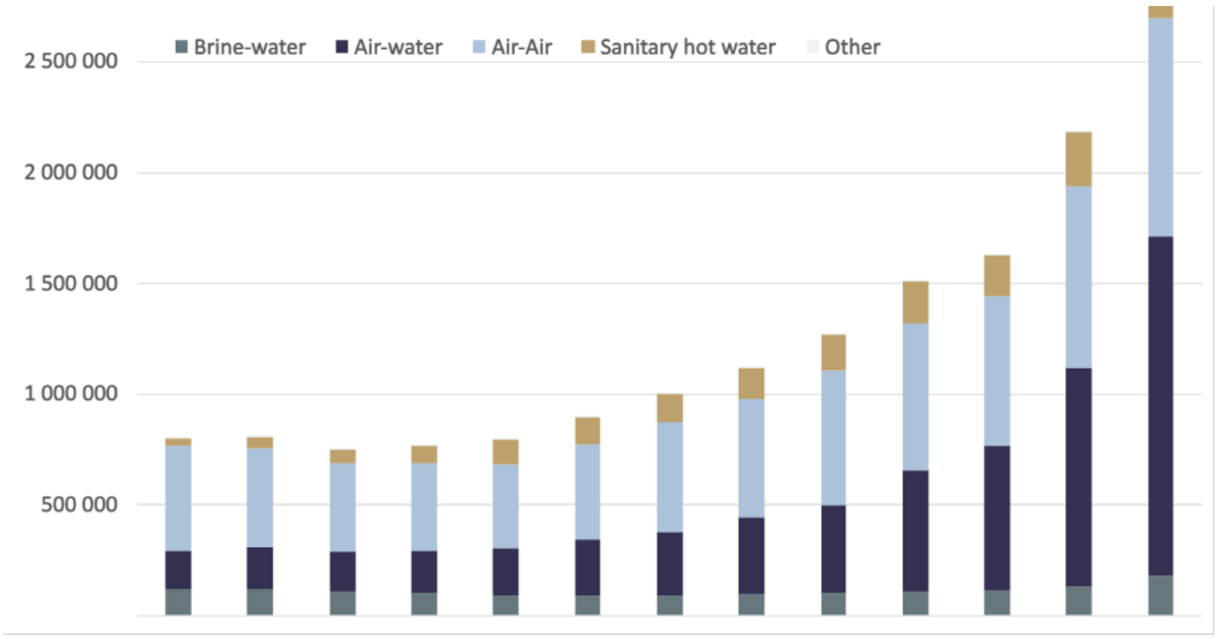

Figure 2: European heat pump market. Sources: [Heat pump record: 3 million units sold in 2022, contributing to REPowerEU targets – European Heat Pump Association (ehpa.org)]

In France, heat pumps outsold fossil fuel boilers in buildings for the first time in 2022, according to IEAs commentary, coinciding with a national ban on gas boilers in new buildings. However, fossil fuel boilers still have a higher market share than heat pumps in some countries like Italy and Germany, where there were twice as many fossil fuel boilers sold as heat pumps in 2022. Nonetheless, the phasing out of polluting technologies and fuels is being proposed, with 17 European countries implementing or announcing bans on installations of boilers that run solely on fossil fuels.

In addition, the IEA report shows that North America has the largest installed capacity of heat pumps for heating buildings, with the United States leading the market. In 2022, heat pump sales in the US surpassed gas furnace sales after years of almost equal growth. While most heat pumps are still installed in single-family homes, the number of apartments using heat pumps as their primary heating technology more than doubled between 2015 and 2020. Manufacturers have developed specialised heat pumps that work efficiently in cold climates to accelerate their deployment in regions where less than 5% of households use this technology. Air-to-air models in ducted air systems are the most common type of residential units in the US.

According to the IEA analysis, more heat pump units were sold in China in 2022 than in any other country, and around 40% of heat pumps worldwide are manufactured there. Northern China still relies on district heating, but many households also have heat pumps for space cooling and additional heating. Southern China uses air-to-air reversible units for space heating, while air-to-water heat pumps saw growth of over 20% in 2022. In Japan and Korea, sales of air-to-air heat pumps remained stable, with most units sold to replace less efficient existing installations. In Australia and New Zealand, air-to-air heat pumps are the most common source of heating, with increased market penetration in colder regions. Large-scale heat pumps could be a decarbonisation option for district heating networks in Central Asia and Eastern Europe, where upfront costs remain a challenge.

IEA states that financial incentives for heat pumps have been introduced or strengthened in over 30 countries, which collectively account for over 70% of global heating demand for buildings. In 2022, several countries, including the United States, Poland, Ireland, and Austria, increased their subsidies for heat pumps, making the purchase of the cheapest models comparable to that of a new gas boiler. However, electricity tariffs and energy taxation still put heat pumps at a disadvantage in some countries, and addressing other barriers such as a shortage of installers and restrictions for new installations remains a challenge.

IEA recommend, that to ensure continued growth in heat pump deployment, secure and resilient supply chains are needed. Manufacturers have already announced over EUR 4 billion in expanded heat pump production capacity, with further manufacturing announcements expected, driven by new incentives for consumers and direct support for manufacturers through various government programs. Expanding production capacity to the level outlined in the IEA's pathway to net-zero emissions by 2050 would require additional investments of USD 15 billion globally by 2030.

HPT TCP New Projects

Annex 62 "Heat pumps for multi-family residential buil-dings in cities"

HPT TCP is very happy to announce that the new project Annex 62, "Heat pumps for multi-family residential buil-dings in cities", has been launched. There is no doubt about the necessity to act decisively to reduce the future impact of the climate change by reducing the emission of greenhouse gases. A major solution to preventing CO_2 emissions in the heating and cooling sector is to use heat pumps instead of technologies based on fossil fuels. Annex 62 build further on the results achieved in the Annex 50, "Heat Pumps in Multi-Family Buildings for Space Heating and DHW".

Scope

The new Annex will focus on heat pump solutions for multi-family houses in high-density cities. With respect to the demand of the participating countries, new buil-dings and retrofit will be considered, as well as buildings with higher specific heating demand.

Key data

- Project duration: 1 January 2023 – 31 December 2025
- Operating Agent: Mr Marek Miara, marek.miara@ise.fraunhofer.de
- Participating countries: France, Germany
- Website: https://heatpumpingtechnologies.org/annex62/

There is still time to join the project. For information on how to participate, contact operating agent Marek Miara: marek.miara@ise.fraunhofer.de

Annex 63 "Placement Impact on Heat Pump Acoustics"

HPT TCP is pleased to announce that Annex 63, "Pla-cement Impact on Heat Pump Acoustics" is being laun-ched. The new Annex 63 has been set up as a follow-up to the recently finalized Annex 51, "Acoustic Signatures of Heat Pumps". Noise emissions are a potential thre-at to further spreading of heat pumps in the years to come. Thus, working on the acceptance of heat pumps by minimizing these adverse environmental impacts while keeping high energy efficiency is of great impor-tance. Annex 63 enriches independent information and expertise on the benefits of heat pumping technologies by focusing on the field of acoustics.

Scope

- Building Acoustics Impact of Heat Pumps
- Urban Acoustics Impact of Heat Pumps
- Psychoacoustics of Heat Pumps
- Digitally Assisted Heat Pump Placement
- Dissemination

Key data

- Project duration: 1 January 2023 – 31 December 2025
- Operating Agent: Christoph Reichl,
- christoph.reichl@ait.ac.at
- Participating countries: Austria, Germany
- Website: https://heatpumpingtechnologies.org/annex63/

HPT TCP New Projects

Annex 64 "Safety measures for flammable refrigerants"

HPT TCP is pleased to announce that Annex 64, "Safety measures for flammable refrigerants", will be launched soon. The ultimate goal of the Annex is to contribute to a broader safe use of flammable refrigerants. To reach this goal, the aim of the Annex is to increase the understanding of the risks related to the use of flammable refrigerants and to develop methods and system designs to maintain the risks at acceptable levels also for systems with a larger capacity than what is available on the market today.

Objectives
The objective is that the findings generated in the Annex will be used as background information when regulations regarding the use of flammable refrigerants are updated. It is expected that one outcome of the Annex is a set of recommendations for updates of the regulations. We have seen the important work done within Lifefront, and continued research in international cooperation can further support the safe use of flammable refrigerants.

Scope
The Annex will include investigations of a selected set of measures to limit the risks associated with using flammable refrigerants in heat pumps, AC-systems, refrigeration systems or similar based on the vapour compression cycle. The main focus will be on systems for heating/cooling or hot water production in single-family buildings or for use in multifamily houses (up to 50 kW) on heat pumps placed indoors. It will also include risk assessments related to such use. The fluids considered could be hydrocarbons and synthetics. Safety issues during servicing and at the systems´ end of life will also be considered.

Large industrial heat pumps, heat pumps for district heating, heat pumps/AC systems for automotive and heat pumps built into home appliances like dishwashers, tumble dryers etc. will not be included.

Key data

- Project duration: 1 April 2023 – 31 March 2026
- Operating Agent: Björn Palm
- Bjorn.Palm@energy.kth.se
- Participating countries: Germany, South Korea, Sweden (TBC).
- Website: https://heatpumpingtechnologies.org

There is still time to join the project. For information on how to participate, contact operating agent Björn Palm Bjorn.Palm@energy.kth.se

INFORMATION

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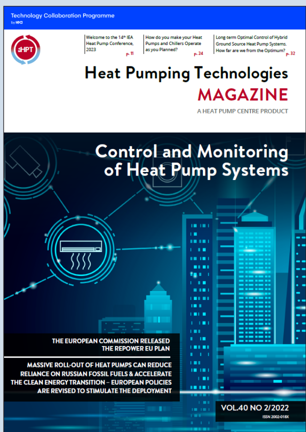

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Opportunities for high-temperature heat pumps as grid flexibility providers

Alessia Arteconi, Chiara Magni, Belgium
A. Phong Tran, Johannes Oehler, Panagiotis Stathopoulos, Germany

Electrification of the process of heat generation is essential to reduce fossil fuel use in industry. High-temperature heat pumps can efficiently convert power to heat up to 200 °C where waste heat is available. The study discusses the need for a more in-depth modelling of industrial processes and their ability to accommodate variable electric loads in order to quantify the real impact on the grid of high-temperature heat pumps integration. It further shows how industrial heat pumps can contribute to the grid's frequency containment reserve and stability.

Introduction

Thermal processes represent a significant fraction of industrial energy consumption. Due to the high temperatures involved, industrial heat is considered hard to decarbonise, and the sector still highly relies on fossil fuels. However, thanks to technological innovation, efficient high-temperature heat pumps (HTHPs) are becoming more and more available in the market, representing a promising solution for the electrification of industrial heat. These technologies could unlock the electrification of thermal processes and ensure high efficiencies thanks to the possibility to recover waste heat sources and upgrade them at temperatures up to 200°C. Moreover, the coupling of these devices with thermal energy storage (TES) would unleash a flexibility potential deriving from the industrial sector electrification. The deployment of Demand Side Management (DSM) strategies in high energy-intensive processes could lead to significant benefits for both industrial actors and grid operators in terms of balancing, cost of energy, renewable integration and overall carbon emissions reduction.

Nevertheless, to enable the large deployment of high-temperature heat pumps and thermal storage in the industry, it is of utmost importance to increase awareness of the benefits these technologies could bring both to the manufacturing sector and the energy system. This paper discusses the most relevant aspects and research gaps for system-level analysis. Furthermore, the end-user level implementation is analysed through a HTHP performance analysis.

System level analysis

Energy systems need more flexibility, which according to the International Energy Agency, can be defined as the extent to which a power system can modify electricity production or consumption in response to variabilities. With the integration of higher shares of non-dispatchable renewables sources, the flexibility is expected to be provided more and more from the demand side through the uptake of Demand Response (DR), which includes a series of actions aiming at modifying the energy load in response to price signals, generally during periods of peak demand. Large electricity consumers such as energy-intensive industries are considered good candidates for flexibility provision in the short-medium term and are already part of the portfolios of aggregators, monetizing their services to the grids on electricity and ancillary markets. Although the current industrial energy demand for thermal processes is still mainly supplied by fossil fuels, significant decarbonisation and electrification of the sector is expected in the upcoming years. The importance of industrial thermal demand electrification and its potential benefits have been demonstrated by many studies in recent years as well as the need for R&D on heat pumps that are promising technologies to provide flexibility to the grid.

The main Demand Side Management strategies for enhancing the flexibility of industrial thermal loads can be summarised in three categories: (i) process rescheduling (typically described as "load shifting"), (ii) thermal inertia exploitation of the process and (iii) use of thermal buffers. The variation of the final thermal energy demand associated with these three types of flexibility is represented in Figure 1.

In general, the less viable flexibility option is represented by rescheduling since the latter has a high impact on the industrial processes. Process rescheduling options find their application in cases characterised by intermittent operations, such as refrigeration systems and electric arc furnaces. Instead, the exploitation of thermal inertia could be easily implemented in those processes that present at least a limited tolerance in the operating temperatures of their processes, such as the majority of the pulp & paper or food sector processes. Finally, the integration of a thermal storage system is suitable for

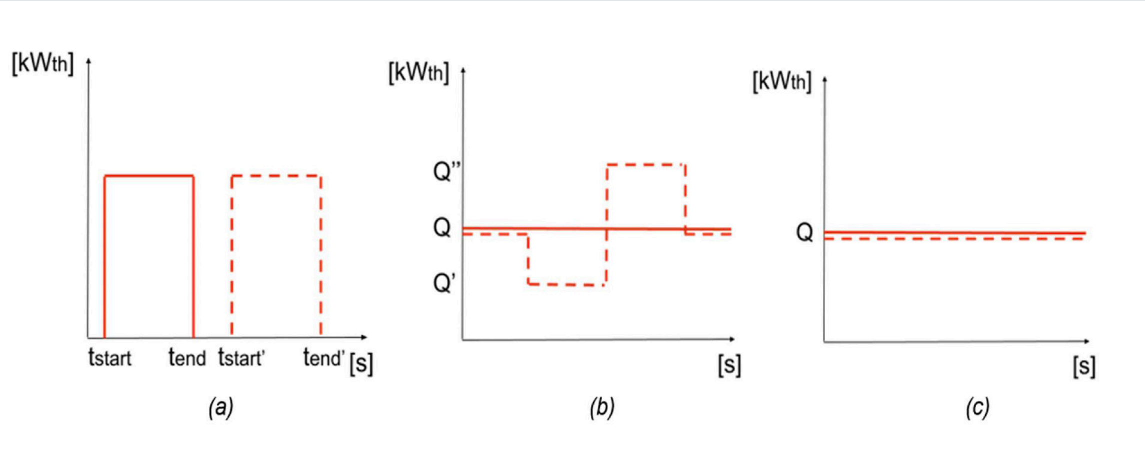

Figure 1: Industrial process thermal energy demand with adoption of different DSM schemes: load shifting (a), process thermal inertia (b), thermal buffer (c) [1]

all thermal processes since it does not affect their operations.

In order to perform a meaningful analysis at energy system level about the role of energy flexibility provided by industrial thermal processes with HTHP, some key aspects have to be taken into account in future research.

First of all, the industrial thermal processes need to be analysed in detail. The operating temperatures and detailed characteristics of the processes have to be considered to assess the integration potential of HTHPs. Neglecting the thermal behaviour of the technologies involved can lead to significant inaccuracies in the outcomes and estimation of HTHP efficiency. In this sense, process archetypes are suggested, representative of given processes, temperature levels and temperature glides (latent or sensible thermal processes).

Secondly, the model has to represent with the same accuracy both the supply side and demand side and their interaction. Previous studies [2] demonstrated the importance of integrated modelling approaches, which arguably lead to more realistic results and evaluations. Indeed, a detailed model of the industrial processes without the integration in an energy system model can be useful to perform a cost-benefit analysis from the consumer perspective under current market conditions (price-taker hypothesis), but fails in forecasting the impact of the energy transition on the future deployment and profitability flexible technologies in the industry. On the other hand, focusing on the representation of the energy system and representing the diversity of processes through a lumped load-shedding potential is an oversimplification, in particular in the case of thermal processes where neglecting the relationship between energy consumption and operating temperatures can

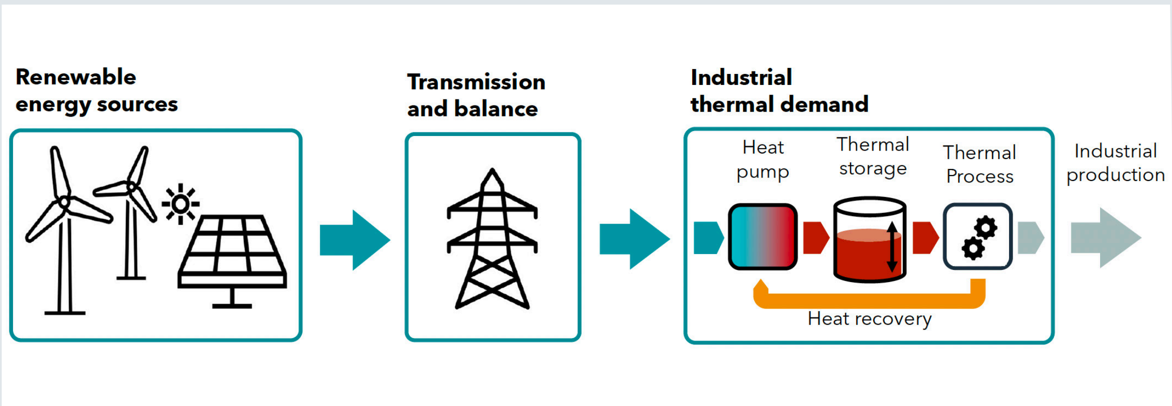

Figure 2 - System level integration of high-temperature heat pumps in industrial processes.

lead to important modelling errors. In this regard, an integrated modelling framework, such as Dispa-SET [3], is suggested. It is an open-source tool that can represent the operations of large-scale power systems with high level of detail with the aim to optimally solve the unit commitment problem for the chosen time horizon for each time step (1 hour). It is possible to integrate here, through the concept of process archetypes mentioned above, a heterogeneous thermal demand and, thus, an accurate efficiency of the HTHP (the COP, coefficient of performance, can be correctly calculated knowing the source and sink temperatures). Eventually, different penetrations of the HTHP can be considered; however, it is evident from preliminary analysis that an impact can be noticed only when the power installed reaches a minimum threshold compared to the total electric power generation at system level (e.g. in Belgium, about 200 MWel).

