Annex 58

High-Temperature Heat Pumps

Final report

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, (IEA).

The IEA
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a program of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)
The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a program of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programs in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is generally coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

Disclaimer
The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organized under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Heat Pump Centre
A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology, including researchers, engineers, manufacturers, installers, equipment users, and energy policymakers in utilities, government offices, and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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The Annex is being operated from 01/2020 to 09/2024. The main information can be found on the Annex 58 homepage: https://heatpumpingtechnologies.org/annex58/

Participating countries of Annex 58

There is a high number of countries participating in Annex 58, while each country is represented by a national team consisting of a number of organizations. The following countries are formally participating in the Annex:

- Austria
- Belgium
- Canada
- China
- Denmark
- Finland
- France
- Germany
- Japan
- Netherlands
- Norway
- South Korea
- Switzerland
- USA

A presentation of all the national teams can be found on the Annex 58 homepage.

Authors of the report

The Annex 58 reports is the result of a collaborative effort with contributions from various authors that are listed in the table below. The final report was prepared and edited by Benjamin Zühlsdorf (DTI), Virginia Amato (DTI), Jonas Lundsted Poulsen (DTI), Martin Pihl Andersen (DTU), Cordin Arpagaus (OST), Florian Schlosser (Paderborn University), and Sabrina Dusek (AIT).

Table 0-1: Overview of authors of the report, sorted by organization and country.

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Foreword

This report has been compiled as part of the IEA HPT Annex 58 about High-Temperature Heat Pumps (HTHP). The Annex is structured into the following five tasks:

- Task 1: Technologies – State of the art and ongoing developments for systems and components
- Task 2: Integration Concepts – Development of best practice integration concepts for promising application cases
- Task 3: Applications and Transition – Strategies for the conversion to HTHP-based process heat supply
- Task 4: Definition and testing of HP specifications – Recommendations for defining and testing of specifications for high-temperature heat pumps in commercial projects
- Task 5: Dissemination

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).
- Identify technological bottlenecks and clarify the need for technical developments regarding components, working fluids, and system design (Task 1).
- Present best practice system solutions for a range of applications to underline the potential of HTHPs (Task 2).
- Present strategies for the transition to a widespread heat-pump-based process heat supply (Task 3).
- Enhance the overall level of information about industrial heat pumps, potential applications, and potential contribution to the decarbonization of the industry (Task 1, 2 & 3).
- Develop guidelines for handling industrial heat pump projects with a focus on the HP specifications and the testing of these specifications (Task 4).
- Disseminate the findings to various stakeholders and add to the knowledge base for energy planners and policy makers (Task 5).

Annex 58 focuses on HTHPs, which are heat pumps that supply a relevant share of their main product at temperatures above 100 °C. In this context, the focus is on developing, summarizing, and communicating information about the most relevant technologies and applications rather than covering all technologies. The relevance was mainly determined by the various participants and indirectly given by the technologies' application potential and market perspectives. Therefore, the Annex is primarily focused on applications for industrial heat supply but will not specifically be limited to these applications.

Executive Summary

The decarbonization of industrial process heating is a top priority to achieve climate goals as process heating accounts for a considerable share of the final energy consumption and greenhouse gas emissions of industries. High-temperature heat pumps are a promising alternative to fossil fuels to provide process heating at the highest efficiency using potentially emissions-free electricity. However, the deployment of heat pumps for temperatures above 100 °C is still limited. Enabling a large variety of industries to convert their process heat supply to high-temperature heat pumps requires a common understanding of the technology, its potentials, and its perspectives.

The overall objective of the Annex is to provide an overview of the technological possibilities and applications as well as to develop concepts 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 role of high-temperature heat pump-based process heating for industrial applications. The work was structured in five tasks: Task 1 - Technologies, Task 2 - Integration Concepts, Task 3 - Applications and Transitions, Task 4 - Definition and Testing of Heat Pump Specifications, and Task 5 - Communication.

Task 1 provided an overview of the state of the art and future perspectives. The first part of the report is a technology review covering high-temperature heat pump technologies with supply temperatures above 100 °C that are available in the market or under development. The review was based on a systematic description that includes information on the layout, development status, expected performance, capacity and temperature range, compressor type, working fluid, investment cost, footprint and weight. The reviewed solutions included 34 technologies with a technology readiness level between 4 to 9, specific investment cost between 200 €/kW to 1500 €/kW, capacities between 30 kW to 70 MW and maximum supply temperature between 100 °C and 280 °C. The second part is a review of realized demonstration cases described by sector, application, process integration, technology type, manufacturer, operating experiences. The demonstration review highlighted 15 demonstration cases in various industrial sectors (food, refinery, electronics, chemicals). Lastly, an overview of the high-temperature heat pump industries, markets, application potentials and development perspectives were given on a national basis for 13 countries. The national reviews indicate a generally large application potential with differences on a national and local level depending on the composition of the industrial sector. The work from Task 1 showed that some high-temperature heat pump solutions are already available and implemented. However, it also highlighted the need for further efforts for a transition towards heat pump-based process heat supply. The high-temperature heat pump technology is currently under development and therefore the technology and demonstration cases review database is continuously updated on the Annex 58 homepage always conveying the state of development

Task 2 focused on developing guidelines for the integration of high-temperature heat pumps in the most promising application areas. The first part of the report included a description and analysis of integration concepts for selected industrial processes and heat pump concepts for selected heat pump applications. A standardized template was used for a more structured collection of information about the concepts. The study included 12 industrial processes described by their temperatures, heating and cooling demands, mass flows and production patterns. 27 different integration concepts were identified, and it was found that the optimal integration practices vary depending on the case-specific process requirements, but processes using the same heat pump application share similar process requirements. The second part of the study described technology concepts that can be developed for three heat pump applications: steam generation, hot water/oil production and heating with large temperature glides such as heating air for drying. Information about 15 heat pump concepts was collected using another template and described their functioning principle, layout, refrigerant, compressor type and expected performance. Based on these data material, it was found that processes with similar characteristics typically benefit from the implementation of the same heat pump technologies, allowing for the development of blueprint solution for selecting heat pump concepts for specific applications, thereby reducing developmental efforts. Nonetheless, the prevailing regulatory and economic conditions, such as electricity prices and available subsidy schemes continues to play a crucial role.

In Task 3, instructions for creating decarbonization strategies for industries were developed. The aim of the task was to develop a long-term strategy that includes both technologies available today and in the near future and that takes a holistic view of all the measures that can be implemented. The first part of the development of a decarbonization strategy addressed the definition of overarching goals, the timeline in which the goals must be achieved and the factors influencing targets and timelines. The second aspect is the collection of data about the status of the site in order to develop the decarbonization strategy and the reference scenario for its evaluation. The required data includes cooling and heating demand of the individual processes, medium, temperature and mass flow, existing waste heat flows, and site-specific aspects. Third, Task 3 investigated how to develop and evaluate concept solutions for decarbonization. The report gives an overview of the possible technologies, with a focus on heat pump technology. The possible integration levels for heat pump technologies in industrial processes and the methods for the development of integration concepts were explained. The evaluation criteria for evaluating the solutions were also discussed. The last aspect addressed in the Task 3 report was the development of an implementation roadmap for the transition, which includes a definition of milestones, targets, and required expertise.

Task 4 investigated many aspects important to consider during a large-scale high-temperature heat pump project with the aim of supporting both contractors and end-users in heat pump projects. The main outcomes are three sets of guidelines for defining heat pump specifications, testing and validating heat pump performance in large-scale projects. The first guideline is for the definition of heat pump specifications, in which the parameters, performance metrics, safety, and testing procedures are discussed. The second guideline is for laboratory testing conditions, including recommendations for the type of tests, and methodology for performing tests, assessing deviations and uncertainties, and presenting results. The third guideline for site testing outlines similar recommendations as for the guideline for laboratory testing, in addition to the use of simulation models in combination with site testing. Besides the three guidelines, the task 4 report also includes a review of existing heat pump standards, examples and lessons learned from heat pump projects for process heating and district heating, together with descriptions of the phases from a typical heat pump project from idea to heat production.