In this way, the impact on the electricity demand can be assessed in a precise manner, and the real potential of energy flexible operation of HTHP quantified (Figure 2).

Heat pump flexibility analysis

Only if the industrial heat pumps, that couple the electricity grid to the heat demand, can respond quickly to grid requirements the aforementioned thermal inertia of industrial processes can be exploited. The DLR Institute of Low-Carbon Industrial Processes evaluated the part load behaviour of their Brayton cycle heat pump prototype to assess its practical capabilities for load shifting. The prototype (see fig. 3) features a turbo compressor and turbine since turbomachines are readily available in multi-MW sizes for future industrial heat pumps. This way, the 200 kW thermal-output prototype with air as a working fluid is used to explore the specific transient behaviour of possible large-scale turbomachine-driven HTHPs. Brayton heat pumps generally offer a great deal of flexibility since the working fluid does not undergo a phase change. System pressure and source/sink temperature levels can be freely selected during the design process and varied independently during operation. When operating the heat pump, the compressor shaft speed can be varied to control the pressure ratio and, thereby, the temperature lift.

Industrial processes typically require a variable amount of process heat at constant temperatures. To meet this variable heat demand, the pressure levels within a closed-loop Brayton heat pump can be adjusted. This control technique is called fluid inventory control and involves releasing or injecting refrigerant into the working cycle. In [4], it is shown that part load operation at 25 % of design power is possible with negligible effect on the system efficiency.

Modelica was used to model fluid and heat transfers in the proposed Brayton heat pump, including dynamic effects such as thermal inertia and volume dynamics. Transient simulations of the heat pump show that the power consumption can be reduced by 80 % (or increased by 80 %) within 30 s from the nominal operation point.

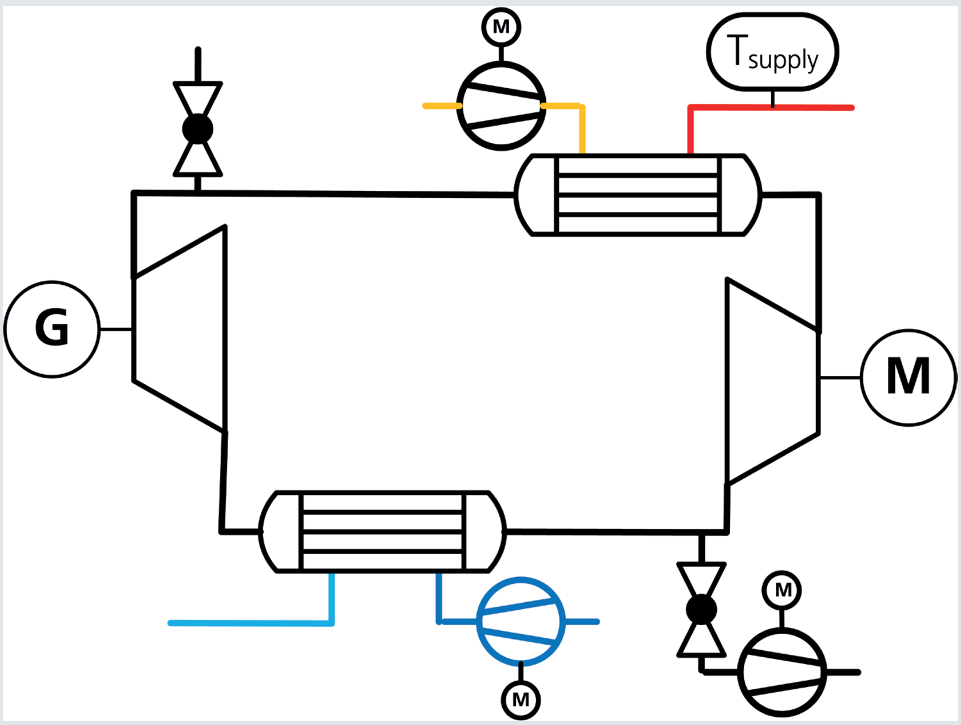

Figure 3 - Sketch of the Brayton cycle HTHP with heat source (blue) and heat sink (orange/red) and two discharge valves connecting the working cycle to the atmosphere and a vacuum pump

Figure 4 presents the system's response during a decrease of fluid inventory, which is accomplished through the removal of air via two discharge valves, leading to a reduction in pressure within the heat pump. This, in turn, results in a decrease in power consumption. To maintain a constant sink temperature, the mass flow rate of the heated fluid is adjusted using a suitable control mechanism.

This fast behaviour demonstrates the possibility of using HTHPs to provide frequency containment reserve (FCR) for the electricity grid by reducing or increasing the electric demand. In order to offer this grid service, a utility must prove that it can adapt its load within 30 s and keep it at the deviated level for up to 15 minutes. Given the process' thermal inertia allows for power deviations as long as 15 min (see Fig. 1, this could offer an additional revenue stream or become a requirement for large industrial consumers joining the power grid in their effort to decarbonize and reduce fossil fuel use.

Conclusions

The opportunities for industrial heat pumps to offer grid services such as demand side management and frequency containment reserve need to be evaluated more thoroughly. Therefore a characterization and quantitative parameterization of industrial processes is needed. Also, large-scale industrial heat pump behaviour and their interaction with the connected industrial process must be analysed. The results of the heat pump prototype discussed in this article are promising since they suggest that industrial heat pumps could contribute to the frequency containment reserve that requires a response time of 30 s. Further research is needed in this direction in the near future to quantify and unlock the flexibility potential of industrial heat pumps.

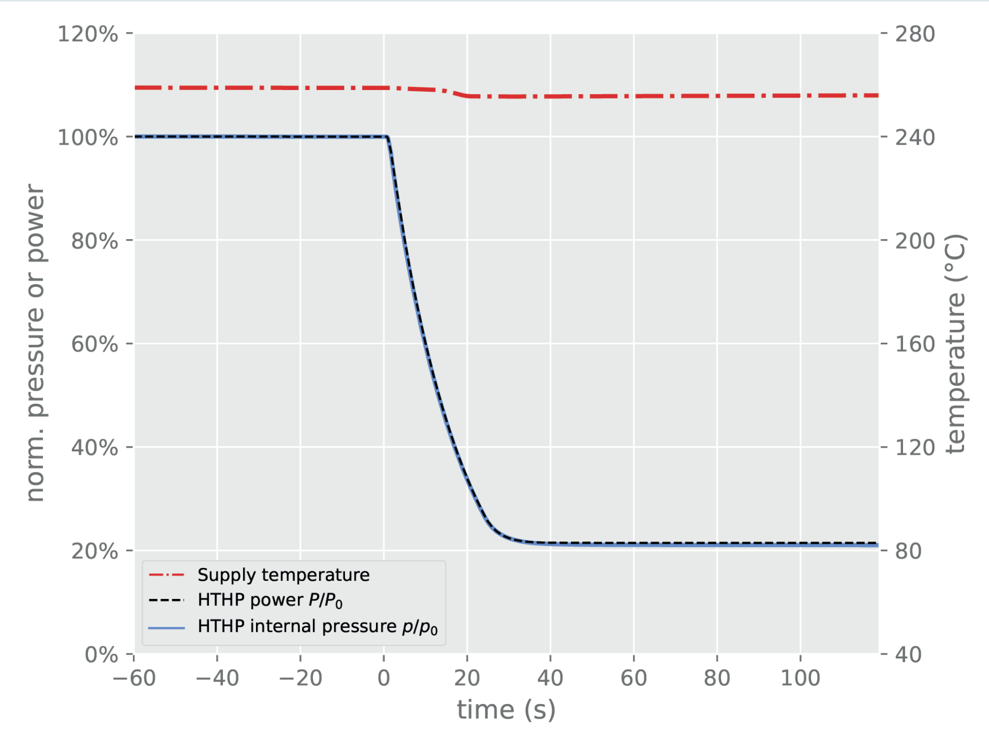

Figure 4: Power demand and supply temperature of a Brayton-cycle HTHP for a quick load reduction down to 20 % nominal power (model as in [5])

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Conceptualization of wet and dry steam compression with liquid water injection for high-temperature heat pumps - A thermodynamic approach

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Water has been used as a natural, extremely low global warming potential refrigerant in high-temperature heat pumps. The steam compressor's extra high discharge temperature at high-pressure ratios (e.g., 15) can be prevented via liquid water injection during the compression process as an effective desuperheating method. The proposed thermodynamic approach provides insights into the compression process with liquid injection (above and below the saturated vapor line), temperature/pressure build-ups, compression work, and the coefficient of performance of a heat pump equipped with a rotary vane compressor to deliver heat at 200°C.

High-temperature heat pumps (HTHPs) are an effective means to decarbonize the required energy in the industrial sector via electrification. In this context, as an example, they should supply thermal energy at high temperatures, near 200°C. Current low global warming potential refrigerants such as HFOs (e.g., R1336mzz(Z), R1234ze(Z)) and HCFOs (e.g., R1233zd(E)) have basic limitations like (i) their low critical temperatures and the (ii) decomposition of refrigerant/lubrication oil at high temperatures while running for a long time. The mentioned obstacles force the maximum possible temperature reachable by the mentioned refrigerants to 175°C [1]. Water, aka R718, presents excellent properties that makes it unique as a refrigerant to be utilized in a HTHP system: high critical temperature of 373.9°C, large heat of vaporization, low cost, abundant, and non-toxic.

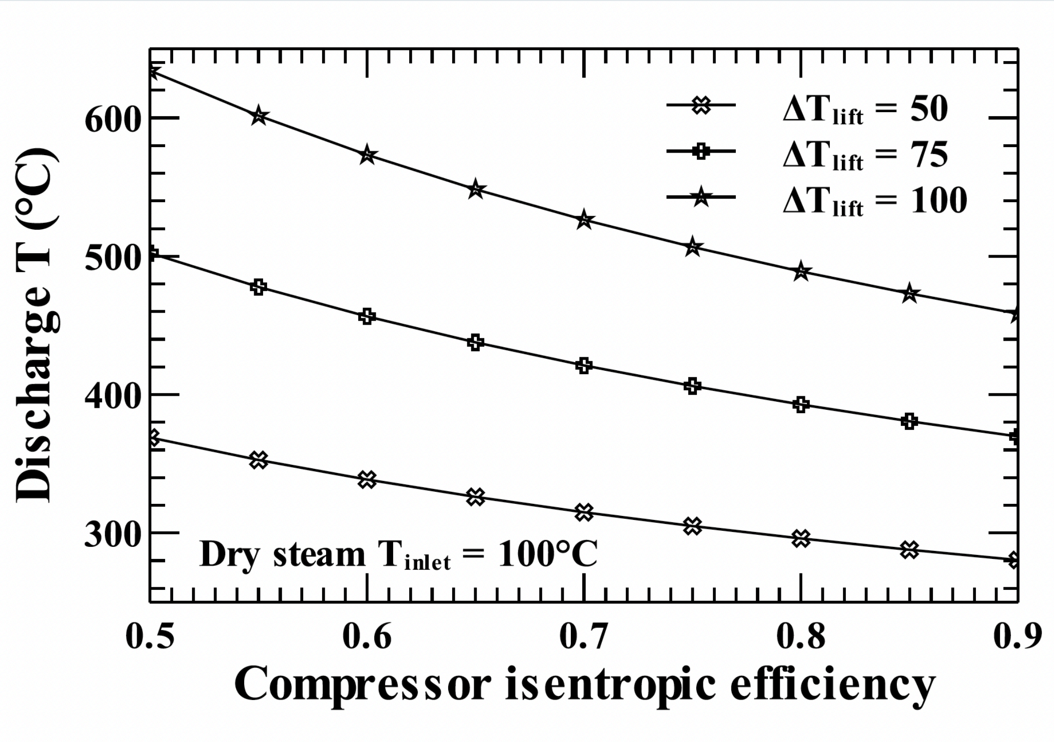

Figure 1. Dry steam discharge temperature at different rotary vane compressor isentropic efficiencies and temperature lifts

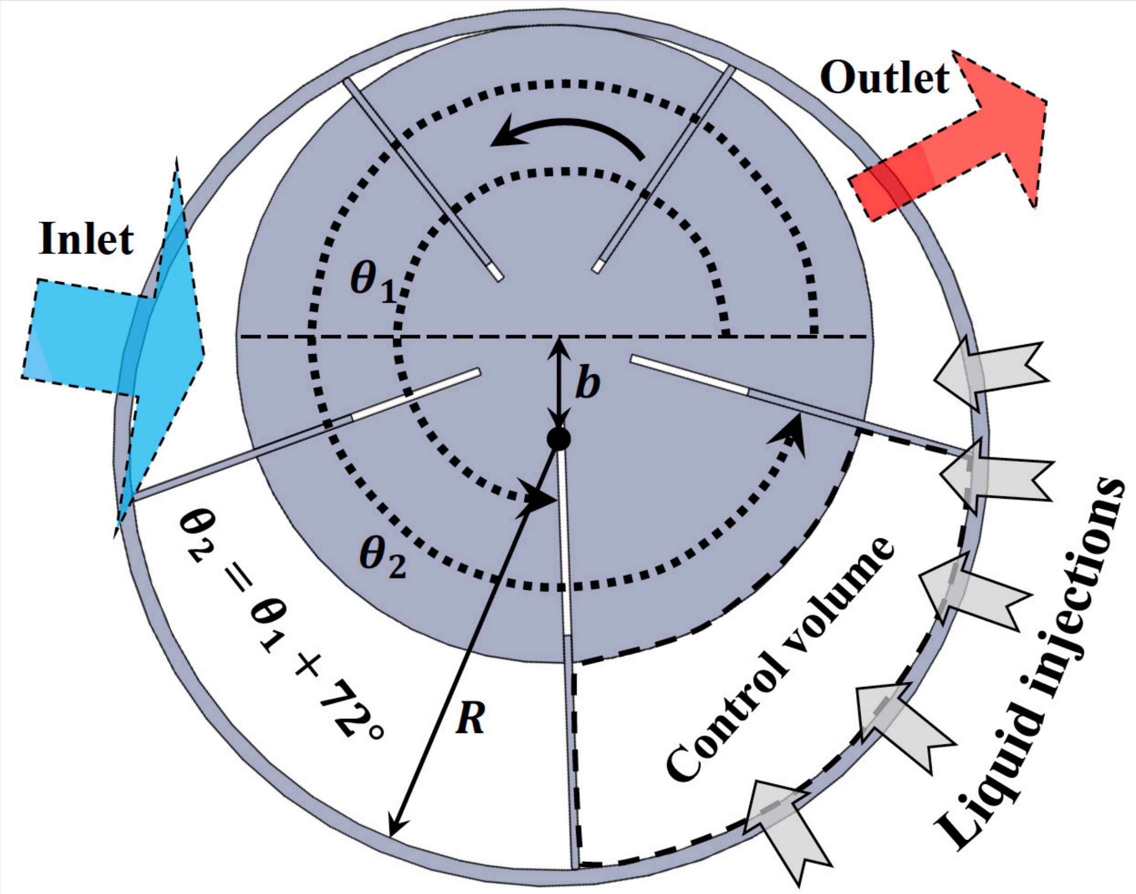

Figure 2. Liquid injections into a rotary vane compressor chamber. The inner cylinder is the rotor, the larger outer cylinder is the stator.

How hot steam can go during compression?

Due to mentioned properties, water is suitable to be selected as the refrigerant in the high stage of a high-temperature cascade heat pump system. Nonetheless, by assuming an initial temperature of 100°C, steam shows extremely high discharge temperature during the compression process in even relatively small temperature lifts. Figure 1 illustrates the discharge temperature of dry steam at different temperature lifts (from inlet temperature of 100°C). Even at a very high compressor isentropic efficiency of 0.9, the steam discharge temperature can easily pass 280°C, while the condensation temperature is just 150°C. The discharge temperature is 458.5°C for 200°C condensation temperature, corresponding to 15.6 bar discharge pressure. It should be noted that a more reasonable isentropic efficiency falls on 0.65, where the discharge temperature of dry steam will be 548.4°C for 200°C condensation temperature. Therefore, researchers have been actively seeking some ways to desuperheat the steam while keeping the same discharge pressure.

Liquid injection for desuperheating

Injecting liquid into compression process has been iterated recently to desuperheat the steam and bring it to the saturated state at compressor discharge [2, 3]. However, the theoretical framework of the compression with liquid injection should be investigated in detail as the presented thermodynamic models have assumed several oversimplifying assumptions, such as constant pressure and/or temperature during injection. These assumptions might not be valid as the expansion of the liquid inside the pressure chamber can decrease or increase the pressure/temperature of the mixture. The current thermodynamic approach attempts to provide solid insights for designers by having more realistic assumptions.

Figure 2 schematically illustrates a rotary vane compressor with several liquid injections. The control volume is also shown between two arbitrary vanes. It should be noted that the concept will remain almost the same for other compressor types. When the steam is compressed between two vanes, its temperature and pressure rise. The temperature of compressed steam is reduced via injecting liquid water.

Further, it has been shown that the rotary vane compressors can be useful for compressing two-phase liquid-gas mixture [4,5]. Therefore, the superheated steam can be basically prevented by compressing wet steam instead of dry steam. Figure 3 depicts the thermodynamic concepts of both dry and wet steam compression

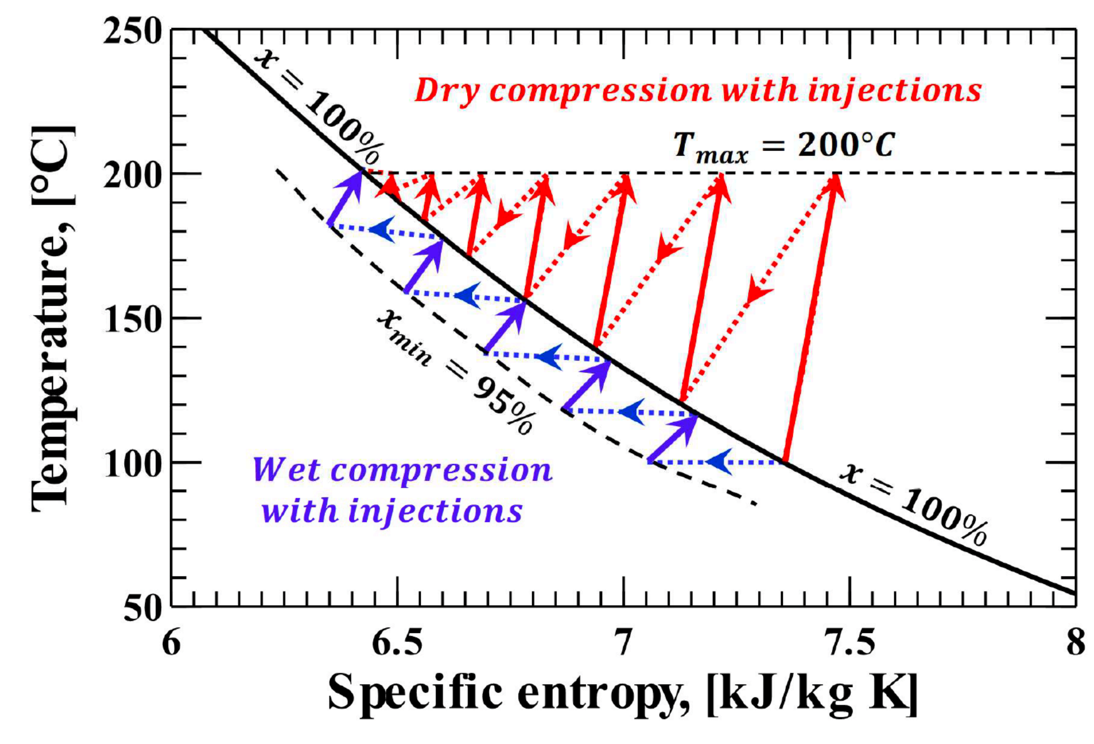

Figure 3. Dry and wet compression with injections for R718

with several injections in temperature-specific entropy diagram for water.

The red lines above the saturated vapor line (i.e., x = 100%) are called dry compression with injections, while the blue lines below the saturation line is named wet compression with injections. The solid lines are just compression, while the dotted lines are compression with injections for both concepts. Regarding the dry compression, the injections should be performed when the temperature of the compressed steam reaches a pre-set value (e.g., Tmax = 200°C). The injection brings the superheated steam to the saturation point. For the wet (aka two-phase) compression, the injection is performed during the compression to bring the wet steam quality to a predefined value (e.g., xmin = 95%), then the two-phase mixture is compressed to bring it to the saturated vapor state. The compressions with injections continue until the vapor reaches the desired discharge pressure.

Additionally, it has been observed that the injection process does not occur during a constant pressure or temperature, especially at higher temperature lifts; on the contrary, the pressure and temperature rises during injection (see Figure 3).

Compressor work and COP of the cycle

The compressor work is the summation of each compression step and the compression step during injections. The results show that the wet compression with injection requires 344.2 kW, and the dry compression with injection needs 405.82 kW. Moreover, the coefficient of performance (COP) is a good indicator to compare the effect of the dry and wet compressions with injections on the entire high-temperature heat pump system. In this study, it is assumed that the condenser outlet is a subcooled water with 2°C subcooling degree (i.e., 198°C). The COP is computed by dividing the delivered heat at condenser to the compressor work. COPs are extracted as 3.48 and 2.94 for wet and dry compressions with injections, respectively. Therefore, the wet or two-phase compression with liquid injections provides superior performance for the high-temperature heat pump system.

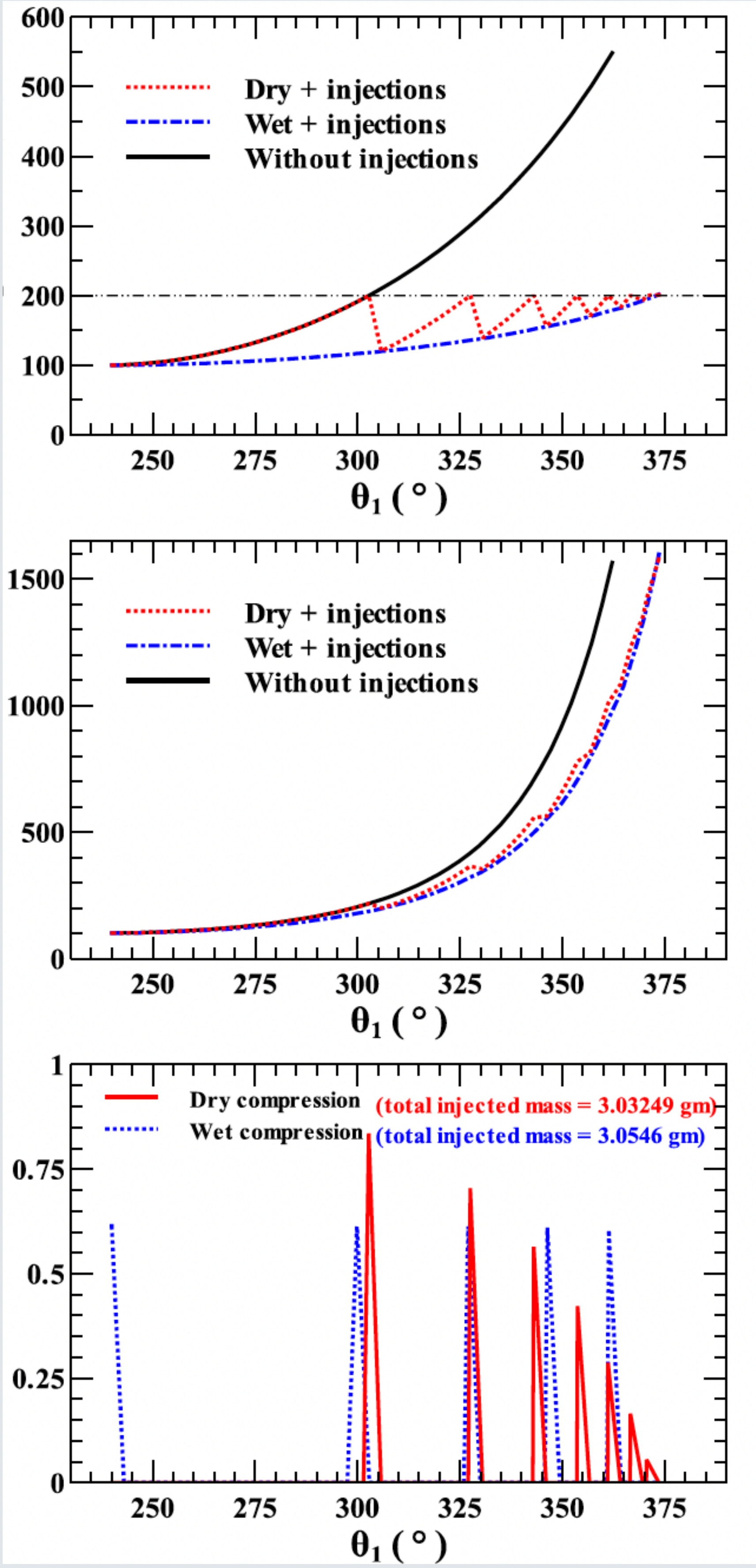

Figure 5. Temperature, pressure, and injected mass for wet and dry compressions with injections compared to the no injection case

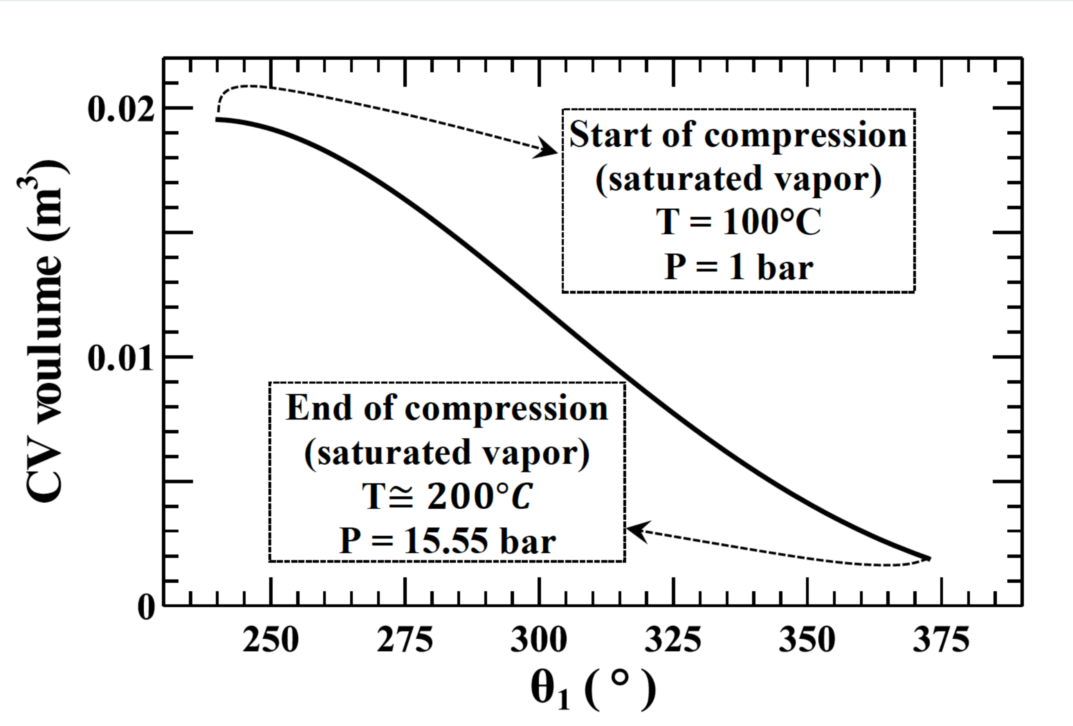

Figure 4. CV volume variations at different rotor angles

Conclusion

Desuperheating approach by injecting liquid into the compressor is an effective way that guarantees the desired temperature lifts at much lower compressor discharge temperature. The compression process can be performed under the saturated vapor line, wet compression with liquid injections, or above this line, dry compression with liquid injections. As an example, both approaches are analyzed through thermodynamic modeling of a rotary vane compressor. It is shown that the wet compression results in higher COP of the high-temperature heat pump. Detailed heat and mass transfer of the compression with injections can be simulated by a computational fluid dynamic tool in the next step. The obtained results can verify the validity of the considered assumptions in the presented thermodynamic analysis.

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Developing a high-temperature heat pump technology concept using natural refrigerants

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High-temperature heat pumps show great potential for delivering process heat between 100 °C and 200 °C at high efficiencies compared to conventional boiler technology. Exploiting the potential and achieving the highest possible efficiencies for various applications requires various technical solutions. This article presents a technology portfolio based on the natural refrigerants CO_2, steam, and hydrocarbons and outlines the application potential through three representative case studies. A spray dryer for proteins, a brewery with a hot water requirement at 145 °C, and a dairy culture working with an inlet pressure of 8 bar steam were analyzed. The heat was supplied while reaching COPs between 2.02 and 4.93, ensuring efficient electrification.

Introduction

Heat pumps (HPs) are a key technology in the transition towards sustainable energy systems as they can provide electricity-based process heat at the highest efficiencies. High-temperature heat pumps (HTHPs) can be integrated into a variety of applications - both in existing plants and as part of new process equipment. Thereby, they contribute to the electrification and decarbonization of industrial process heat supply - helping end-users to achieve their climate targets while being economically competitive. This article looks at the potential of using natural refrigerants to cover a broad range of industrial applications at temperature levels up to 200 °C with a concise and cost-effective portfolio at high efficiencies.
High-temperature heat pumps for industrial applications
Exploiting the large implementation potential for high-temperature heat pumps for a variety of applications requires technologies which provide satisfying performances for a wide range of applications and can be provided at large scales.

To achieve adequate performance, there must be a good match between the temperature profiles of the process heat demands and the heat pump technology. This creates the need for the development of a concise portfolio of multiple future-proof technologies that cover a broad range of applications. While there is a variety of solutions for applications below 100 °C, there is a lack of viable solutions for higher temperatures.

Different processes require heat in diverse forms, such as steam, hot water, or hot air, and at different temperature profiles. Some processes require heat at a constant temperature and thereby have a low glide in the temperature profile, e.g., evaporation processes. In contrast, processes where a fluid is heated experience a large increase in temperature, such as drying processes. The type of working fluid, in combination with the system layout, defines the temperature profile of the HP system and the application potential of the respective working fluid to applications with a particular temperature glide.

Besides the proper integration and utilization of the HPs, using cost-effective equipment may decrease system costs. Existing equipment like compressors may be modified and optimized for higher temperatures, ensuring proper utilization of the existing knowledge with the technology enabling the benefit from existing production infrastructures.

A handful of refrigerants

Natural refrigerants are substances that can be found naturally occurring in the environment, with zero ozone depletion potential (ODP) and very low or zero global warming potential (GWP),They are readily available at a reasonable cost, are extensively researched, and cover a wide range of properties, providing a promising candidate for various applications.

The group of hydrocarbons covers a broad range of thermodynamic properties, suitable for a wide selection of operating regions. Longer hydrocarbon chains have a higher critical temperature allowing for high delivery temperatures in subcritical operation. However, equally higher normal boiling points potentially result in sub-atmospheric operation with low source temperatures. Hydrocarbons show little need for intercooling the compression process, even for large pressure ratios ensuring efficient compression. Hydrocarbon systems are expected to provide promising performances in applications with moderate-temperature glides like hot water production. Additionally, hydrocarbons show good miscibility with each other and may also be used as mixtures. However, hydrocarbons are flammable, which requires the implementation of certain safety measures.

R-718 (water) is well-known from steam systems and as a heat transfer fluid, ensuring commercially available components with high performance, such as turbo compressors. Water has a high heat of evaporation, enabling a large specific heat transfer rate, potentially yielding high COPs. However, low source temperatures

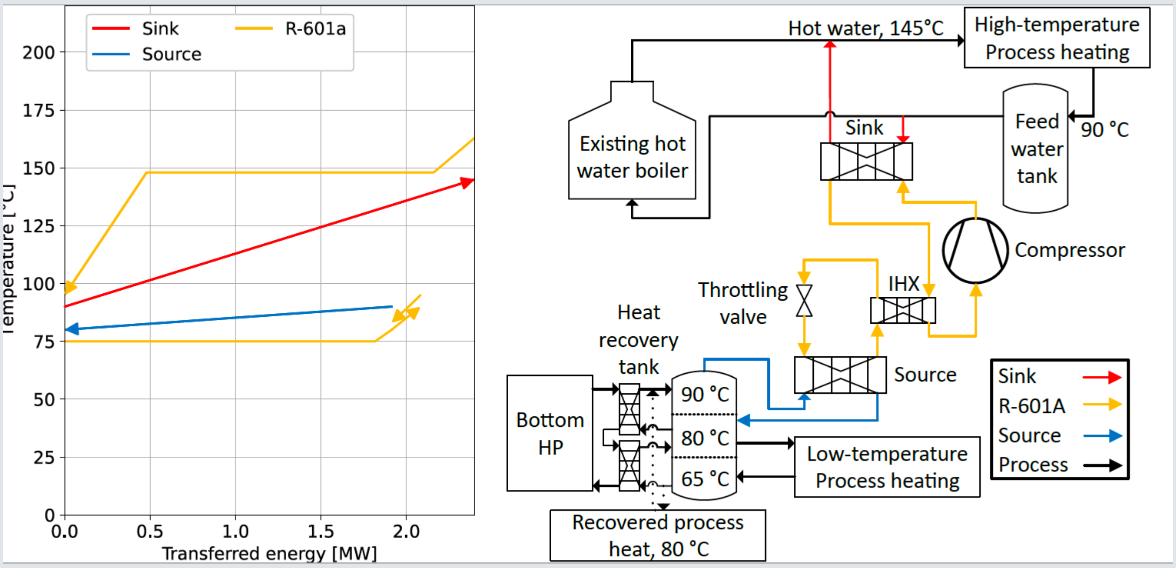

Figure 1a: Hot water system for a brewery.