Task 5 revolves around the dissemination activities conducted to report valuable information about high-temperature heat pumps. The activities include the reports of Task 1, 2, 3, and 4, workshops and presentations at international conferences, articles, and webinars. The task reports are published on the homepage https://heatpumpingtechnologies.org/annex58/. Several “Deep Dives”, webinars of around 2 hours about selected topics, were organized within Annex 58. Selected speakers were invited, and the “Deep Dives” sessions were open to all interested participants. The topics covered included process integration, application potential for high-temperature heat pumps, heat-driven heat pump technologies, working fluid and cycle optimization, steam generation and mechanical vapor recompression. Finally, the outcomes from the activities of the Annex were disseminated in a final webinar and the webinar slides are published on the homepage.

Looking ahead, the development and deployment of HTHPs are expected to accelerate significantly, driven by technological advancements, increasing industrial demand for sustainable energy solutions, and supportive regulatory environments. Technology developments, end-user adoption, and boundary conditions are mutually dependent with one increasing with the other. By 2030, HTHPs are projected to be a key technology in industrial process heating, with advancements leading to increased efficiencies, reduced costs, and broader industry adoption. Collaboration among technology providers, end-users, policymakers, and R&D organizations will be crucial in overcoming existing barriers and ensuring the successful integration and operation of HTHPs across various industrial sectors. Thus, there is an ever-increasing potential in gathering, coordinating, and disseminating information between the different groups of stakeholders to support increased installations consequently accelerating decarbonization of industry.

Table of Content

1. Introduction

The decarbonization of industrial process heating is a top priority for industries as it accounts for a large share of their greenhouse gas emissions. High-temperature heat pumps (HTHP) are considered a key technology for decarbonizing the industrial process heat supply by increasing system efficiencies and using potentially emission-free electricity. However, the commercial availability of heat pumps with supply temperatures above 100 °C is currently limited.

The European statistics show that 67 % of the process heat demand between 100 °C and 200 °C was directly covered by fossil fuels. From this, a considerable application potential for industrial heat pumps and the associated emission reductions can be derived for that range. High-temperature heat pumps are expected to have the most promising performance in terms of levelized cost of heat in a variety of applications. Extending the range of application to supply temperatures of up to 200 °C would allow high-temperature heat pumps to cover 37 % of the entire process heat demand of European industry.

Therefore, this Annex aims to support the transition towards a heat pump-based supply of process heating by improving the understanding of the technology and providing supporting material.

The objectives of the tasks are the following:

- Task 1: Give an overview of available and close-to-market technologies,
- Task 2: Develop integration concepts for heat pump-based process heat supply
- Task 3: Provide supporting material to facilitate the implementation of these concepts.
- Task 4: Develop guidelines for defining and testing HTHPs specifications
- Task 5: Disseminate the findings to increase the awareness and understanding of various stakeholders, such as manufacturers, consultants, end-users, R&D institutes and policy makers.

This overall objective was reached by carrying out different activities divided into five tasks, as shown in Figure 1.

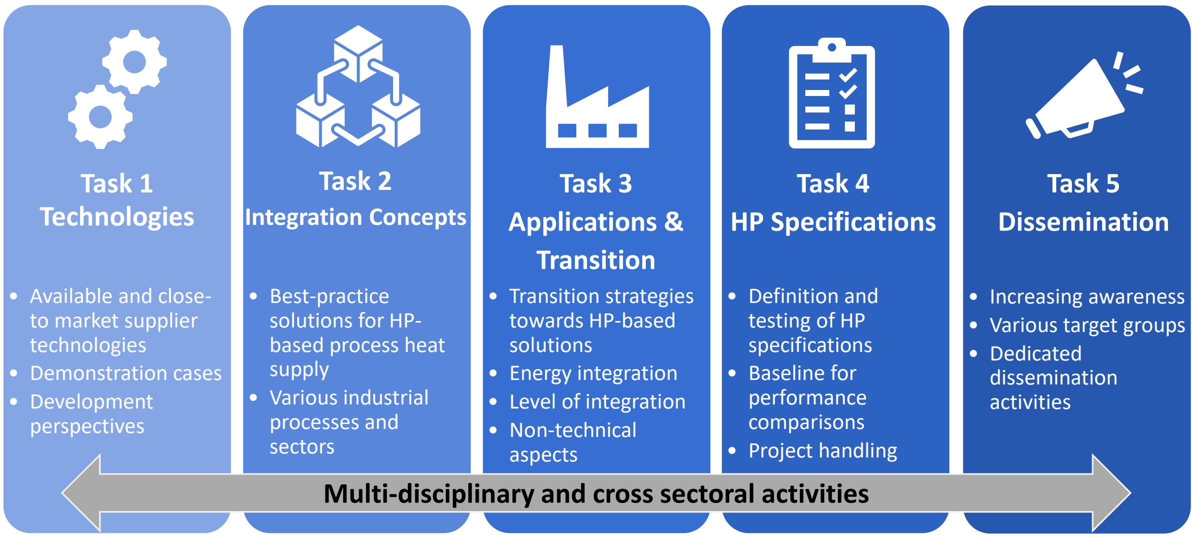


Figure 1: Overview of activities in Annex 58

The tasks required the collection of data on the current high-temperature heat pump market and realized demonstration cases in a standardized format. Both commercial products and research projects were considered. Additionally, the existing standards were reviewed, and guidelines were developed for creating successful decarbonization roadmaps and implementing high-temperature heat pumps efficiently.

In the following chapters, the methods and results are presented in a compact way to provide guidance for the different documents.

2. Task 1 - Technologies

2.1. Introduction

High-temperature heat pumps are a promising alternative to fossil fuels to provide process heating at the highest efficiency using potentially emissions-free electricity. However, the deployment of heat pumps for temperatures above 100 °C is still limited. Enabling a large variety of industries to convert their process heat supply to use high-temperature heat pumps requires a common understanding of the technology, its potential, and its perspectives. The aim of Task 1 is to improve the knowledge about high-temperature heat pumps for industrial applications by providing reviews of technologies available and under development, realized demonstrations, and ongoing and future developments on a national and global level.

2.2. Procedure

The first part of the study aimed to give an overview of the technologies currently available in the market and under development. Information about relevant technologies was collected in a standardized two-page template which was filled out by HTHP technology suppliers. These technology descriptions included a general technology description, project examples and key information about performance, capacity range, maximum delivery temperature, working fluid, compressor type, specific investment cost, technical readiness level (TRL), expected lifetime, size, and footprint.

In addition to this information, realized demonstration cases have also been collected and analyzed. The collection of information has been conducted by similar two-page demonstration case descriptions, including information about the application case and the technology (compressor type, manufacturer, installation year, operating hours, working fluid, performance in design point, investment costs, energy savings, estimated CO_2 savings).

Finally, an overview of HTHPs industries, markets, application potentials, and development perspectives were given on a national basis for most of the participating countries. This information was used to give an outlook on the HTHP technology development from a global perspective.

2.3. Results

The task 1 provided an overview of high-temperature heat pumps, including a glossary of key terms and important definitions to create a common vocabulary. Working principles, important technologies, working fluids, components, and promising applications are presented to understand their characteristics and advantages. Further, it will be outlined how these systems can help to reduce energy consumption, lower greenhouse gas emissions, and enhance the sustainability of various sectors.