Wort boiling with hot water system using R-601a from heat recovery tank

- A brewery uses 2.4 MW of hot water at 145 °C for wort boiling distributed several temporally offset batches in parallel. The remaining processes are covered by the heat recovery tank.
- Water returns from the high-temperature processes at 90 °C which is heated back up to 145 °C by the heat pump keeping the conventional gas boiler as a back-up.
- 90 °C hot water from the heat recovery tank supplies the heat pump and returns at 80 °C. The tank is supplied by a ammonia heat pump and recovered process heat.

Heating COP		4.93	
Heating capacity		2.4 MW	
Sink	Source	90 °C → 145 °C	90 °C → 80 °C
Refrigerant		Isopentane, R-601a	
Important remarks		COP of 2.49 w. bottom HP ATEX required	

Figure 1b: Hot water system for a brewery.

result in low densities yielding large volume flows. The R-718 systems are expected to provide the highest performances in applications with low-temperature glides like evaporation processes or steam production. Under certain circumstances, steam compression systems may also be a beneficial choice in larger temperature glide applications, although this might require systems operating with multiple pressure levels.

R-744 (CO2) is already a well-established refrigerant in the supermarket refrigeration sector and, more recently, for industrial HPs. R-744 has a low critical temperature, inducing high operating pressures in many applications, which yields high volumetric heating capacities lowering the investment costs due to more compact equipment. The R-744 system will mostly operate in the vapor phase resulting in no phase change of the refrigerant, hence no heat of evaporation. Therefore, it is intended for applications with large temperature glides like spray drying processes.

It might be appropriate to combine the technologies to mitigate their drawbacks, enhancing their strengths for applications with high-temperature lifts. This can be in cascade systems to produce steam using R-718 in the top cycle and a hydrocarbon in the bottom cycle, getting the high performance of R-718 without the large volume flow rates at sub-ambient pressures.

Commonly occurring industrial applications

To outline the application potential for the three technologies using hydrocarbons, steam, and CO_2, three potential application cases are presented, as they may be found in typical industrial processes.

Figure 1 (a, b) shows the application of a 2.4 MW hydrocarbon HTHP, which is integrated into a brewery with an existing hot water system and an ammonia HP. The HTHP consists of a single-stage HP with an internal heat exchanger (IHX) using R-601a (isopentane) as the refrigerant. The isentropic efficiency of the compressor is assumed to be 70 %, while the pinch temperature difference in all HEXs is 5 K. The HTHP delivers hot water at 145 °C, heating the return process water in parallel with the hot water boiler to ensure redundancy. The heat source at 90 °C is a stratified heat recovery tank supplying low-temperature processes with heat. This is done by an existing ammonia HP. The water is returned at 80 °C to the tank. The HTHP delivers hot water with a temperature glide of 55 K at a high COP of 4.93. The flammability

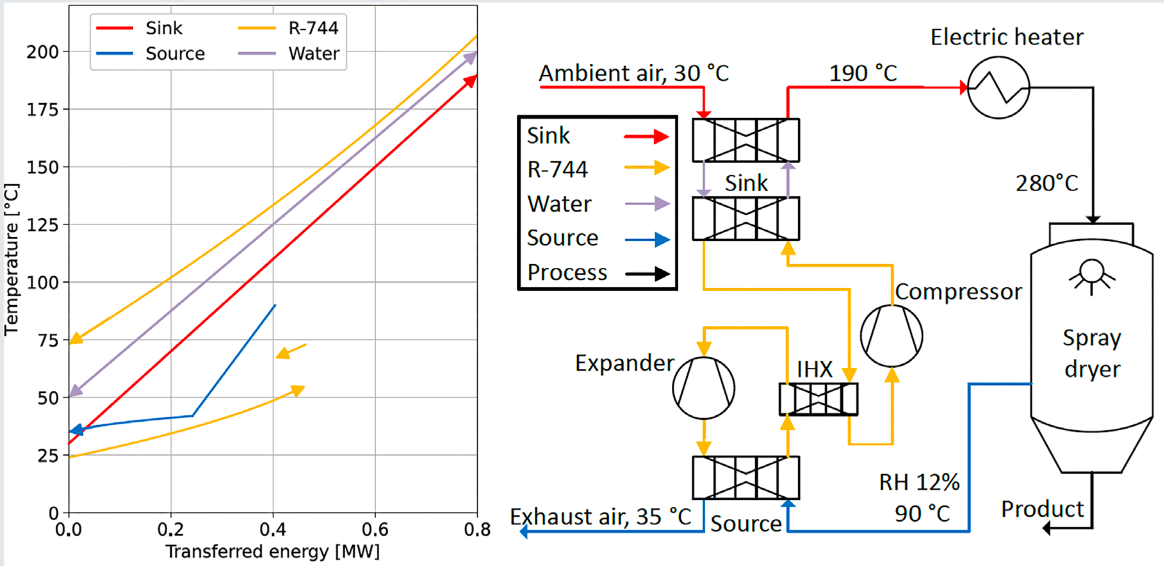

Figure 2a: Spray dryer for protein rich fish food production.

Drying of fish food at 280 °C in spray dryers using R-744 brayton heat pump

- A protein rich substance is dried in several parallel spray dryers using 15,000 kg/hr of dry air heated to 280 °C.
- Ambient air is heated from 30 °C to 190 °C in a heat exchanger connected to the heat pump by a secondary water loop before an electric heater raises the temperature to 280 °C w. a total COP of 1.77.
- The exhaust air comes out at 90 °C at 12 % relative humidity which is used as the source of the heat pump.

Heating COP		2.02	
Heating capacity		0.8 MW	
Sink	Source	30 °C → 190 °C	90 °C → 35 °C
Refrigerant		Carbon dioxide, R-744	
Important remarks		High pressures 150 bar Compact cycle	

Figure 2b: Spray dryer for protein rich fish food production.

of R-601a creates the need for an ATEX safety concept, which may be realized as a ventilated enclosure in the utility area of the plant. The presented setup is a suitable approach for the complete electrification of breweries.

A second case of an industrial site drying proteins in a spray dryer is presented in figure 2 (a, b). A protein-rich substance is dried using 15,000 kg/h of ambient air heated to 280 °C. The full gas cycle HTHP utilizes R-744 to heat the air to 190 °C through a secondary water loop before an electric heater delivers the remaining temperature rise. The pinch temperature difference in the air HEX is 10 K. The R-744 uses an IHX in addition to an expander with an isentropic efficiency of 30 %, delivering 0.8 MW heating using the exhaust air from the spray dryer as the heat source at 90 °C and a dew point of 42 °C. The temperature-heat load diagram shows a good match between the temperature profiles of the process heat demand and the R-744 resulting in a COP 2.02, which may be higher with more efficient compressors or expanders. Including the electric heater yields a system COP of 1.77

Steam is a common heat carrier in industrial facilities. The steam systems operate at different temperatures depending on the specific process requirements, but 4 bar to 10 bar are common in the food, pulp & paper, and chemical industry. A case with a cascade HTHP delivering 8 bar steam to a dairy culture production facility is presented in Figure 3 (a, b). The maximal consumption is 10.5 t/h of steam, which can be covered by a 6 MW HTHP. The steam is produced from the return condensate, which is pressurized to 8 bar before being evaporated in the sink. The chosen HP is a cascade system with a bottom cycle like for the brewery case, while a single-stage R-718 top cycle ensures the temperature lift from 120 °C to 170 °C. Liquid injection during the compression of R-718 mitigates excessive discharge temperatures. The local 70 °C district heating system is utilized as the heat source returning at 50 °C. The large evaporation heat of R-718 ensures a great temperature profile match with the steam and the bottom cycle. The IHX of the R-601a cycle yields the necessary superheating of the refrigerant, substantially improving the COP. In the suggested layout, the process steam is generated in a heat exchanger while condensing the steam from the HP cycle, which is preferred when there are high safety requirements for the purity of the steam. Steam could be provided directly from the compressor in an open loop cycle, which implies the risk of contamination with compressor oil (if present in the compressor) and might be more challenging to control for varying steam consumption. The cascade HTHP delivers the 8 bar steam with a

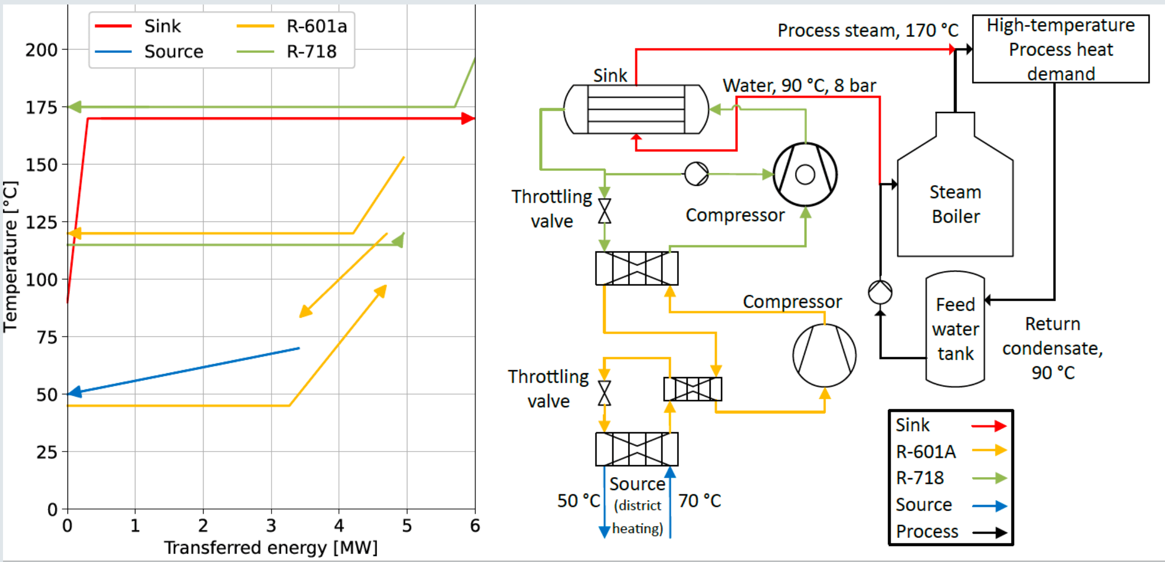

Figure 3a: Steam production from district heating for a dairy culture production facility.

Wort boiling with hot water system using R-601a from heat recovery tank

- A brewery uses 2.4 MW of hot water at 145 °C for wort boiling distributed several temporally offset batches in parallel. The remaining processes are covered by the heat recovery tank.
- Water returns from the high-temperature processes at 90 °C which is heated back up to 145 °C by the heat pump keeping the conventional gas boiler as a back-up.
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Heating COP	4.93
Heating capacity	2.4 MW
Sink | Source	90 °C → 145 °C | 90 °C → 80 °C
Refrigerant	Isopentane, R-601a
Important remarks	COP of 2.49 w. bottom HP ATEX required

Figure 3b: Steam production from district heating for a dairy culture production facility.

COP of 2.31.

The three different application concepts indicated technically promising cases for the three technologies, based on hydrocarbons, steam, and CO_2, and outlined their broad application potential for industrial process heating at highest performances. It may accordingly be derived that these technologies are representing a good basis for a portfolio of HTHPs based on natural refrigerants as currently being developed, tested, and demonstrated at large scales in the SuPrHeat project (http://www.suprheat.dk/).

Conclusions

High-temperature heat pumps can be implemented in a variety of industrial process applications, including existing plants and novel process equipment. The boundary conditions and performance may vary considerably depending on the application and require vastly different heat pump technologies to achieve the highest efficiency possible. This study indicates that using R-744, R-718, and hydrocarbons, it is possible to deliver process heat in the form of steam, hot water, or air at temperatures up to 190 °C with competitive COPs between 2.02 and 4.93. The three refrigerants exhibit fundamentally different thermodynamic properties, making them suitable for a broad range of applications with a concise, future-proof technology portfolio.

Acknowledgements

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Storing Electricity with Industrial Heat Pumps: Carnot Batteries for Grid-Level Energy Storage

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To mitigate environmental impacts, there is an urgent need to reduce CO_2 emissions in all sectors. In particular, electrification of energy-intensive processes is the key to avoiding CO_2 emissions aiming at the full provision of electricity from renewable energy sources [1]. However, electricity generation from renewable energy sources depends highly on time-variant boundary conditions, e.g. sun or wind, and is hence not permanently available. To overcome the availability gap, efficient electricity storage systems are essential as they shift energy from low-demand periods to high-demand periods [2]. Today, Pumped Hydro Energy Storage (PHES) is the predominant grid-scale electricity storage technology proven to be technically and economically viable, making up 95 % of the overall global storage capacity [3]. However, for most electrified systems, the easily-exploitable potential is almost exhausted [4]. Alternative electricity storage solutions must therefore be investigated and brought to market.

Electricity storage solutions are typically characterized by their power-to-capacity ratio, charge and discharge time, energy density, and specific costs. Hence, matching each technology to a specific application case is essential to exploit the entire electrification potential at all scales. Especially at grid-scale, systems are designed to operate for more than four hours. They require high storage capacities of typically more than 100 MWh and low discharge times, resulting in power-to-capacity ratios of about $1/4\ h^1$. Furthermore, the urgent need for market deployment calls for unit costs to be as cheap as possible, ruling out concepts based on lithium-ion batteries [5].

Avoiding material bottlenecks when only focusing on one technology, these requirements shift the focus of discussion toward alternative storage concepts. Although efficiencies of alternative concepts in most cases cannot compete with lithium-ion batteries, there are many studies investigating [6]. One option is called Carnot Batteries (CB). CB combine heat engines with thermal energy storage systems: electricity is stored as thermal exergy and recovered during discharge [7]. The charging process can be performed with a large-scale heat pump or any other technology using electricity to elevate thermal energy from a low to a higher temperature level. When using a heat pump, the discharge process is performed with an Organic-Rankine-Cycle (ORC) heat engine. This article aims to give a comprehensive introduction to Carnot Batteries for grid-scale electricity storage and motivates an integrated design approach for large-scale heat pumps as a key component.

Carnot Batteries: definition and characteristic

The term Carnot Battery refers to a set of technologies based on a concept originally proposed in 1922 by Marguerre [8]. Dumont et al. [7] provide a definition according to which a CB is primarily used to store electricity. An electric input is used to create a temperature difference between a high and a low-temperature reservoir. When discharging, the heat flows with the thermal gradient from the high to the low-temperature reservoir, powering a heat engine whereby a fraction of the electrical input is recovered. The definition is illustrated in Figure 1. Following the definition, the storage concept of pumped thermal energy storage (PTES) belongs to CB as well as other concepts such as liquid air storage or Lamm-Honigmann storage.

CBs comprise a low technology readiness level [7]. To push CBs to the market, it is promising to focus on commercially available equipment. A promising concept is based on the Rankine cycle [7]. The charging process is thereby realized with a vapor compression heat pump and the discharging process with a steam or an organic Rankine cycle (ORC), depending on the temperature level. A charging process with an electric heater is also possible [9]; however, since renewably generated electricity is highly limited in the next years, optimal use of electricity from renewable energy sources should be provided with a heat pump, even if it still leads to higher investments than electric heaters.

The overall efficiency of CBs depends on the coefficient of performance (COP) of the heat pump COP_{LSHP} and the efficiencies of the storage system η_{TES} and the ORC η_{ORC}. It is calculated according to Equation (1).

Equation (1).

$$\eta_{CB}= COP_{LSHP}\cdot\eta_{TES}\cdot\eta_{ORC}$$

The thermodynamic limit of such a system can be evaluated by considering two reversible Carnot cycles and an ideal storage system ($\eta_{TES}=1$) [10]. In this case, the overall efficiency does only depend on the temperatures of the high T_H (storage temperature) and of the low-temperature reservoir T_L (ambient temperature) and reaches 100 %, as shown in Equation (2).

Equation (2).

$$\eta_{(CB,ideal)}=COP_{(Carnot,LSHP)}\cdot\eta_{(Carnot,ORC)}=\frac{T_H}{T_H-T_L}\cdot\left(1-\frac{T_L}{T_H}\right)=1$$

Losses in the energy conversion processes impair the potential of CBs resulting in lower efficiencies. The overall efficiency depends highly on the temperature levels of both reservoirs. An apparent solution is using the ambient air as the low-temperature reservoir and, thus, as the heat source for the heat pump. For the ORC to work properly, the high-temperature reservoir should lay above 100 °C [11]. However, the temperature gradient yields to poor heat pump efficiencies. An alternative is using additional heat sources, for example, waste heat [7]. Integrating additional heat sources allows to reduce of the temperature gradient and hence improves the heat pump efficiency. The implied sector-coupling potential is hence worth investigating, subject to the availability of suitable heat sources [12].

Large-Scale Heat Pump

Following equation (1), the thermodynamic estimation shows that the COP of the large-scale heat pump (LSHP) has a huge impact on the overall efficiency. The COP of a heat pump itself is influenced by many factors. On one hand, the thermodynamic potential is limited by the temperature-dependent COP_(Carnot, LSHP). On the other hand, the operating point dependents energy conversion losses.

When designing a heat pump, one must consider the choice of refrigerant, the flow rate and the sizing of the components (e.g. compressor, heat exchanger, expansion valve) [13]. The choice of refrigerant is directly related to the required temperature levels due to its thermodynamic properties. At the same time, the choice of refrigerant influences the energy conversion efficiency. Among others, the isentropic efficiency of the compressor is influenced by the choice of refrigerant [14]. Furthermore, the refrigerant changes the requirements on the heat exchangers, for example, if refrigerant mixtures with temperature glide are used. In addition to the sizing, the operational strategy, including the controller design, takes on a decisive role in an efficiently performing machine. The part load behaviour, the compressor's operational envelope, superheating, and subcooling are major aspects that influence efficiency.

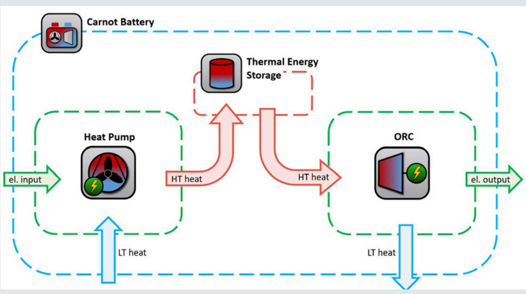

Figure 1: Graphical definition of a CB with its components (heat pump, thermal energy storage, ORC) and energy flows (electrical (el) energy, high temperature (HT) heat, low temperature (LT) heat).

Due to the underlying complexity, studies have investigated the possibilities of integrated system design methods for heat pumps in the building sector with outputs of up to 20 kW [13]. These design methods include all the mentioned aspects in the design process and result in a more efficient heat pump for a specific use case.

CBs call for large-scale heat pumps with power outputs higher than 10 MW and temperature levels reaching 80 °C in comparison to heat pumps for buildings. These different requirements lead to new degrees of freedom in the design decision process, increasing the overall solution space and making it an even more complex task. The development of heat sources that may not be feasible due to its economics for small systems may become attractive for large-scale systems. Possible scenarios include the use of residual heat in wastewater from the sewer system, river water as a heat source, or waste heat from industrial processes or data centers. Furthermore, the options for designing heat pumps are expanding. The use of alternative refrigerants, such as ammonia subject to special safety regulations and flow sheets, becomes attractive to maximize the energy conversion efficiency. Moreover, the use of compressor technologies such as flow compressors becomes possible.

When widening the scope to the whole CB, the design task becomes even more complex. Next to the individual component design of storage and ORC, the interaction between components becomes crucial. In particular, the use of a large-scale heat pump with a storage system represents a challenging operational scenario due to a highly transient operating behavior. To meet these challenges, future work should develop an integrated design method for CBs considering the design and operation of all components and maximizing the efficiency of the system.

Conclusion

When widening the scope to the whole CB, the design task becomes even more complex. Next to the individual component design of storage and ORC, the interaction between components becomes crucial. In particular, the use of a large-scale heat pump with a storage system represents a challenging operational scenario due to a highly transient operating behavior. To meet these challenges, future work should develop an integrated design method for CBs considering the design and operation of all components and maximizing the efficiency of the system.

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Heat Pumps in the United States: Market Potentials, Challenges and Opportunities

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The US heat pump market has been affected by the socioeconomic impacts of the COVID-19 pandemic. However, the US administration's electrification goal accelerates the deployment of heat pumps, and the US heat pump market has experienced steady growth since 2010. In 2020, heat pumps surpassed gas furnace shipments for the first time, and the trend maintained through 2022. The heat pump market share is expected to grow as policies, and financial incentives steer the building sector toward decarbonization. This paper reviews the US heat pump market trends and discusses the challenges and opportunities in the current policy landscape.

Introduction

The halt in manufacturing and construction activities due to partial or complete lockdown during the COVID-19 pandemic severely impacted the global economy, including the heat pump market, in 2020 [1]. In 2021, the global economic recovery began. However, the growth has been fragile because of the continued pandemic and geopolitical and economic uncertainties [2]. According to the United Nations [3], the economic impacts of the war in Ukraine have had both positive and negative effects on climate action. In particular, countries have an opportunity to address high prices and resource availability concerns by accelerating the adoption of clean energy, which also strengthens the fight against climate change [3]. Specifically, heat pump technologies are receiving unprecedented priority to reduce the use of fossil fuels and vulnerability to supply disruptions in response to the global energy crisis [4].

US Policies and Programs

The Biden administration's affirmatory response to international climate change agreements, including Paris Climate Accord to limit and resist climate change [5], and the Kigali Amendment to the Montreal Protocol to phase down the consumption and production of hydrofluorocarbons [6], confirms a commitment toward global clean energy economy. The United States has set forth the goals to reduce greenhouse gas (GHG) emissions by 50%–52% from 2005 levels in 2030, decarbonize the US power sector by 2035, and achieve a net-zero emissions economy by 2050 [7]. Minimizing the emissions from buildings has been a priority to accomplish these goals [8]. Federal investments have been allocated to modernizing and upgrading buildings to be affordable, resilient, accessible, energy-efficient, and electrified [9]. A number of policies have been implemented, and targeted actions have been taken to support heat pump technology research, expand deployment, and address supply chain vulnerabilities. Figure 1 shows a timeline of policies since 2020 that have supported the development and adoption of heat pump–related technologies.

US Heat Pump Shipments

As shown in Figure 2, US heat pump market shipments predominantly comprise air-source heat pumps. More than 96% of air-source heat pumps have a capacity of 19 kW or less [10]. Heat pump water heaters, water loop heat pumps, and ground source heat pumps comprised a little over 7% of heat pump sales in 2022 [11].

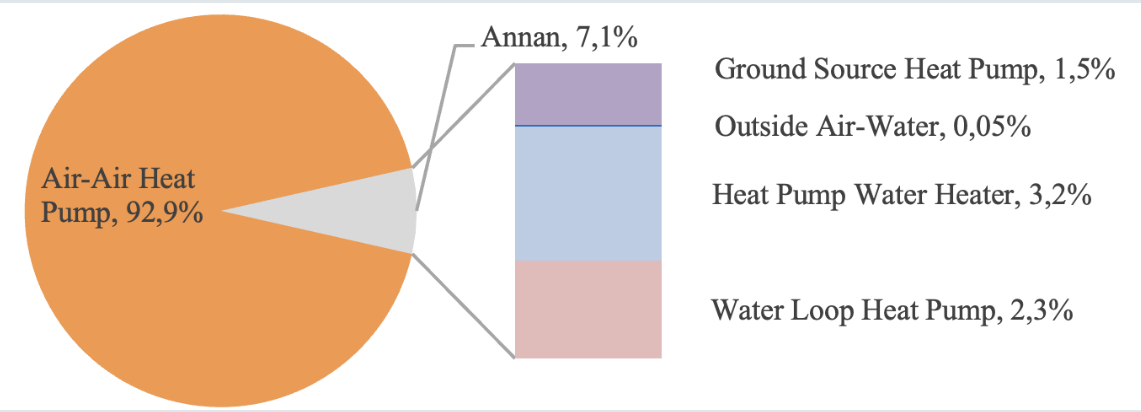

Figure. 2. 2022 market distribution of heat pump technologies.

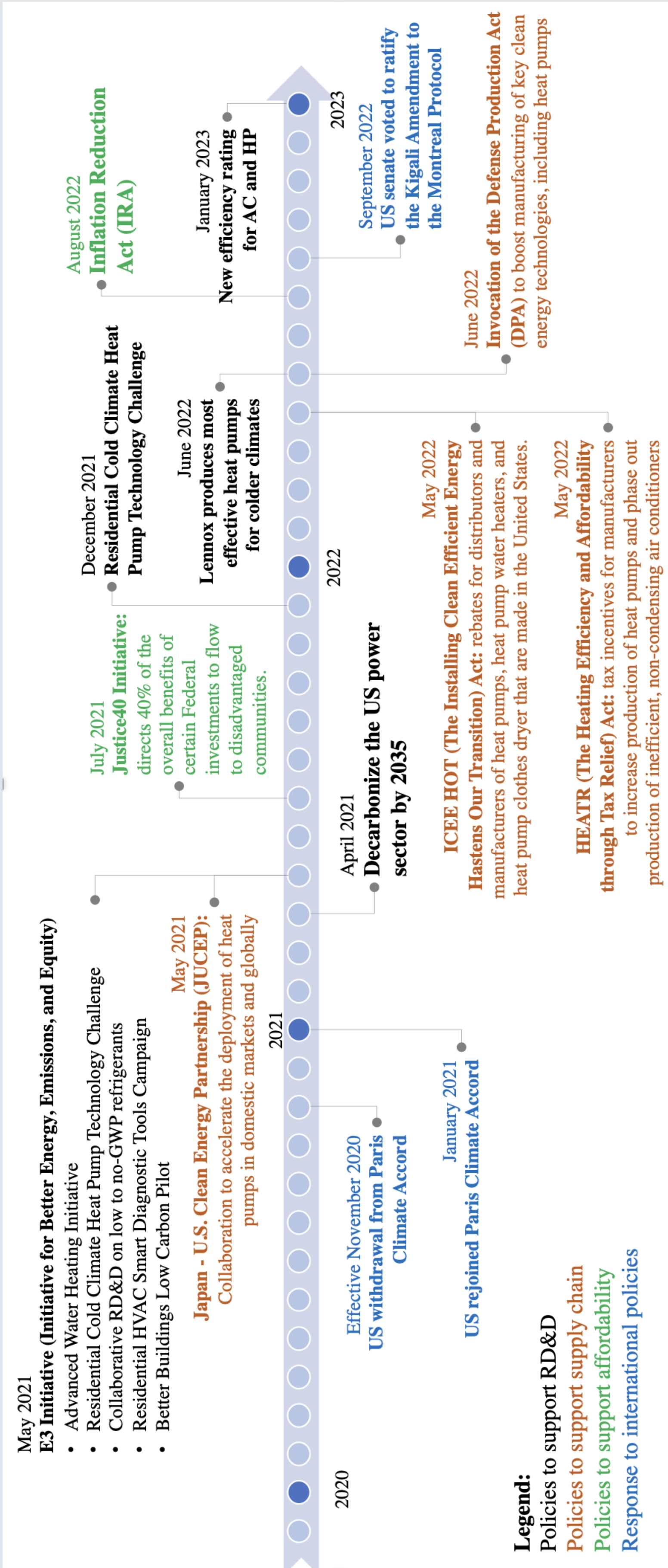

Figure. 1. Heat pump–related policies since 2020.

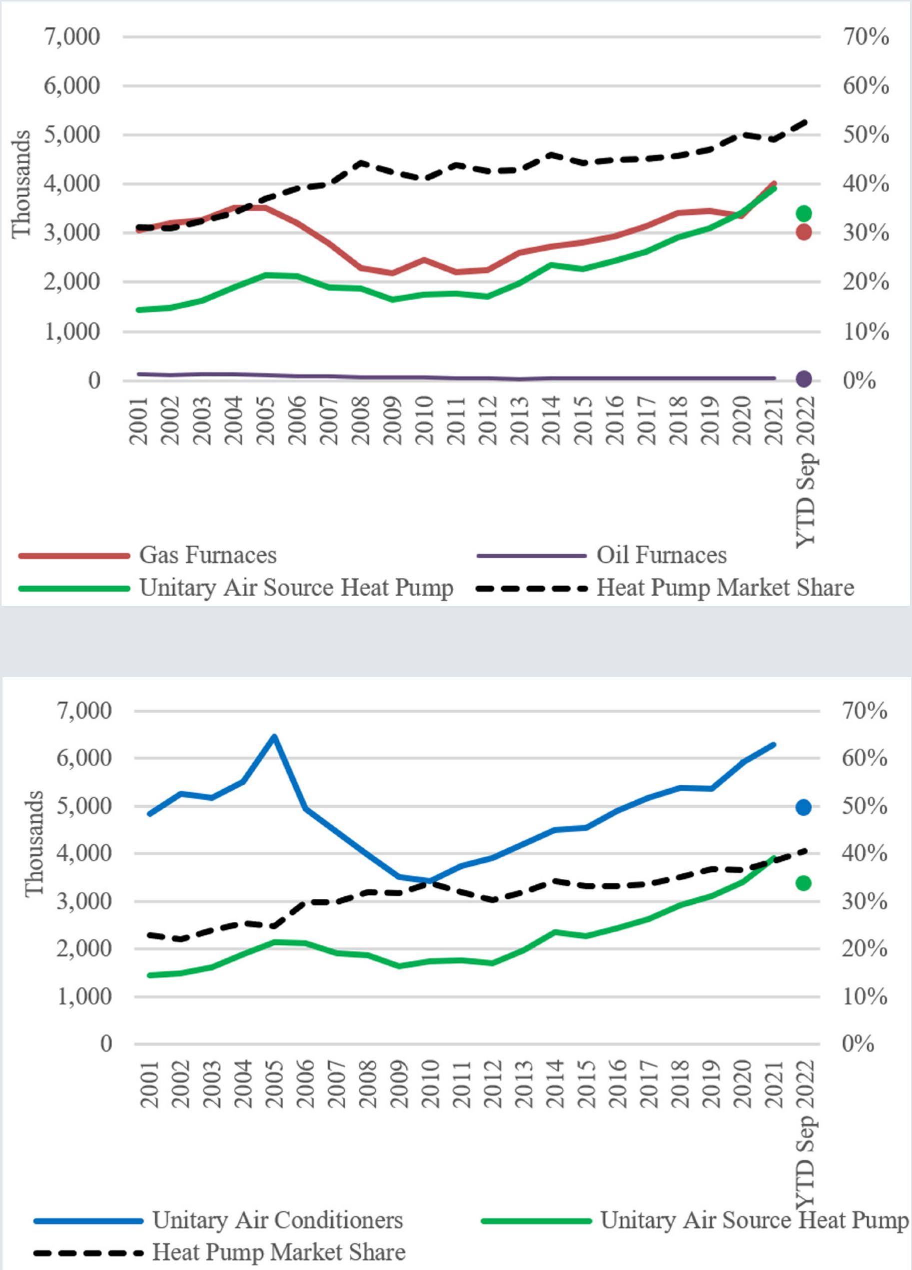

Figure. 3. Air source heat pump shipments compared with furnaces (top) and central air conditioners (bottom).

Figure 3 shows the annual shipments of air source heat pumps (green) compared with gas and oil furnaces (orange and yellow, respectively) and central air conditioners (blue) since 2001. Despite the sharp drop in the shipments of all heating and cooling equipment during the 2006–2007 housing market collapse, the share of heat pumps (black dotted) has shown a relatively consistent increasing trend. In 2020, heat pump shipments surpassed that of gas furnaces for the first time, and the trend maintains through 2022, reaching 52.6% in September 2022 year-to-date (YTD). Meanwhile, the heat pump share in the cooling equipment market reached 40.6% in September 2022 YTD [10].