The information about technologies and demonstration cases was collected by various participants in the standardized format. This resulted in the collection of 34 technology descriptions and 15 descriptions of realized demonstration cases. The filled-out templates of two of the demonstration cases in shown Figure 2, including pictures, process diagrams, and information about performance.

Figure 2: Examples of two-page brochures of the technology and demonstration cases reviews.

The technology overview showed that there is a wide range of different technologies for HTHP from the various suppliers, and that the suppliers indicate a very varying TRL and costs, which depend on the given application and size of the heat pump. The heat pumps were primarily from European and Japanese manufacturers. The TRL varied from 4 to 9, including everything from laboratory validated tests to actual systems proven in operational environment. The specific investment cost was between 200 €/kW to 1200 €/kW, and the thermal capacities between 30 kW and 100 MW. The indicated maximum supply temperature varied between 100 °C and 280 °C. Figure 3 show the maximum supply temperature of the HTHP technologies as a function of thermal capacity which indicated a weak, but positive correlation between the two. Figure 4 show the COP as a function of temperature lift which revealed a strong correlation for lower indicated COP at higher mean temperature lifts with large variations depending on the technology design.

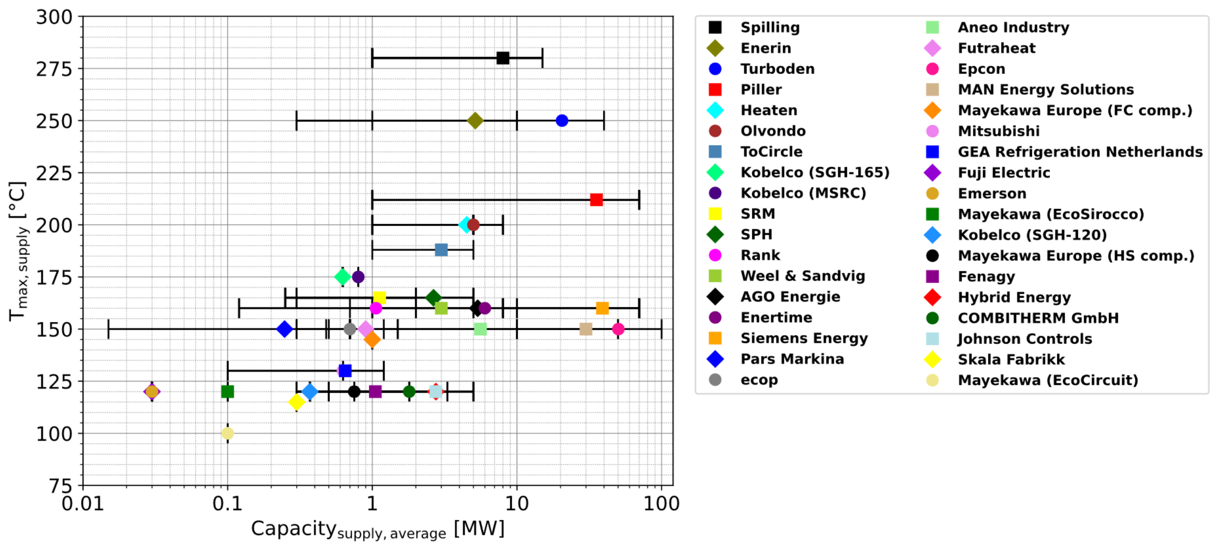


Figure 3: Maximum supply temperature as a function of capacity.

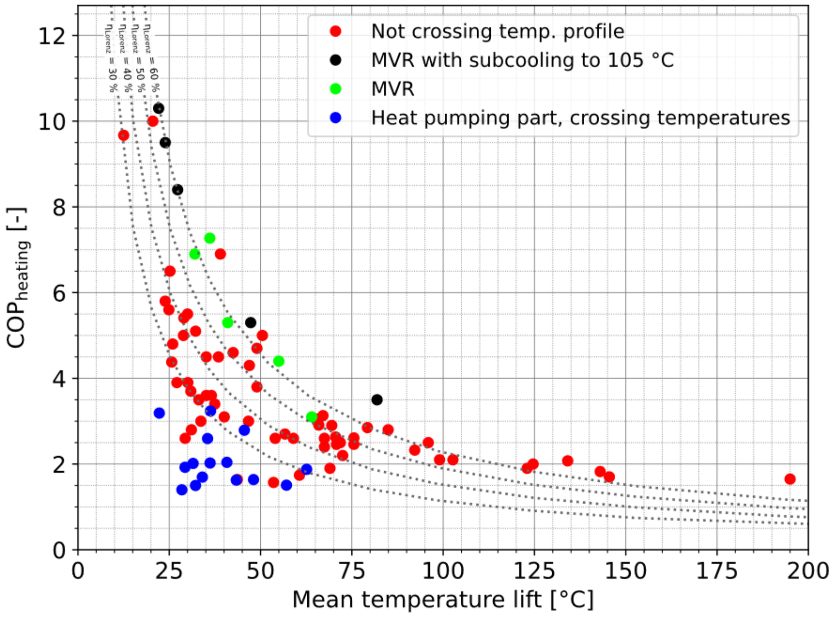


Figure 4: COP as a function of temperature lift.

Moreover, a review of 15 realized demonstrations of high-temperature heat pumps in various sectors is provided. The identified demonstrations were installed in various sectors as presented in Figure 5. The case studies were from sectors such as food and beverage, refinery, and the chemical sector.

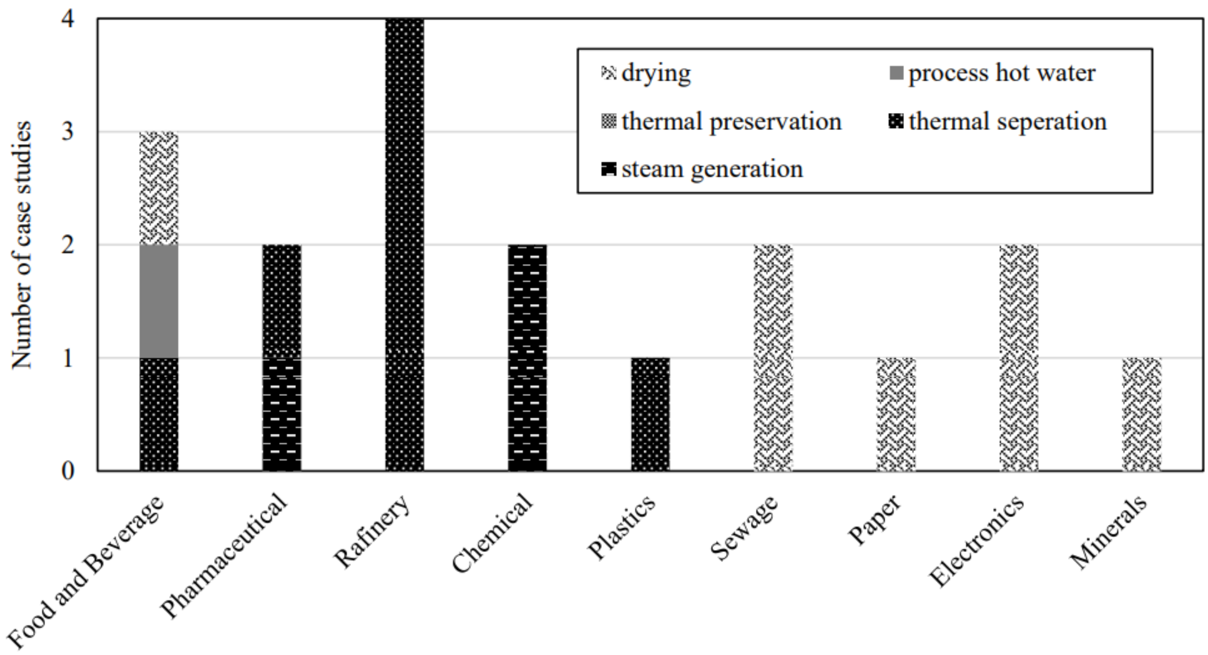


Figure 5: Number of case studies by industries and application processes.

The technologies were mainly based on closed vapor compression cycles, steam compression, and heat transformers. The supply temperatures were between 115 °C and 240 °C where the latter was achieved by mechanical vapor recompression. The range of mean temperature lifts that was reached with the HTHPs varied from 26 K up to 145 K. These examples underline the applicability to a variety of processes and the benefits of heat pumps in real applications.

The heat pump industry, market and application potentials, together with development perspectives were described on a national level for 13 countries: Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Japan, Netherlands, South Corea, and Switzerland. The national reviews indicate that the market potential is generally large, even though there are differences on national and local levels depending on the composition of the industrial sectors.

Finally, the overview of the global development perspectives of high-temperature heat pumps was derived from the national descriptions. Analyzing the description collectively showed that some heat pump solutions are already established and implemented, especially at supply temperature up to 100 °C. Europe and Japan are the forerunners with respect to technology development, with well-established industries for industrial heat pumps, which is being extended to high-temperature heat pumps. Japan showed multiple high-temperature heat pumps with high TRL but are only available on a national level. The maturity of the technology generally decreases with higher supply temperatures, as depicted in Figure 6). It is expected that high-temperature heat pump technologies will become commercially available on a global level and implemented from 2024 to 2025 for supply at up to 120 °C. This development is expected to continue from 2025 for temperatures up to 160 °C, and from 2026 for even higher supply temperatures.

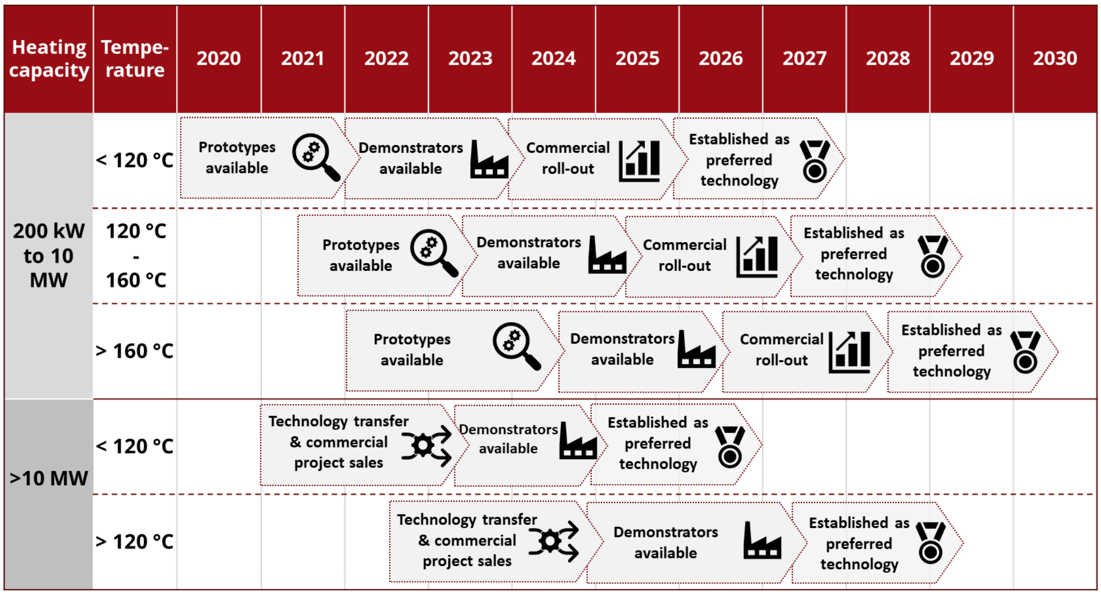


Figure 6: Development perspectives for HTHPs towards 2030.

The factors that influence the transition are the technological development, the ability of end-users to convert the heat supply of their processes, and the regulatory and economic constraints. Therefore, considerable effort is needed to alleviate these barriers to accelerate the transition towards electrified industrial process heating and achieve decarbonizing of the sector.

2.4. Conclusion

The work on Annex 58 Task 1 comprised of a report including a comprehensive review of HTHP technologies, including development perspectives for the market in 13 countries. The terminology and the basic working principles of high-temperature heat pumps was defined, and an overview of high-temperature heat pump technologies with supply temperatures above 100 °C was presented, considering market ready technologies as well as technologies under development.

The review shows that several high-temperature heat pump solutions are available and applied to a variety of processes up to 240 °C, but more effort is needed for transitioning to a heat pump-based process heat supply. The development status of the technology varies depending on temperatures thermal capacity, but also on achievable efficiencies, the cost of the technology and the geographical availability of a sales, service and maintenance network. It is expected that high-temperature heat pump technologies will become commercially available on a global level and implemented from 2024 to 2025 for supply at up to 120 °C. This development is expected to continue from 2025 for temperatures up to 160 °C, and from 2026 for even higher supply temperatures.

An overview is given of the HTHP industries, the markets and application potentials, the development perspectives of the technologies and selected R&D projects. The national reviews indicate a large technical application potential, with geographical variations in terms of market potential and motivations. For the European market, both electrification and energy efficiency are driving factors, while energy efficiency is the dominating factor for markets such as North America. Europe and Japan are the forerunners with respect to technology development, with well-established industries for industrial heat pumps, which is being extended to high-temperature heat pumps.

The report, the suppliers and demonstration case descriptions are available on the home page of Annex 58 (https://heatpumpingtechnologies.org/annex58/task1/). High-temperature heat pump technology is continuously being developed and therefore the database on the Annex 58 home page is regularly updated with new technology and demonstration reviews.

3. Task 2 – Integration Concept

3.1. Introduction

A wide range of HTHP solutions (as presented in Task 1) are available, that can be applied to a variety of industrial processes with diverse requirements. This makes it challenging to define generally applicable integration guidelines and concepts. Therefore, Task 2 of the IEA HPT Annex 58 project aimed to determine best practices for integrating HTHPs into the most promising application areas, improving understanding of the potential of the technology. This contribution summarizes the procedure used to describe and classify HTHP integration solutions and the main findings.

3.2. Procedure

Firstly, industrial systems or processes with heating demands and supply temperatures above 100 °C have been selected and described based on their characteristics, such as heating and cooling demands, temperatures, and production patterns. A system is defined as a combination of various processes, typically at the level of an entire production process. Relevant systems that can be considered include various types of dairies, slaughterhouses, breweries, pharmaceutical production sites, and industrial symbioses. Figure 7 provides an overview of the terminology and its application.