Heat pump water heaters have experienced a dramatic increase in sales due to the National Appliance Energy Conservation Act of 2015, which requires higher energy factor ratings on all residential and some light-duty commercial products, and requires all electric water heaters of over 208 L (55 gallons) to use heat pump water heat-

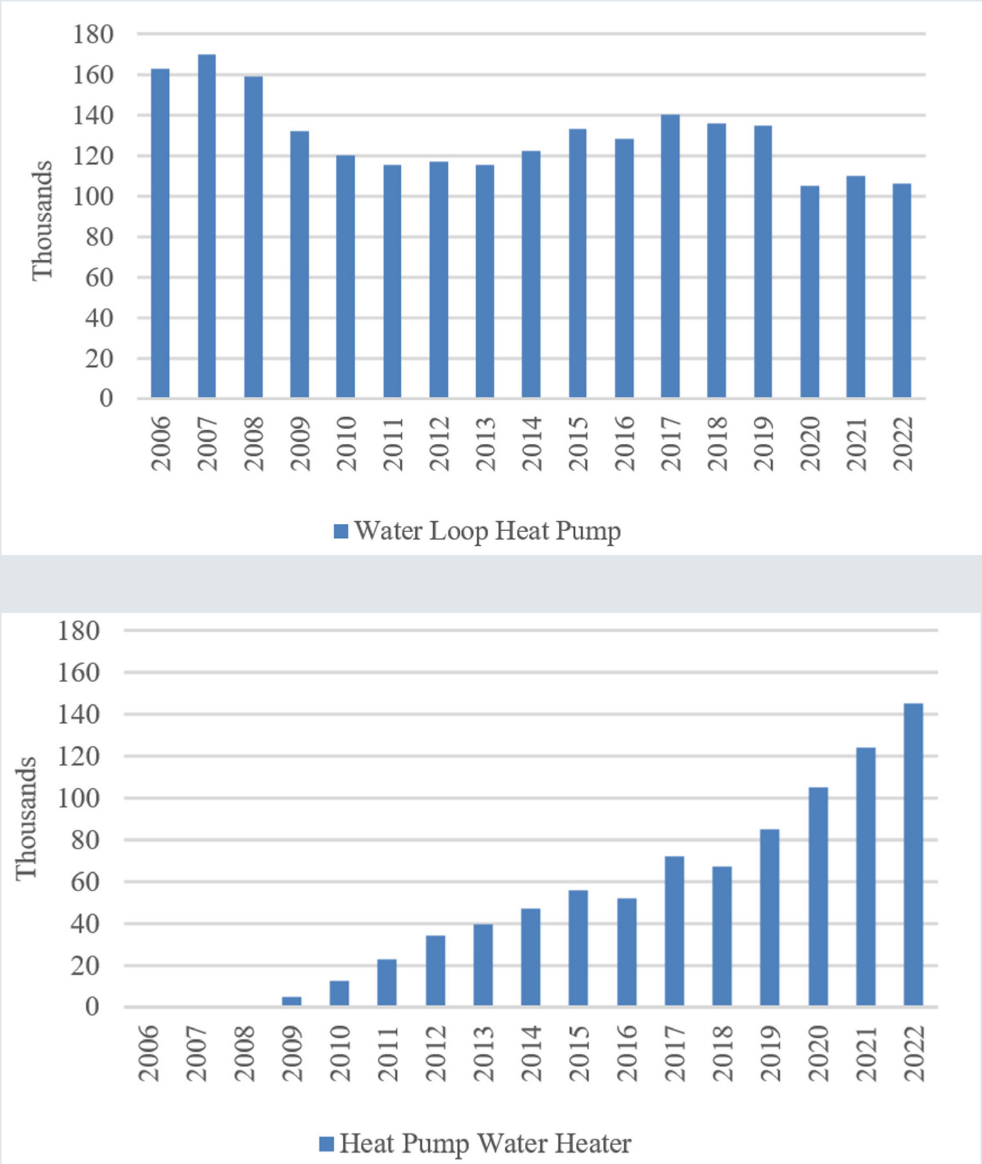

Figure. 4. Water loop heat pump (top) and heat pump water heater sales (bottom).

Figure. 5. GSHP sales.

ing technology. Figure 4 shows the sales of water loop heat pumps and heat pump water heaters since 2006 [11]. Water loop heat pumps are typically installed in multifamily buildings, hotels, dormitories, and so on, which may require simultaneous heating and cooling. Water loop heat pump shipments also saw a drop since 2007 due to the housing market collapse and, again, since 2019, as construction activities slowed down due to the COVID-19 pandemic. Figure 5 shows the annual shipments of ground source heat pumps (GSHP) in the last 20 years [17]. It shows a steady increase from 2003 to 2011, first due to increasing natural gas prices and since 2009, when the federal government started offering tax rebates for GSHP installations. GSHP shipments were apparently affected when tax credits expired in 2016 but jumped back in 2019 when tax credits were reinstated. The GSHP shipment dropped again in 2020 due to the COVID-19 pandemic and the resulting halt in construction activities and supply chain issues [17]. The low natural gas price during the pandemic may also have contributed to the staggering growth of GSHP applications in the US.

Market Share

The US Energy Information Administration's (EIA's) 2020 Residential Energy Consumption Survey estimates that approximately 15% of existing US homes use electric heat pumps as their primary heating source. The heat pump market share is higher in the South, where heat pumps serve one-third of existing homes [13]. The heat pump market share is smaller in the commercial building sector. According to EIA's 2018 Commercial Building Energy Consumption Survey, only 4.5% of existing US commercial building floor space is served by electric heat pumps [14].

The market share of heat pumps in new single-family construction has stayed relatively constant since 2012. More than 39% of single-family homes constructed in the United States in 2021 used a heat pump as their primary heating source (Figure 6 top) [15]. An estimated 59% of single-family homes completed in the South in 2021 used a heat pump for heating. The share has remained at 60% or more since 2011 (Figure 6 bottom). In the West, the installation of heat pumps has been ramping up, reaching 17% in 2021, the highest share since 1986. The housing construction, as well as the heat pump share, has declined in the Midwest. The heat pump market share has fluctuated in the Northeast but stayed at a share of less than 10% [11].

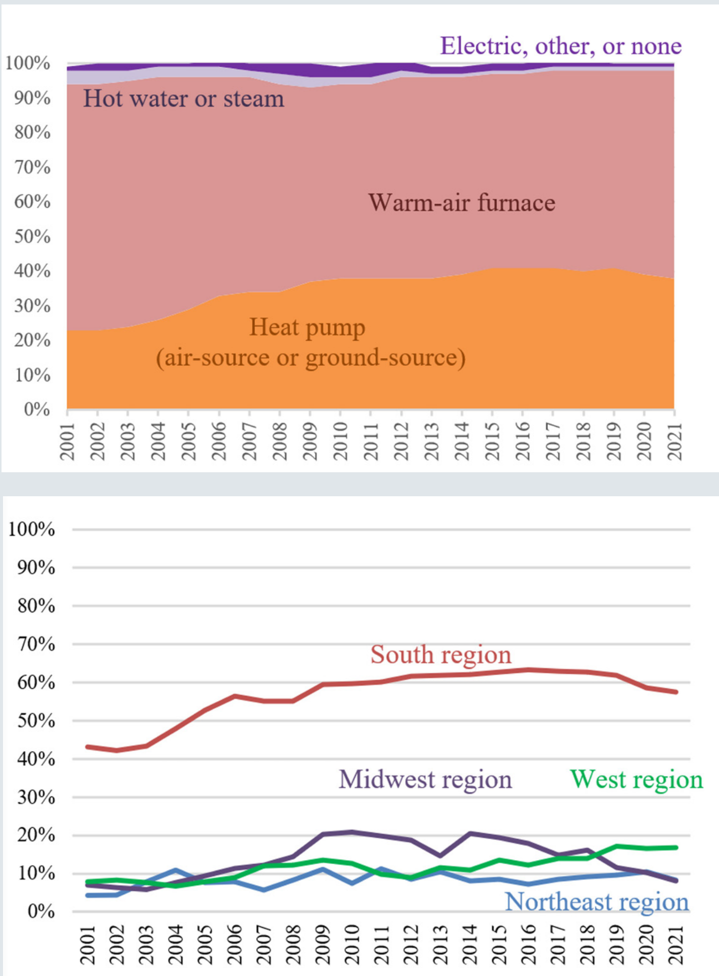

Figure. 6. Share of heat pumps in new single-family houses: (top) Comparison with other heating system types across the United States, and (bottom) heat pump share by US census region.

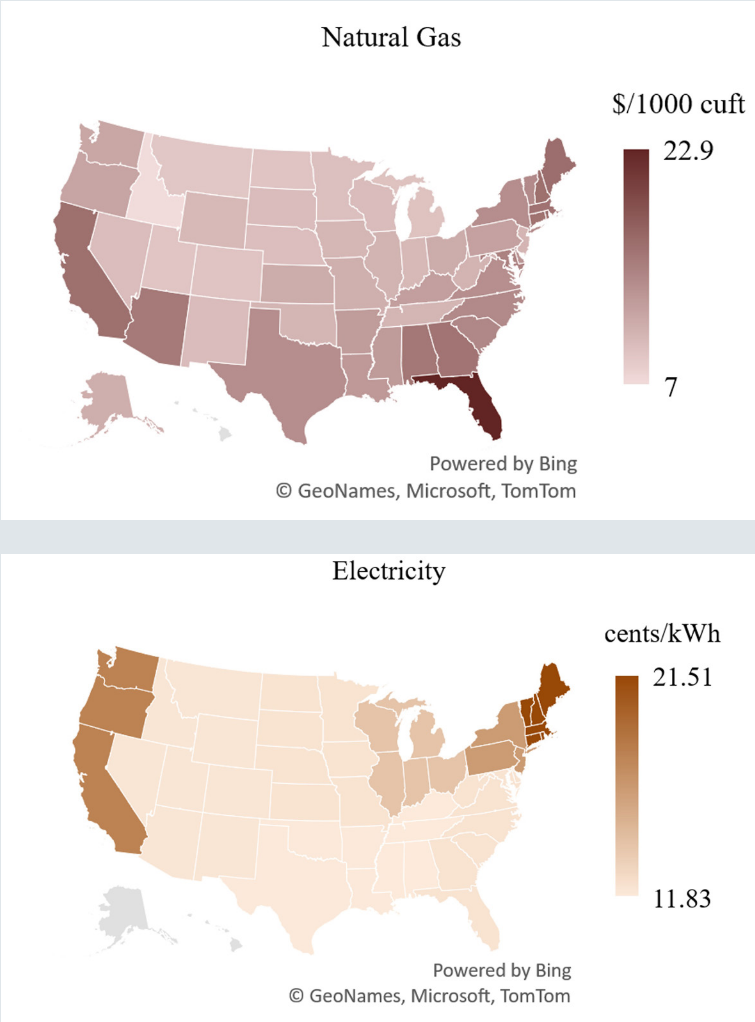

Figure. 7. 2021 regional fuel prices: (top) natural gas and (bottom) electricity.

Energy Price

The regional differences in the heat pump market share can be attributed to the mild winter and lower electricity and higher natural gas prices in the South, as shown in the 2021 regional natural gas and electricity prices in Figure 7 [16], [17].

Figure 8 shows the historical comparison of the electricity and national gas prices in the United States. For future prediction of energy prices, IEA publishes projected retail and residential energy prices for the United States through 2050 in the EIA Annual Energy Outlook [18]. The projections show very little change in retail and residential energy prices over that time frame. Natural gas prices are predicted to increase marginally, from $10.14 per million Btu in 2020 to $11.76 in 2050. Electricity rates are predicted to decrease marginally, from $35.77 per million Btu in 2020 to $34.96 in 2050.

Financial Incentives

Heat pump installations in the United States have been, in part, driven by an array of tax credits. As part of the Inflation Reduction Act of 2022, federal tax credits have been extended through 2032 [19]. Equipment tax credits of $300 is available for installing air source heat pumps and heat pump water heaters in existing homes that meet specified efficiency criteria. Renewable energy tax credits are available for geothermal heat pump installation in existing homes and new construction, with a gradual step down in the credit value (i.e., 22%–30% of system cost) based on the year the system is placed into service. In addition, most states offer rebate programs for air source and geothermal heat pump installations [20]. Other common financial incentive mechanisms are available as loan programs, grant programs, and Property-Assessed Clean Energy financing [20]. The recent high natural gas prices and the uncertainties in natural gas supplies make the investment in GSHP systems more economically viable now than during the pandemic. For example, New York and Massachusetts have invested in several pilot projects for district-scale GSHP systems [21].

Furthermore, under the High-Efficiency Electric Home Rebate Act, a part of the Inflation Reduction Act of 2022, point-of-sale consumer rebates are available for low- and moderate-income households to electrify their homes. The rebate covers 50%–100% of purchase and installation costs up to $14,000 on electrification measures, including heat pumps, heat pump water heaters,

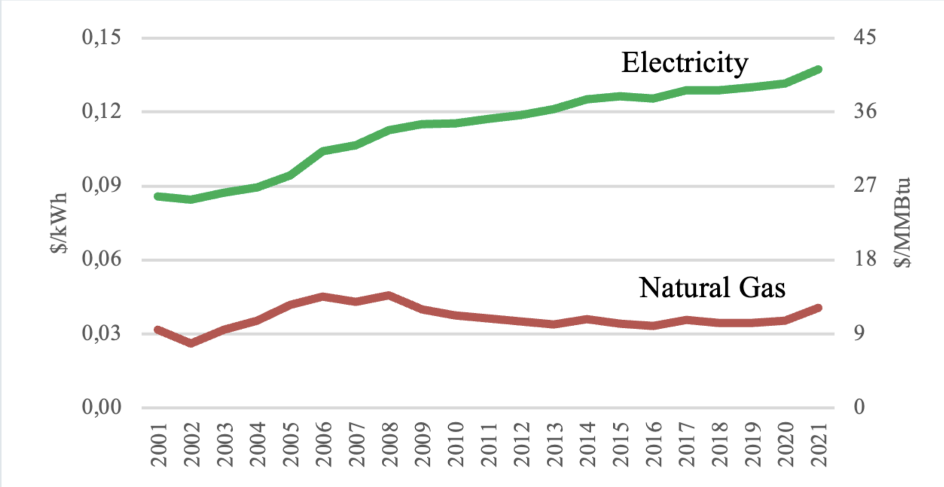

Figure. 8. US average electricity and natural gas prices.

panel/service upgrades, electric stoves, clothes dryers, and insulation/air sealing measures [22]. These financial incentives help reduce the cost burden on consumers of heat pump technologies and support electrification.

Challenges and Opportunities

The US government's decarbonization goal and the supporting policies and programs have presented an unprecedented opportunity for advancing the research, development, and deployment of heat pump technologies. Electrification of buildings and large-scale deployment of heat pumps are key to accomplishing this goal. Key technological challenges include a lack of regional solutions for cold climates, high initial cost, complicated design and control of the components and system for hybrid heat pumps with multiple heat sources, compromised energy benefits due to installation challenges, and space constraints that potentially limit the installation of heat pumps. Specific research topics to address these challenges include the following:

1. Improve efficiency and capacity of heat pumps for cold climates, and efficiency of systems for warm climates
2. Reduce installed cost and improve the reliability of high-efficiency systems
3. Develop solutions for problematic heat pump installations, such as space and electrical panels, particularly for retrofit and renovation applications
4. Develop alternative refrigeration technologies and lower-GWP refrigerants to reduce direct emissions

Tackling these challenges requires technological, economic, social, and political innovations from all stakeholders by developing efficient systems with efficient components, smart monitoring, optimal control, innovative system integration, aggregation, and servicing.

Conclusions

The US government's decarbonization goal and the supporting policies and programs have presented an unprecedented opportunity for advancing the research, development, and deployment of heat pump technologies. The US Department of Energy (DOE) is investing heavily in heat pump technology. Governmental actions, along with public and private sector incentive programs for heat pumps and building electrification, promote deploying more efficient heat pump systems.

The US heat pump market has shown steady growth since 2010, faster relative to competing space heating technologies. However, the market growth is uneven geographically, with a very small market share in cold climates. The heat pump market share is also very small in the commercial sector. GSHP market trends show a direct and immediate influence of tax credits.

Heat pump technology is mature, and production and installation can, in principle, be scaled up quickly. There are several hurdles to expanding heat pump deployment, including the relatively high cost of installation; high operational costs in cold climates; various supply chain constraints such as limited manufacturing capacity and shortages of skilled workers; and existing building stock with fossil fuel systems and constraints for fuel-switching. Long-term solutions, including policy consistency, targeted action to strengthen supply chains, building the grid capacity, and expanding renewables, thermal storage, and smart technology (such as smart thermostats, zoning control, and auxiliary heat control) at lower costs, are needed to encourage further investment. The future of heat pump technologies will be highly influenced by the evolving minimum standards, R&D, tax credits, and incentive programs.

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Ongoing Annexes in HPT TCP

The projects within the HPT TCP are known as Annexes. Participation in an Annex is an efficient way of increasing national knowledge, both regarding the specific project objective, but also by international information exchange. Annexes operate for a limited period of time, and the objectives may vary from research to implementation of new technology.

ADVANCED COOLING/ REFRIGERATION TECHNOLOGIES DEVELOPMENT	53	CN, DE, IT, KR, **US**
HEAT PUMP SYSTEMS WITH LOW GWP REFRIGERANTS	54	AT, DE, FR, IT, JP, KR, SE, **US**
INTERNET OF THINGS FOR HEAT PUMPS	56	**AT**, CH, DE, DK, FR, NO, SE
FLEXIBILITY BY IMPLEMENTATION OF HEAT PUMPS IN MULTI-VECTOR ENERGY SYSTEMS AND THERMAL NETWORKS	57	AT, **DK**, DE, FR, NL, SE
HIGH-TEMPERATURE HEAT PUMPS	58	AT, BE, CA, CH, DE, **DK**, FR, NL, NO, JP
HEAT PUMPS FOR DRYING	59	**AT**, CN, DK, SE
RETROFIT HEAT PUMP SYSTEMS IN LARGE NON-DOMESTIC BUILDINGS	60	AT, **UK**, IT
HEAT PUMPS IN POSITIVE ENERGY DISTRICTS	61	AT, **CH**, DE, JP, US
HEAT PUMPS FOR MULTI-FAMILYRESIDENTIAL BUILDINGS IN CITIES (NEW)	62	**DE**, FR
PLACEMENT IMPACT ON HEAT PUMP ACOUSTICS (NEW)	63	**DE**, AT
SAFETY MEASURES FOR FLAMMABLE REFRIGERANTS (NEW)	64	DE, KR, **SE**

For Details of the new Annexes refer to pages 10 - 11.