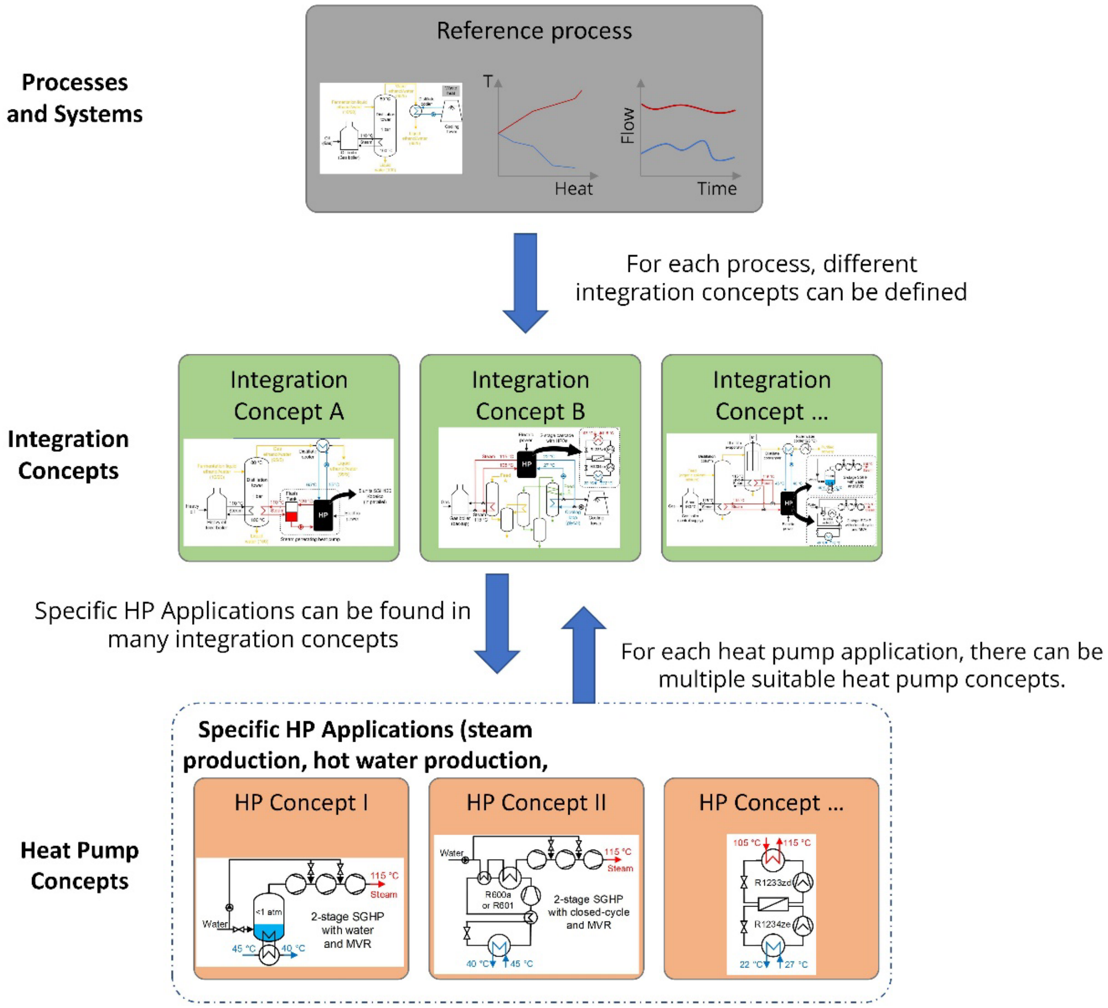


Figure 7: Overview of the terminology related to Task 2 of IEA HPT Annex 58

Based on this information, integration points for HTHPs are identified. Graphical representations of the process requirements using the graphical tools of Pinch Analysis, such as the Grand Composite Curve, support proper identification. An integration concept describes solutions for process integration, including the supply, conversion, distribution, storage and recovery of heating and cooling. The concepts are defined by a system layout, including the heat transfer media, the heat exchanger network, and other devices, such as storage and heat pumps. The heat pump systems are considered as black box units, while the boundary conditions, such as temperatures and capacities, define the specifications for each heat pump application.

The second part of the study identified typical HTHP applications described by the direct boundary conditions, such as the temperature profiles, capacities, and media of source and sink. Examples of HTHP applications can be steam production, hot water production, applications with large temperature glides, and others. Depending on the integration concept, a heat pump application can occur in various processes and systems.

Various heat pump concepts can be developed for each of these heat pump applications. For example, there are different heat pump concepts for producing steam through steam compression, including open cycles, closed cycles, and cascade systems. A heat pump concept consists of one or more cycles and is defined by its main functioning principle, system layout, refrigerant, compressor types, and expected performance.

The descriptions of the concepts were structured using two templates: one for the development of integration concepts, processes, or systems and another for the development of heat pump concepts for selected heat pump applications.

3.3. Results

The report shows that HTHPs can be integrated into various industrial processes. However, the best practices for system layout and conditions vary depending on the case. To find the optimal integration concept for each process, it is crucial to understand the process requirements. It may be necessary to examine industrial sector profiles, applications, temperature conditions, energy, and Pinch Analysis. Pinch Analysis provides a graphical representation for accurately targeting integration points.

It was found that unit operations share similar process requirements. Therefore, heat pump concepts can be standardized to meet these requirements and can be assigned to the three basic applications. These are steam generation, hot water production, and heating with large temperature glides. Figure 8 provides an overview of process types and influencing parameters for characterizing heat sources and heat sinks. It also provides qualitative recommendations on which heat pump concepts from the different heat pump applications are suitable for fulfilling the different process requirements.

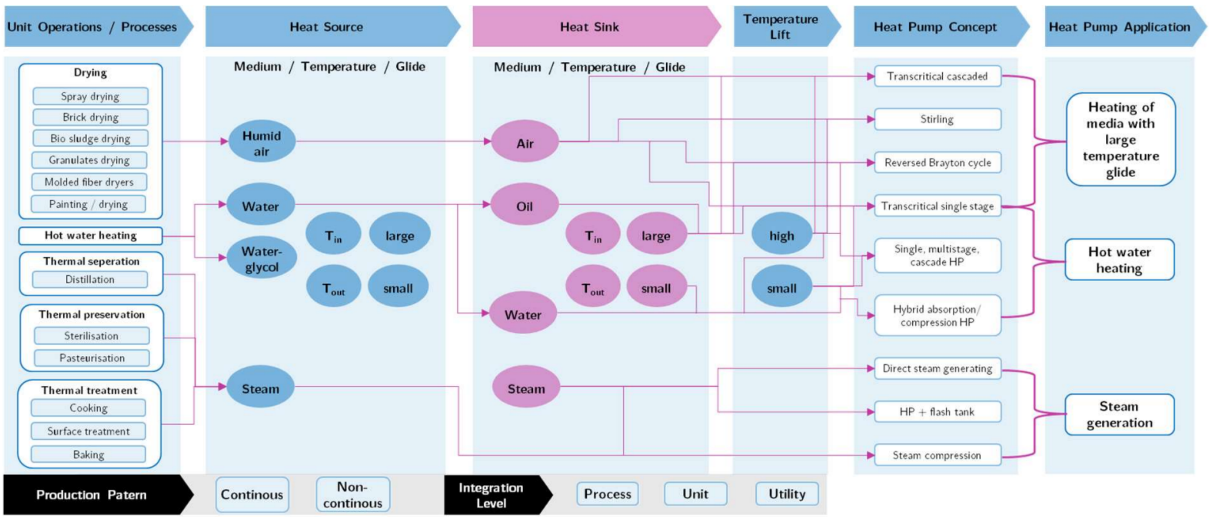


Figure 8: Matching for blueprint integration concepts.

Based on these findings, recommendations were developed for selecting appropriate heat pump concepts for processes within the same unit operation. A comprehensive overview of the application potential was created and presented in Table 2, which included:

- 12 processes, falling under the categories of drying (6), thermal treatment (3), thermal separation (2), and thermal preservation (1)

- 27 integration concepts
- 15 heat pump concepts

Table 2: Overview of integration concepts

	Process			Source				Sink				Temperature ranges [°C]				
		Unit Operation	Production Pattern	Medium	T_{in} [°C]	T_{out} [°C]	ΔT_{Glide} [K]	Medium	T_{in} [°C]	T_{out} [°C]	ΔT_{Glide} [K]	10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250	Mean ΔT_{Lift} [K]	Integration Level	Heat Pump Concept	Heat Pump Application
1.	Baking ovens	Baking	Continuous	Humid air	110	90	20	Air	180	220	40		100	Unit	Transcritical cascaded	Heating along large temperature glides
					90	65	25		150	180	30		88			
2.	Molded fiber dryers	Drying	Continuous	Humid air	150	70	80	Air	150	250	100		90	Process	Reversed Brayton cycle	Heating along large temperature glides
					150	100	50	Steam	150	165	15		33		Single HP	Steam generation
3.	Spray Drying	Drying	Continuous	Humid air	50	20	30	Air	64	210	146		102	Process	Cascaded HP	Heating along large temperature glides
					70	15	55		15	210	195		70		Transcritical cascaded	
					50	23	27		64	210	146		101		Reversed Brayton cycle	
				Water	40	12	28		15	210	195		87		Cascaded HP	
					40	12	28		15	210	195		87		Transcritical cascaded	
					40	12	28		64	210	146		111		Reversed Brayton cycle	
4.	Brick Drying	Drying	Continuous	Air (Water intermediate circuit)	50	- (*)	- (*)	Air (Water intermediate circuit)	- (*)	180	- (*)		- (*)	Unit	Cascaded HP	Heating along large temperature glides
			Continuous		50	- (*)	- (*)		- (*)	90	- (*)		- (*)		Single HP	Heating along large temperature glides
5.	Painting & Drying	Drying	Non-continuous	Humid air	28	22	6	Liquid	130	150	20		115	Unit	Cascaded HP	Heating along large temperature glides
							6		70	90	20		80			
6.	Biosludge drying	Drying	Continuous	Steam	120	100	20	Steam	100	146	46		13	Process	Steam compression	Steam generation
7.	Plastic granules	Drying	Continuous	Humid air	60	30	30	Air	50	80	30		20	Process	Transcritical single stage	Heating along large temperature glides
8.	Batch Sterilization	Thermal preservation	Batch	Water	40	20	20	Water	100	150	50		95	Utility	Trancritical HP	Heating along large temperature glides
					80	52	28	Steam	80	130	50		39		Flash tank + MVR	Steam generation
9.	Distillation	Thermal separation	Continuous	Water	65	60	5	Steam	110	115	5		50	Utility	HP + flash tank	Steam generation
					27	22	5	Steam	105	115	10		86		Cascaded HP	
					45	40	5	Steam	100	115	15		65		SGHP/Flash tank + MVR	
10.	Anodizing	Utility water heating	Non-continuous	Water	60	50	10	Water	82	95	13		34	Unit	Single HP	Hot water production
		Thermal treatment			20	15	5	Steam	110	120	10		98		Cascaded HP	Steam generation
		Utility water heating			40	35	5	Water	80	85	5		45		Single HP	Hot water production
		Thermal treatment			20	15	5	Steam	110	120	10		98		Cascaded HP	Steam generation
11.	Oil and Gas Processing	Thermal separation	Continuous	Oil	70	50	20	Oil	85	105	20		35	Process	Transcritical single stage	Heating along large temperature glides
				Water-glycol	45	35	10		100	140	40		80	Supply	Cascaded HP	Hot water production
12.	Extrusion cooking	Thermal treatment	Continuous	Humid air	50	45	5	Water	100	160	60		83	Process	Transcritical single stage	Hot water production

Applications with large temperature glides: Drying processes frequently involve large temperature glides on the heat sink side. Heat pump concepts can exploit efficiency advantages by closely matching the temperature-load profile of a heat sink, as it can be done by sensible gas cooling in contrast to an isothermal heat transfer during condensation of a subcritical heat pump. In drying processes, the simultaneous occurrence of heat sinks in the form of drying air and heat sources in hot, moist exhaust air is obligatory. High temperature lifts must be overcome depending on the drying air and exhaust air temperature. This can be achieved using cascaded heat pumps or technologies with high temperature lifts, such as the Stirling heat pump. To integrate them into a drying process with large temperature glides, heat pump concepts such as transcritical cycles, stirling heat pumps or reversed Brayton cycles can be applied.

Steam production: Integration concepts for processes within the unit operations thermal separation, preservation, and treatment primarily rely on steam as an energy carrier medium due to its efficient heat transfer properties and existing and smaller-sized heat exchanger equipment. Steam is also used as a reactant when in direct contact with the product, such as in pasteurization with steam injection. Another possible application is drying with superheated steam, which is frequently done in the textile, food, or paper industry. Typical heat sources are cooling loads, waste heat streams, or vapors that can be recompressed. The following concepts can be applied depending on the required steam pressure and temperature:

- Direct steam-generating compression heat pumps using hydrocarbons or hydrofluoroolefins.
- Heat pump for hot water production using a flash tank for steam generation.
- Direct steam generating heat pump in combination with downstream steam compressor.
- Steam compression in combination with an evaporator for steam generation.

Hot water production: Heat supply with hot water is used in several applications and industries, such as process heating utility, e.g., in the pharmaceutical and food industries. Typical supply temperatures range from 90 °C to 140 °C, with a corresponding pressure that ensures the water is in liquid form. In addition, applications based on other liquid energy carriers, such as thermal oil, are also described in this context. The heat source for the heat pump can be excess heat from the process, resulting in a reduced cooling system load or another internal or external heat source. There are various potential heat pump concepts for hot water production with promising thermodynamic and economic performances for various applications. The obtainable performance, and thereby the competitiveness of each concept, depends on the specific boundary conditions, such as the temperature profile of the heat source and the heat sink:

- Single-stage, multi-stage and cascade heat pump cycle using hydrocarbons or hydrofluoroolefins.
- Transcritical single-stage cycle with gas bypass, ejector or expander using R-744
- Hybrid absorption compression heat pump using R-717/R-718 (ammonia/water)

Moreover, for heat pump integration, a storage device can be included both on the sink and on the source side of the heat pump. This is especially important if the demand does not coincide with the availability of the waste heat source.

3.4. Conclusion

Standardized templates allow for a structured collection and presentation of information. The heat pump concepts aim to raise awareness of their application potential and give inspiration for similar processes and systems. Other heat pump concepts beyond those mentioned are possible. It should also be kept in mind that some of the heat pump concepts mentioned are still under development and are purely demonstrated on a laboratory scale.

The study concludes that HTHPs can be integrated into various processes. However, the best practices for system layout and conditions vary depending on the case. Proper integration of heat pumps requires an understanding of process requirements. Pinch Analysis provides a graphical representation for targeting integration points accurately. To find the optimal integration concept for each process, examining the industrial sector profiles, applications, temperature conditions, energy, and Pinch Analysis may be necessary.

It was found that unit operations share similar process requirements. Therefore, heat pump concepts can be standardized to meet these requirements and assigned to the three basic applications: steam generation, hot water production and heating along large temperature glides.

Based on these findings, sensible heat pump concepts can now be considered for other processes within the same unit operation. A comprehensive overview of application potentials can be created by presenting 12 processes, 27 integration concepts, and 15 heat pump concepts. The final report of IEA HPT Annex 58 Task 2 final report (https://heatpumpingtechnologies.org/annex58/task-2-integration-concepts/) provides more detailed descriptions.

4. Task 3 – Applications and Transition

4.1. Introduction

Efficient decarbonization of an industrial site often requires several measures to be implemented and matched to one another. In order to obtain the most efficient set of measures and implement them as quickly as possible, it is necessary to develop a strategy based on a holistic view. The development of such a strategy is often complex and requires a high degree of knowledge about the processes and boundary conditions at the site as well as possible technologies and the company's objectives. Furthermore, expertise on technologies that will be available in the near future should be included in the strategy development process. As shown in Task 1, several heat pump technologies are already available at different Technology Readiness Level (TRL) that cover a wide range of applications (high temperature range) for industry. It is expected that the range of applications will expand soon and that the TRL of the individual technologies will increase. In many industrial sites, at least one of the measures to be implemented is the use of a heat pump, e.g. to utilize excess heat and provide process heat. Task 3 of the IEA HPT Annex 58 deals with the development of decarbonization strategies in which heat pumps play an important role. More specifically, instructions and information for the development of a decarbonization strategy were prepared. These procedures are intended to support the process of decarbonizing, which often requires the integration of heat pump technology. The procedure and the results are summarized below.