NEW

The Technology Collaboration Programme on Heat Pumping Technologies participating countries are:

Austria (AT), Belgium (BE), Canada (CA), China (CN), Czech Republic (CZ), Denmark (DK), Finland (FI), France (FR), Germany (DE), Italy (IT), Japan (JP), the Netherlands (NL), Norway (NO), South Korea (KR), Sweden (SE), Switzerland (CH), the United Kingdom (UK), and the United States (US).

Bold, red text indicates Operating Agent (Project Leader).

ANNEX 53 ADVANCED COOLING/REFRIGERATION TECHNOLOGIES DEVELOPMENT

Introduction

It is widely acknowledged that air conditioning (AC) and refrigeration systems are responsible for a large share of worldwide energy consumption today, and this demand is expected to increase sharply over the next 50 years absent action to ameliorate the increase. IEA projects that AC energy use by 2050 will increase 4.5 times over 2013 levels for non-Organization of Economic Coordination and Development (OECD) countries and 1.3 times for OECD countries). Worldwide action, both near-term (e.g., increase deployment of current "best" technologies) and longer-term (RD&D – research, development and demonstration – to develop advanced, higher efficiency technology solutions), is urgently needed to address this challenge. HPT Annex 53 was initiated in late 2018 and focuses on the longer-term RD&D need. Technologies under investigation include the vapor compression (VC) based systems and non-traditional cooling approaches. Advanced VC R&D underway by participant teams includes a combined absorption/VC/thermal storage concept, a large chiller based on water (R-718) as refrigerant, a novel pressure exchange (PX) concept for expansion work recovery, and enhanced source and sink stream matching using zeotropic refrigerants. Significant efforts are also underway aiming at advancing state of development of cooling systems based on the magneto caloric (MC), elastocaloric (EC), and electrocaloric effect (ECE) cooling cycle concepts. This includes work on identifying materials with improved fatigue performance, etc., for MC, EC and ECE concepts.

Objectives

Annex 53's main objective is longer-term R&D and information sharing to push the development of higher efficiency and reduced greenhouse gas (GHG) emission AC/refrigeration focused HP technologies. Specific areas of investigation include but are not limited to the following:

- Advance the technology readiness level (TRL) of non-traditional cooling technologies and alternative compression technologies
- Independent control of latent and sensible cooling and tailoring systems for different climates (e.g. hot dry or hot humid)
- Advances to VC-based technologies, both conventional and non-traditional.
- Final reports to be published during 2023

Key data

- Project duration: October 2018–December 2022
- Operation Agent: Reinhard Radermacher University of Maryland, USA
- raderm@umd.edu and Brian Fricke, Oak Ridge National Laboratory, frickeba@ornl.gov
- Participating countries: China, Germany, Italy, South Korea and USA
- Website: www.heatpumpingtechnologies.org/annex53/

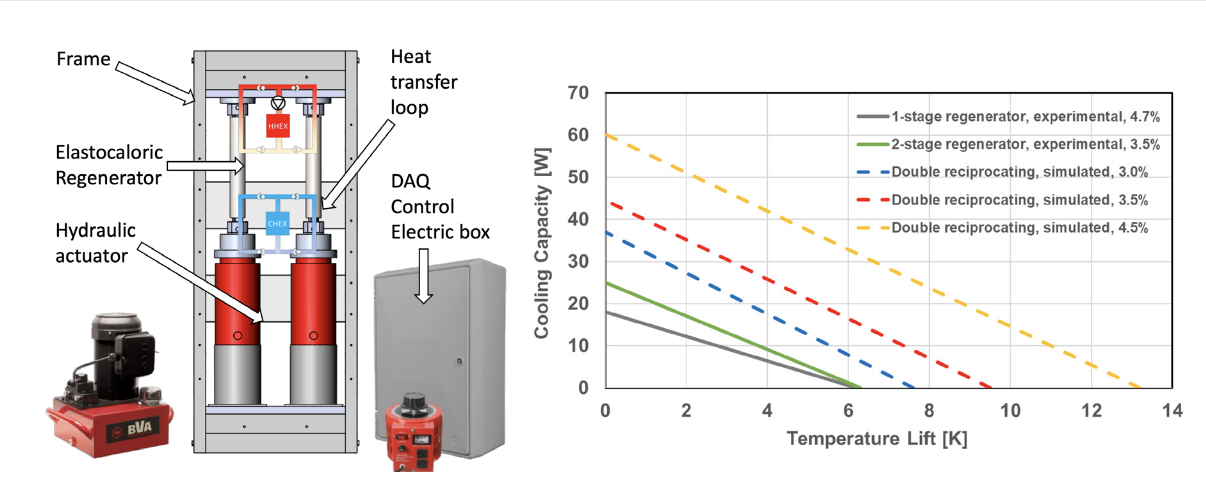

Figure 1: (Left) Elastocaloric single and double reciprocating schematic; (Right) Simulation results of cooling capacity and useful temperature lift generated by different EC configurations

ANNEX 54

HEAT PUMP SYSTEMS WITH LOW GWP REFRIGERANTS

Introduction

Low-GWP refrigerants are considered long-term solutions for environmentally friendly heat pump systems. Considerable studies have shown that design modifications are necessary to optimize low-GWP refrigerants. In particular, system-level design, analysis, and optimizations are much needed. Annex 54 aims to address the challenge via 1) a comprehensive review of recent R&D (research and development) progress on component- and system-level design, analysis, and optimization using low GWP refrigerants, 2) in-depth case studies of system-level optimization, which can provide design guidelines and real-world experiences, 3) review of design optimization and advancement impacts on LCCP reduction, and 4) outlook for 2030. All the efforts are accomplished by academic and industrial participating countries. The work can be a valuable reference for researchers, engineers, and policymakers across the HVAC industry. It is of particular interest to those to dive deep into the R&D of heat pump systems.

Objectives

Annex 54 promotes the application of low-GWP refrigerants to air-conditioning and heat pump systems with the following objectives:

» A comprehensive review of recent R&D progress on system-level design, analysis, and optimization using low-GWP refrigerants (fulfilled),

» In-depth case studies of system-level optimization, which can provide design guidelines and real-world experiences (partially fulfilled),

» Optimization of heat pump systems for low-GWP refrigerants (partially fulfilled),

» Analysis of the LCCP impacts by the current design and optimized design with low-GWP refrigerants (partially fulfilled), and

» Making an outlook for heat pumps with low-GWP refrigerant for 2030 (partially fulfilled)

Key data

- Project duration: January 2019 to December 2023
- Operating Agent: Yunho Hwang, University of Maryland, College Park, yhhwang@umd.edu
- Participating countries: Austria, France, Germany, Italy, Japan, Korea, Sweden, and the USA.
- Further information: All workshop presentation materials, meeting agenda, minutes, and attendee list are available from the Annex 54 website. at https://heatpumpingtechnologies.org/annex54/

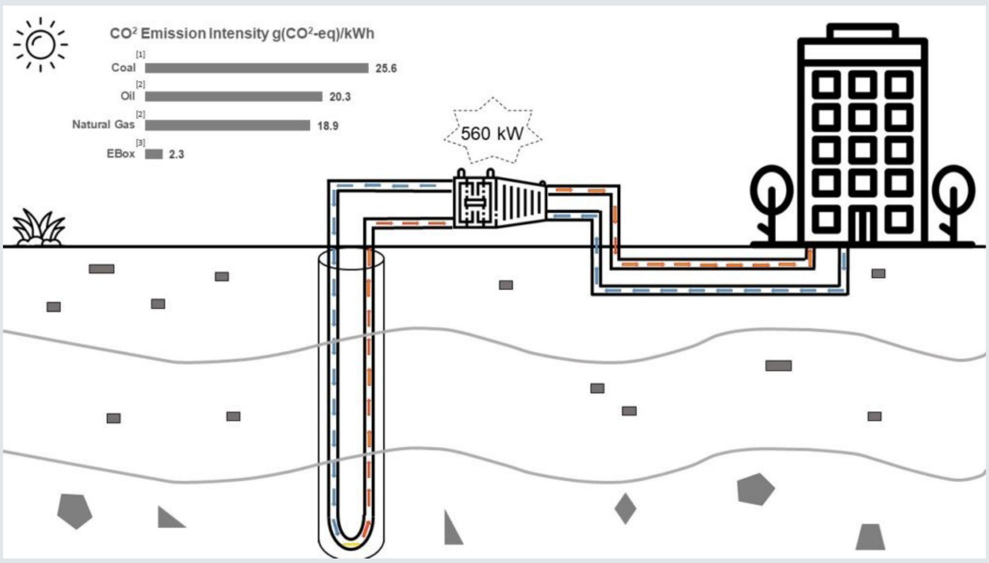

Figure 1: Principle of EBox-Geothermal R290 Heat Pump (Source: https://megawattsolutions.se)

ANNEX
56

INTERNET OF THINGS FOR HEAT PUMPS

Introduction
Today, more and more devices are connected to the Internet and can interact due to increasing digitalization – the Internet of Things (IoT). In the energy transition, digital technologies are intended to enable flexible energy generation and consumption in various sectors, thus leading to greater use of renewable energies. This also applies to heat pumps and their components.

The IoT Annex explores the opportunities and challenges of connected heat pumps in household applications and industrial environment. There are a variety of new use cases and services for IoT-enabled heat pumps. Data can be used for preventive analytics, such as what-if analysis for operation decisions, predictive maintenance, fine-tuning of the operation parameters and benchmarking. Connected heat pumps allow for demand response to reduce peak load and to optimize electricity consumption, e.g. as a function of the electricity price. Digitalization in industry can range from automated equipment, advanced process control systems to connected supply value chains.

IoT-enabled heat pumps allow for integration into the process control system and a higher-level energy management system, which can be used for the overall optimization of the process. Each level of participation of a heat pump in a connected world (Figure 1) is also associated to different important risks and requirements to connectivity, data analysis, privacy and security for a variety of stakeholders. Therefore, this Annex has a broad scope looking at different aspects of digitalization and will create a knowledge base on connected heat pumps. The Annex will provide information for heat pump manufacturers, component manufacturers, system integrators and other actors involved in IoT.

Objectives

- Provide guidance, data and knowledge about heat pump technologies with respect to IoT applications
- Review the status of currently available IoT-enabled heat pumps, heat pump components and related services
- Identify requirements for data acquisition from newly designed or already implemented heat pump systems considering types of signals, protocols and platforms for buildings and industrial applications and related privacy issues and ongoing standardization activities
- Evaluate data analysis methods and applications (digital twins), including machine learning, semantic models, hybrid models, data-driven models and soft sensors
- Analyse business models for IoT enables heat pumps (strengths, weaknesses, opportunities, threats)
- Evaluate market opportunities created by IoT-enabled heat pumps and identify success factors and further demands to software and hardware infrastructure.

Key data

- Project duration: January 2020 - December 2022
- Final reports to be published during 2023
- Operation Agent: Veronika Wilk, Austrian Institute of Technology GmbH, Austria veronika.wilk@ait.ac.at
- Participating countries: Austria, Denmark, France, Germany, Norway, Sweden, Switzerland
- Further information: https://heatpumping-technologies.org/annex56

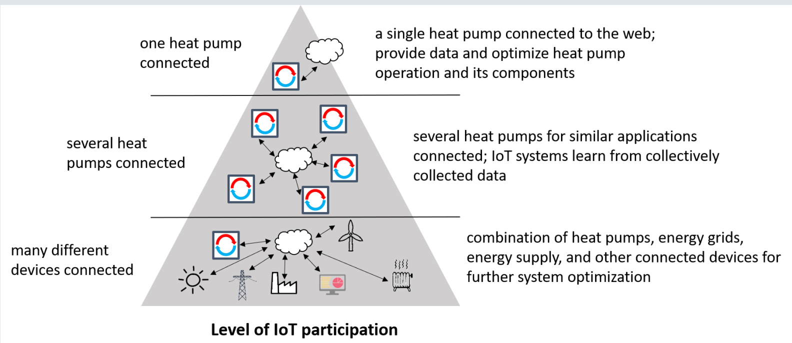

Figure 1. Heat pumps as a part of the Internet of Things (source: AIT Austrian Institute of Technology GmbH)

ANNEX
57
FLEXIBILITY BY IMPLEMENTATION OF HEAT PUMPS IN MULTI-VECTOR ENERGY SYSTEMS AND THERMAL NETWORKS

Introduction
Since the start of 2022, the need and interest regarding flexibility and smart control of heat pumps have been growing rapidly, as the implementation rate has increased very fast due to the accelerated phase-out of gas in Europe. The energy prices have grown in this period, but also the variation in the hourly spot market price for electricity is changing a lot. This means that the consumers are trying to move the electricity consumption away from the peak price hours very fast. The high implementation rate regarding heat pumps in Europe means that the need for moving consumption has increased, both due to electricity price variation but also due to the need to minimize grid constraints

Annex 57 focuses on coming technologies, and the possibilities of heat pumps to increase the flexibility in energy systems with different sources such as PV, wind-power, and biomass and where end users can be consumer or prosumer or both (Multi-Vector). Individual heat pumps, as well as heat pumps in a district or local grid, can increase the flexibility.

The CO_2 reduction goals mean the need for using excess heat from industries, the commercial sector and other sources are growing. Heat pumps, combined with District Heating, are a way to make these energy sources available in buildings. At the moment, the interest in heat pumps for district heating and processes is growing.

District heating, in general, and heat pumps connected to the grids, in particular, are predicted to play a key role in the energy grid and supply for the future. With the implementation of district heating, it is possible to cover up to 50% of the heating demand in Europe, and heat pumps can deliver around 25 % of the energy to the district heating grid. The Heat Roadmap Europe 4 scenarios, with a larger share of district heating in the energy system, show that CO_2 emissions can be reduced by more than 70 % compared to today's situation.

Objectives
» Task 1: Energy market analysis – Future developments and sector coupling.
» Task 2: Best practice examples – Description of existing projects with flexible solutions with heat pumps in thermal grids
» Task 3: Concepts – development of representative and promising solutions
» Task 4: Flexibility – Assessment and Analyses of different options
» Task 5: Business models – Development and evaluation of innovative concepts
» Task 6: Dissemination

Key data
- Project duration: January 2021 - December 2023
- Operating agent: Danish Technological Institute, Mr. Svend Pedersen svp@teknologisk.dk
- Participating countries: Austria, Denmark, France, Germany, Netherlands, Sweden
- Furtherinformation: www.heatpumpingtechnologies.org/annex57

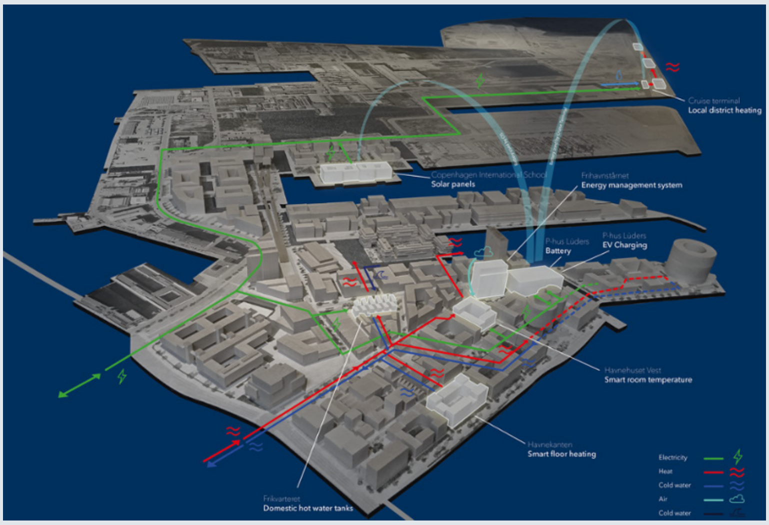

Figure 1. Integrated energy sytems in EnergyLabs Nordhavn

ANNEX 58 HIGH-TEMPERATURE HEAT PUMPS

Introduction

Heat pump-based heat supply at high temperatures has considerable potential for decarbonizing the industrial process heat supply but is often facing various challenges. Exploiting the full potential of high-temperature heat pumps (HTHP) requires a common understanding of the technology, its potentials, and its perspectives at a variety of stakeholders. High-temperature heat pumps are considered a key technology for decarbonizing industrial process heating towards 2030, while a successful wide-scale implementation of the technology will require the consideration of technologies that are currently approaching the market and still under development.

Therefore, this Annex gives an overview of available technologies and close-to-market technologies and outlines the need for further RD&D developments. In order to maximize the impact of high-temperature heat pumps, this Annex also looks at process integration by developing concepts for heat pump-based process heat supply, and the implementation of these concepts see Figure 1.

Objectives

The overall objective of the Annex is to provide an overview of the technological possibilities and applications as well as to develop best practice recommendations and strategies for the transition towards heat pump-based process heat supply. The intention is to improve the understanding of the technology's potential among various stakeholders, such as manufacturers, potential end-users, consultants, energy planners and policy makers. In addition, the Annex aims to provide supporting material to facilitate and enhance the transition to a heat pump-based process heat supply for industrial applications.