4.2. Procedure

Various topics that should be considered in the development of a decarbonization strategy were discussed and described in Task 3. The content was developed in line with the four main questions:

- How to define a decarbonization goal?
- How to describe the status / reference scenario?
- How to develop and evaluate concept solutions for decarbonized systems?
- How to derive the decarbonization path?

These questions are dealt with in the corresponding task report. Moreover, a guideline was created in which the most important information is presented mainly graphically. The guideline and the task report are intended to support companies in developing a decarbonization strategy. In both documents, the focus is on decarbonizing process heat generation and avoiding scope 1 emissions. The first two questions listed above were considered rather technology independent. Nevertheless, measures to improve efficiency of process heat supply such as heat exchangers and heat pumps were emphasized during the second question. During the third question, heat pump technology is increasingly moving into focus.

The content was developed based on the knowledge and experience of the participants during several meetings and two workshops. The content of both the task report and the guideline, which correspond to the result of this task, are explained in more detail below.

4.3. Results

The development of a decarbonization strategy is not a linear process. It is rather an iterative process in which several loops must be completed before the strategy can be finalized. Furthermore, it is important not only to consider the replacement of fossil fuels, but also to make the system as efficient as possible and thus minimize energy demand.

Under the headline " How to define a decarbonization goal?", the questions " What is important for you?" and "How are goals and targets be defined?" are addressed. At the beginning of the strategy development process, the overarching goal and the timeframe in which it is to be achieved must be defined. Consequently, intermediate targets can be derived, which should be continuously reassessed during the development process. The motivation and the level of ambition play a major role in setting goals and targets as well as corresponding timelines. These can be influenced by both internal and external drivers such as legal requirements or financial benefits.

Clearly defined and well-communicated goals are important in the development of the strategy and its implementation. For example, as a goal setting method, the SMART method is presented. This states that goals should be specific, measurable, achievable, relevant, and timed.

The following questions are dealt with under main question “How to describe the current status / reference scenario?”:

- Which information is needed?
- What do I need in the future?
- How to collect and evaluate the information?
- What needs to be known to assess the feasibility of heat recovery measures?

Collecting information and data is an important and essential part of the strategy development process, but also often a time consuming and difficult task. Information such as the cooling and heating demand of the individual processes, including medium, temperature and mass flow, is required. Furthermore, information on existing waste heat flows is required to be able to consider efficiency-enhancing measures such as direct heat recovery through heat exchangers and heat pumps. This information should be known over a period of time that is characteristic for the relevant process and the related processes so that changes over time can be taken into account when developing measures. The relationships between the processes and the boundary conditions, including also site-specific aspects, also play an essential role. It is important to know the current status in detail while taking known future developments such as an increase in production capacity or equipment to be renewed into account. In addition, it should be evaluated what the processes really need and not just collect information based on the current supply system. Furthermore, the reference scenario for the evaluation of the measures can be defined based on the information.

Possible sources of information, such as production systems or data sheets, are indicated and the fact that the information is up to date is emphasized. It is also mentioned that it must be checked whether information from several different sources is reasonable. Additional measurements, calculations and reasonable assumptions can also be used to close information gaps.

At the end of this part, the information required to be able to evaluate measures such as heat pumps and direct heat recovery with heat exchangers to increase efficiency is given separately. This part is the basis for the development of the concept solutions which are dealt with under the question “How to develop and evaluate concept solutions for decarbonized systems?”.

This question deals with the sub-questions:

- What technologies are available for decarbonization of process heat supply?
- What is the level of integration?
- Can we do better?
- How to get a concept solution?
- Will it pay off?

Decarbonization measures can be summarized in four categories: efficiency increase, electrification, renewable gases, and biomass. The optimal concept solutions are case-specific. The following section focuses on heat pump technology. The level of integration plays a key role for this technology and influences the efficiency of this measure. A distinction can be made here between integration at process, unit, supply and sector level. The closer the integration is to the process, the greater the efficiency can be expected, but the complexity of the integration generally increases at the same time. Moreover, lower flexibility, lower planning horizon and reduced economies of scale must be expected at process level compared to the integration on sector level.

With heat pumps, the temperature lift to be overcome (temperature difference between the sink outlet temperature and the source outlet temperature) has a major influence on efficiency. It is therefore important to investigate what the process really needs and whether the necessary supply temperature can be lowered. This is dealt with in the question "Can we do better?".

To investigate and identify concept solutions possible methods are presented e.g. pinch analysis, physical modelling and mathematical optimization. The integration concepts from Task 2 can also serve as a basis for the development of concept solutions. Once the development of one or more concept solutions has been completed, they must be evaluated. Several evaluation criteria can be considered for this step, and it must therefore be decided which ones are to be applied and to what extent. Different evaluation criteria are listed, both economic criteria such as operating costs and levelized cost of heat as well as non-economic criteria such as space requirement and market availability.

The last main question "How to derive the decarbonization path?" deals with sub-questions "How to define an implementation roadmap?" and "How can a roadmap look like?".

Based on the concept solutions developed, a decarbonization roadmap can be developed to support the implementation process of the decarbonization strategy. When developing a roadmap, sub-projects, milestones and the timeline should be defined. Furthermore, the team must be defined, and it should be clarified whether the internal know-how is sufficient or external know-how is required. Aspects that play a role in the development of such a roadmap, such as TRL or its influence on the production process, are presented. Furthermore, possibilities for risk minimization are indicated such as testing of critical solutions and including of back-up strategies.

At the end, a theoretical example of how a roadmap for the decarbonization of an industrial site could look like is shown (see Figure 9). This industrial site has a hot water and steam requirement that is covered by fossil fuels in the initial state.