This will be achieved by the following sub-objectives:

- » Provide an overview of the technology, including the most relevant systems and components that are commercially available and under development (Task 1 – Ongoing).
- » Identify technological bottlenecks and clarify the need for technical developments regarding components, working fluids and system design (Task 1 – Ongoing).
- » Present best practice system solutions for a range of applications to underline the potential of HTHPs (Task 2 – Ongoing).
- » Present strategies for the transition to heat-pump based process heat supply (Task 3 – Planned).
- » Enhance the information basis about industrial heat pumps, potential applications and potential contribution to the decarbonization of the industry (Task 1, 2 & 3 – Ongoing).
- » Develop guidelines for the handling of industrial heat pump projects with a focus on the HP specifications and the testing of

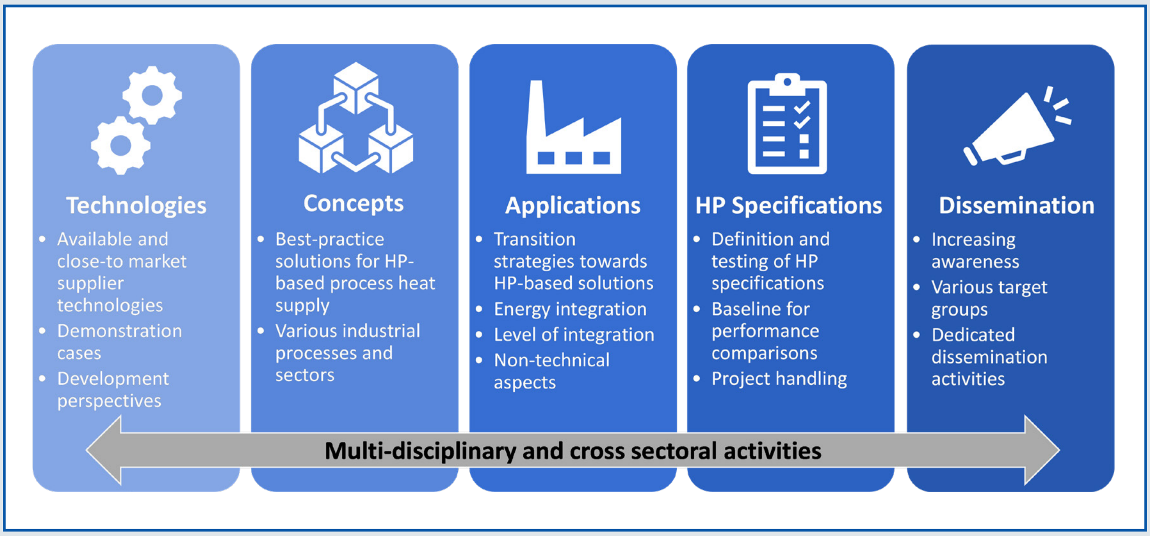

Figure 1. Overview of activities in Annex 58.

these specifications (Task 4 – Planned).

» Disseminate the findings to various stakeholders and add to the knowledge base for energy planners and policy makers (Task 5 – Ongoing).
» (Task 5 – Ongoing).

Key data

- Project duration: Jan 2021 – Dec 2023
- Operating Agent: Danish Technological Institute, Benjamin Zühlsdorf, bez@dti.dk,
- Participating countries: Austria, Belgium, Canada, China, Denmark, France, Germany, Japan, Netherlands, Norway, South Korea, Switzerland ´
- Further information: https://heatpumpingtechnologies.org/annex58/

Results and Progress

High-temperature heat pumps (HTHP) are attracting growing interest and are considered a key technology for decarbonizing industrial process heating. The recently published IEA report "Net Zero by 2050 – A Roadmap for the Global Energy Sector" outlined the importance of industrial heat pumps and concluded that heat pumps should cover 15 % of the process heat demand of light industries at temperatures up to 400 °C, while this share should increase to 30 % by 2050. This corresponds to a required installation capacity of 500 MW per month over the next 30 years. The majority of these systems are expected to have supply temperatures above 100 °C and are accordingly considered high-temperature heat pumps.

The relevance of high-temperature heat pumps is confirmed by the large interest in the Annex 58. Ten countries have already confirmed their participation, and in total, up to twelve participating countries are expected to join the Annex. The national support groups comprise R&D institutes and universities, technology suppliers, consultants, and others and are accordingly supplemented with knowledge from various national and international R&D projects.
As part of Task 1, the activities focused on summarizing the state of the art, including available and close-to-market technologies. In this activity, information about supplier technologies and demonstration cases were collected using review templates. In the general perception of the industrial heat pump industry, supply temperatures of commercially available equipment seem to be limited to around 100 °C, while first technologies are becoming commercially available for higher temperatures. In order to communicate the availability of technologies, the Annex has collected information about supplier technologies and demonstration cases in informative two-page brochures, as shown in Figure 2.

By now, 33 supplier technologies were described, while information could be gathered for 14 demonstration cases. These descriptions are published on the Annex 58 homepage and publicly accessible while the report is in preparation.

Figure 2. Two-page information brochures of high-temperature heat pump systems.

ANNEX
59
HEAT PUMPS FOR DRYING

Introduction

Drying processes are widely used in industry, including the food, paper, chemicals, and ceramics industries, as well as in commercial laundries and in household applications, such as white goods. The Handbook of Industrial Drying describes at least 15 different dryer types and identifies more than 20 different industrial drying sectors, making it challenging to generalize about drying technologies.

Drying processes make a significant contribution to energy consumption, accounting for 10-25% of industrial energy consumption. To this day, drying continues to be the main process used in industrial preservation for a large number of products. Industrialization has helped to optimize drying processes, which are conducted under varying, but controlled conditions. However, the basic principle of drying remains the same as it was thousands of years ago, with convective dryers continuing to be the most commonly used type of dryer.

Industrial convective drying plants are mainly operated by burning fossil fuels and product waste. The moisture extracted from the material to be dried is, in most cases, released into the environment in pure gaseous form or with a drying medium (e.g. air, steam). This exhaust air contains high amounts of energy, which is often only partially utilised by heat recovery. Modern industrial drying processes are either an open loop system using heated ambient air, or closed loop systems that re-circulate the drying air.

Heat pumps offer an opportunity to utilize a heat source at low temperatures (at the evaporator) and supply a heat sink at a higher temperature (condenser). In the case of a closed loop drying system, the combined heating and cooling load is used for the recovery of drying energy, which is essentially the latent heat from the water evaporation, returning this energy back into the drying process in the form of dehumidified and re-heated drying air.

Objectives

The use of heat pumps in drying processes show great energy savings potential for the numerous industries reliant on drying processes. Annex 59 will thus explore and evaluate the potential that can be unlocked in a range of applications. Furthermore, the Annex shall seek to undertake the following:

» Collate relevant data of the state of the art of drying processes equipped with heat pumps
» Analyse drying processes at a theoretical level to find the optimal process design (e.g. lowering temperatures), in-process operation (drying time) as well as in heat pump design and integration.
» Gather experience from demonstration projects through monitoring and simulation of the entire drying system
» Make recommendations regarding the design of heat pump drying systems, taking into account performance compared with conventional dryers
» Highlight and review the most promising dryer concepts that can integrate heat pumps

Key data

- Project duration: 1 January 2022 - 31 December 2024
- Operating Agent: Dr Michael Lauermann, michael.Lauermann@ait.ac.at
- Participating countries: Austria, China, Germany, USA
- Further information: https://heatpumpingtechnologies.org/annex59/

ANNEX
60
RETROFITTING HEAT PUMP SYSTEMS IN LARGE NON-DOMESTIC BUILDINGS

Introduction
The objective of this Annex is to increase the take-up of heat pumps in existing large non-domestic buildings by demonstrating the success of retrofit projects to building owners and their technical advisors and by providing guidance on the selection of appropriate heat pump systems for their specific needs. This is important because the non-domestic sector contributes substantially to carbon emissions, but there is less experience of or guidance on retrofit heat pump systems than for dwellings.

Non-domestic buildings can vary widely in function, provision of energy services and built form. As the number of installed systems in each country is low, it can be difficult to locate local examples that demonstrate particular combinations of retrofit system and building. As a result, it is not always easy to identify which of the many types of heat pump system designs are most suitable for particular situations.

The Annex focuses on providing straightforward, high-level guidance for building owners and other decision-makers. It will provide guidance that helps building owners and their advisors with their decision to make decisions based on experience from working systems. It will compile an accessible database of working systems which will be complemented by an options support tool that provides links to summaries of the existing installations that most closely resemble users' circumstances. The tool will also provide generic advice that reflects the experience of designers and researchers.

The immediate target users are building owners and their advisors, with the aim of reassuring them that their system choices reflect previous relevant experience. This should encourage the take-up of appropriate heat pump systems and accelerate carbon savings.

The outcomes should also be of value to policy makers and to the heat pump industry by identifying areas where there is substantial evidence of successful application and also those where experience is limited.

The key stages are the identification and acquisition of information from installed systems, the construction of the database and options support tool and the delivery of useful information to the target users.

Objectives
» Provide evidence of the practical feasibility and satisfactory operation of a range of installed retrofit systems in large non-domestic buildings in a number of countries, together with insights into the thinking that led to the choice of system.

» Deliver simple-to-use, accessible advice to support the initial selection of system options for specific circumstances, signposted to evidence and summaries of the relative strengths of each option.

Key data
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- Operating Agent: Roger Hitchin roger.hitchin@hotmail.com, Andre Neto-Bradley, andrepaul.netobradley@beis.gov.uk, Oliver Sutton, Oliver.sutton@beis.gov.uk
- Further information: https://heatpumping-technologies.org/annex60/

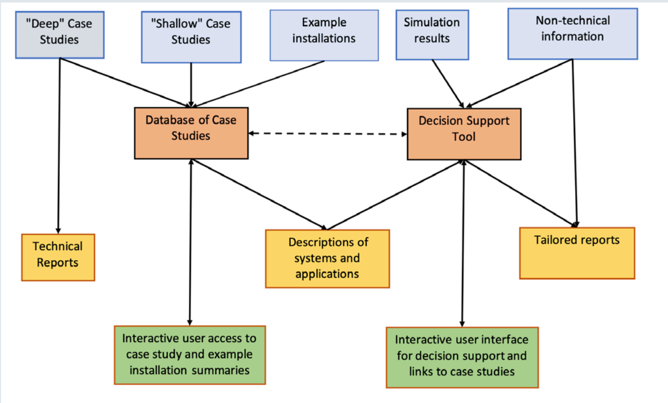

Figure 1. Schematic diagram of annex process.

ANNEX 61 HEAT PUMPS IN POSITIVE ENERGY DISTRICTS

Introduction

Ambitious climate protection targets require a transition to a highly performant and renewable energy system. The built environment is a key sector for fast emission reduction in many countries. For instance, 36% of the emissions in the EU are due to buildings, so reaching ambitious climate targets will be strongly facilitated by transforming the building sector. Heat pumps are seen as the future heating system in many scenarios. The IEA Net Zero by 2050 report, for instance, states that 50% of the global heat demand will be met by heat pumps by 2045.

Thus, the integration of heat pumps into the energy system on a large scale is a future challenge but also an opportunity to derive a highly performant and CO_2-free energy system. Positive energy districts are an ambitious objective to pave the way for the urban energy transformation. Heat pumps can effectively couple different thermal and electric loads in districts at high performance. Thus, using synergies by integrating load profiles in districts can even increase the heat pump performance, while the coupling of electric and thermal loads also provides flexibility to the connected grids.

Annex 61 will investigate heat pump application in building clusters and districts for both new and retrofit districts on a technical, economic and ecological basis. Based on generic systems concepts, promising solutions will be investigated in detail by simulation and monitoring. As a result, optimised design, control and system integration, and other technologies like PV generation and storages, will be derived.

Objectives

- Characterisation and cross-comparison of heat pump application in positive energy districts in the participating countries
- Development of generic system concepts for the integration of heat pumps in districts
- Techno-economic analyses of promising concepts by simulation
- Evaluation of the real performance of heat pumps in districts by monitoring projects

Key data

- Project duration: Sept. 2022 – Dec. 2025
- Operating Agent: Carsten Wemhoener, carsten.wemhoener@ost.ch
- Participating countries: Austria, Germany, Japan, Switzerland, USA
- Website: https://www.heatpumpingtechnologies.org/annex61

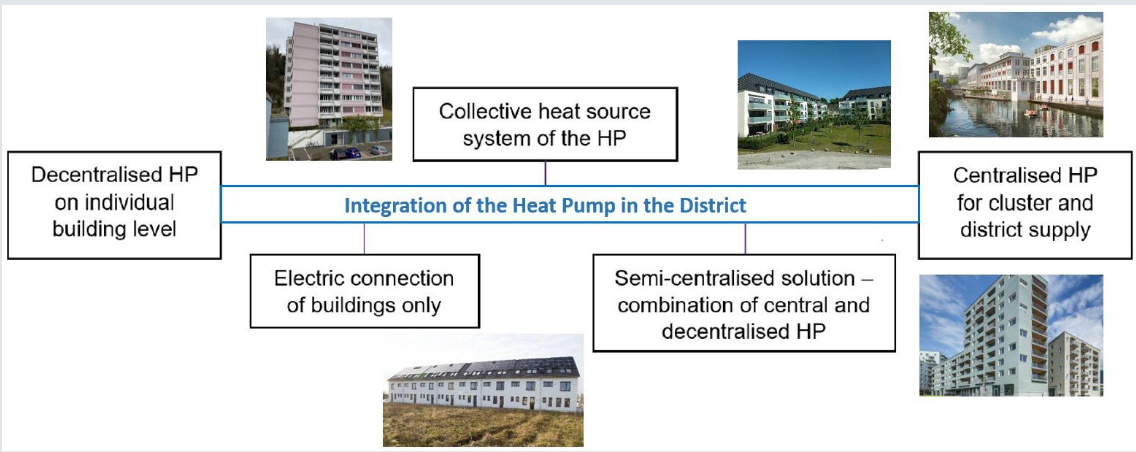

Figure 1. Integration options of heat pumps in clusters of building and districts and corresponding monitoring projects in Annex 61

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Events 2023/2024

Please check for updates for any conference that you plan to attend. Venues and dates may change, due to the pandemic.

2023

24–28 April
17th CRYOGENICS 2023 IIR Conference
Dresden, Germany
https://www.cryogenics-conference.eu/cryogenics2023

27–29 April
10th IIR Conference on Ammonia and CO_2 Refrigeration Technologies
Ohrid, R. Macedonia
https://iifiir.org/en/events/10th-iir-conference-on-ammonia-and-co2-refrigeration-technologies

15–18 May
The 14th IEA Heat Pump Conference "Heat Pumps - Resilient and Efficient" (HPC2023)
Chicago, Illinois, United States
https://www.hpc2023.org/

8–9 June
20th European Conference
Milan, Italy
https://www.centrogalileo.it/

24–28 June
ASHRAE 2023 Annual Conference
Tampa, Florida, USA
https://www.ashrae.org/conferences/2023-annual-conference-tampa

21–25 August
26th IIR International Congress of Refrigeration
Paris, France
https://www.icr2023.org/

11–13 September
13th International Conference on Compressors and their Systems
London, United Kingdom
https://citycompressorsconference.london/

24–25 October
European Heat Pump Summit 2023
Exhibition Center,
Nuremberg, Germany
https://www.nuernberg-messe.de/en/events/european-heat-pump-summit-2023

2024

1–30 June, 2024
8th IIR Conference on Sustainability and the Cold Chain
Tokyo, Japan

11–14 August, 2024
16th IIR-Gustav Lorentzen Conference on Naturals Refrigerants
University of Maryland, United States

1–30 September, 2024
11th IIR Conference on Compressors and Refrigerants
Bratislava, Slovak (Republic)

1–30 September, 2024
10th IIR Conference on Caloric Cooling and Applications of Caloric Materials
Baotou, China

8 – 10 October, 2024
Chillventa 2024 - Refrigeration, AC & Ventilation, Heat Pumps Exhibition
Nuremberg, Germany

IN THE NEXT ISSUE
Special issue dedicated to the
Report from the 14th IEA Heat Pump Conference
"Heat Pumps - Resilient and Efficient"
VOL.41 NO 2/2023

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International Energy Agency
The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among its participating countries, to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development.

Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)
International collaboration for energy efficient heating, refrigeration, and air-conditioning.

Vision
Heat pumping technologies are the cornerstone for a secure, affordable, high-efficiency, clean and net-zero emission energy system for heating, cooling and refrigeration. We are the key worldwide independent actor to achieve this vision across multiple applications and contexts.

We generate and communicate information, expertise and knowledge related to heat pumping technologies as well as enhance international collaboration.

Mission
To accelerate the transformation to an efficient, renewable, clean and secure energy sector in our member countries and beyond by performing collaborative research, demonstration and data collection and enabling innovations and deployment within the area of heat pumping technologies.

Heat Pump Centre
A central role within the HPT TCP is played by the Heat Pump Centre (HPC). The HPC contributes to the general aim of the HPT TCP, through information exchange and promotion. In the member countries, activities are coordinated by National Teams. For further information on HPC products and activities, or for general enquiries on heat pumps and the HPT TCP, contact your National Team at www.heatpumpingtechnologies.org/contact-us/

The Heat Pump Centre is operated by RISE Research Institutes of Sweden.

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