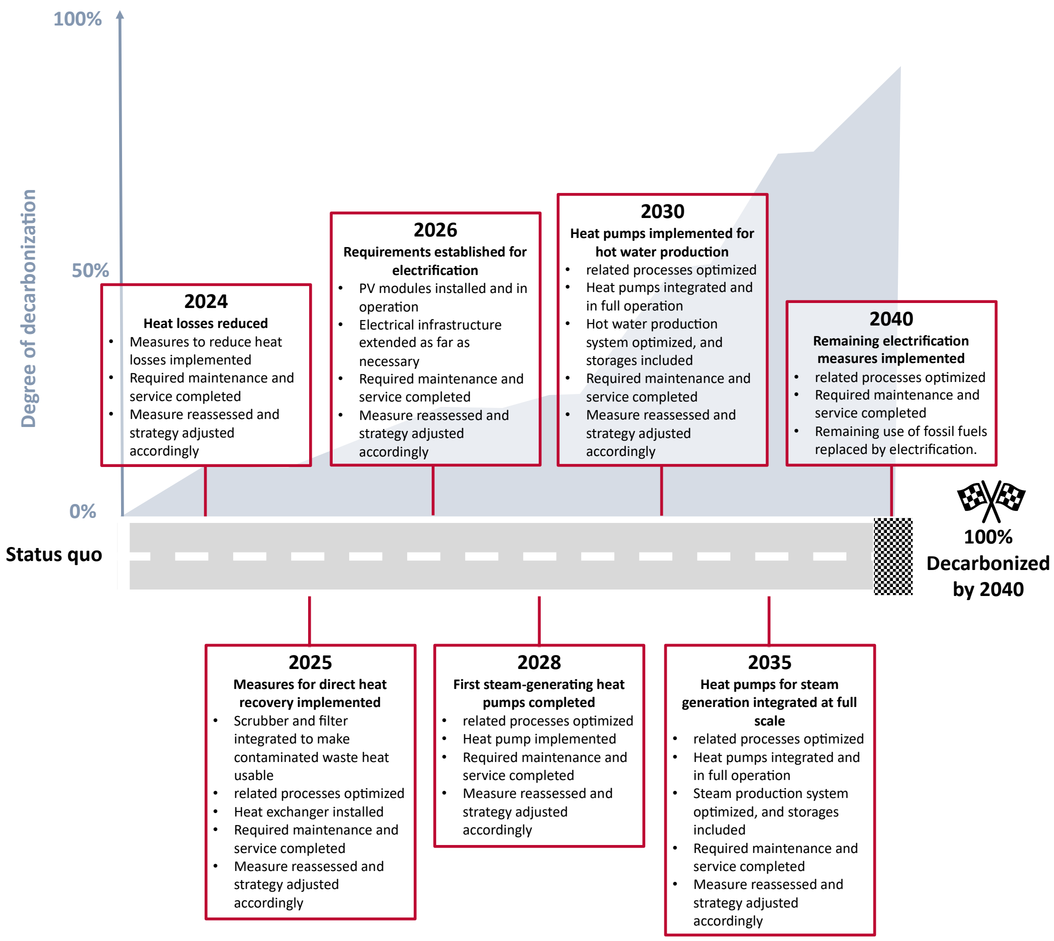


Figure 9: Roadmap example for the decarbonization of an industrial location (Source: AIT Austrian Institute of Technology GmbH)

4.4. Conclusion

Developing a decarbonization strategy is a complex and time-consuming process. This process is explained in more detail on the basis of four main questions. The starting point is the definition of the overarching goal, interim targets, and the timeframe, which is influenced by several drivers. Moreover, the strategy development process requires comprehensive knowledge of the site to be decarbonized. A database that is as complete as possible over a characteristic period must be created. This includes, but is not limited to, the description of process demands, waste heat flows as well as boundary conditions and interconnections between different processes. A good base of data is essential for the development of concept solutions based on the available technologies and those that will be available in the future. The optimal concept solution is case-specific, but many cases are similar in structure. Different methods for the development of concept solutions are available. Various evaluation criteria like economic and environmental factors can play a role in selecting the most suitable concept solution. These must be defined, and their value determined in relation to other criteria. A roadmap can be derived based on the developed solution concepts. The aim is to obtain a roadmap that enables the strategy to be implemented successfully within a realistic timeframe. It is also important that the roadmap is clearly understandable for the involved people and that its meaning and importance is clearly communicated. Developing a decarbonization strategy and a corresponding roadmap is not easy, but it is essential to achieve the most efficient decarbonized site in the shortest possible time.

5. Task 4 – Definition and Testing of Heat Pump Specifications

5.1. Introduction

Most large-scale heat pumps are sold based on a guaranteed COP that is to be obtained in the final application for specified operating conditions. However, there is not a generally acknowledged standard for the specification of the performance requirements and the operating conditions at which these conditions are to be demonstrated. This leads to a variety of specifications from the customer side and to conservative estimations from the contractor side to ensure adherence to costumer expectations. Therefore, task 4 aims to establish guidelines and recommendations for defining heat pump specifications and performance, as well as for testing and validating this performance. This is done to support both contractors and end-users in heat pump projects.

The task 4 report was created in collaboration with a range of Annex 58 participants, which includes research and technology organizations, universities, and consultants. The combined experience of all participants, within testing, project management, and commissioning of large-scale heat pump projects was collected in this work.

5.2. Results

The main results of the report are three guidelines which are summarized in the following sections.

5.2.1. Guideline for Definition of Heat Pump Specifications

To ensure a successful heat pump project, all information that is considered important for the design and operation of the heat pump system needs to be transparent and defined as clearly as possible. In the guideline, certain parameters, performance metrics, safety, and testing procedures to be included in specifications for high temperature large-scale heat pumps are discussed. This discussion of the specifications is meant to primarily serve as inputs for the end-user (owner) of the heat pump for the tender materials and/or for clarification of the heat pump design basis and comparison of the proposed contractor solutions. Clear and precise specifications enable end-users to make informed decisions and facilitate the smooth integration of heat pump systems into various applications and gives contractors clarity about the expectations for the heat pump design. As part of the discussion, it is suggested to use performance maps when clarifying expected performance for the heat pump, as shown in Figure 10.

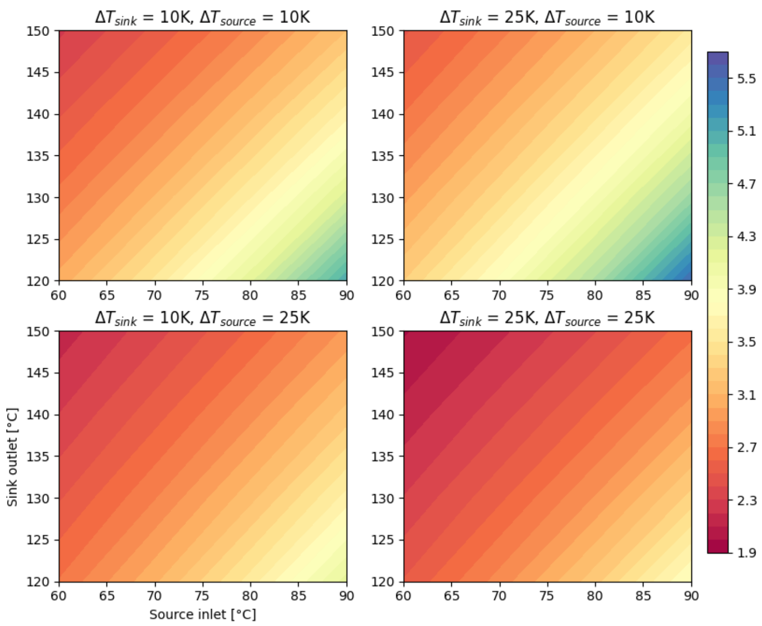
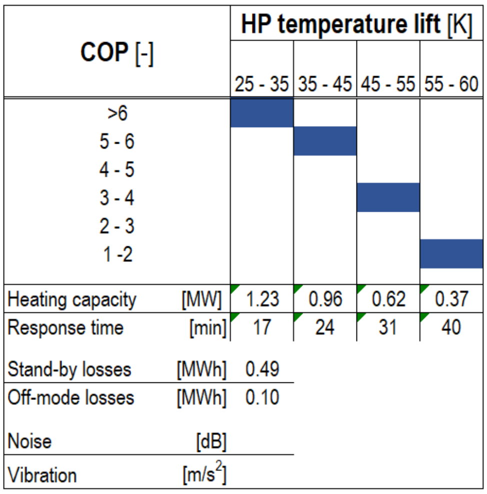


Figure 10: An example of four performance maps for the COP, each valid for their own temperature range and sink- and source temperature glide.

5.2.2. Guideline for laboratory testing conditions

This guideline goes into detail with recommendations for laboratory testing. This includes recommended types of tests, the methodology for performing these tests, recommendations for allowable measurement deviations and uncertainties, and lastly how to present the results. The guideline also presents the available laboratory test facilities among the Annex 58 RTO participants. It is in this guideline suggested to present the test results with labels that summarizes the main results, for example as shown in Figure 11.



COP [-]		HP temperature lift [K]			
		25 - 35	35 - 45	45 - 55	55 - 60
>6					
5 - 6					
4 - 5					
3 - 4					
2 - 3					
1 -2					
Heating capacity	[MW]	1.23	0.96	0.62	0.37
Response time	[min]	17	24	31	40
Stand-by losses	[MWh]	0.49			
Off-mode losses	[MWh]	0.10			
Noise	[dB]				
Vibration	[m/s^2]				

Figure 11: Example of heat pump performance test label.

5.2.3. Guideline for site testing

Similarly, to the guideline for laboratory tests, this guideline outlines the recommended site tests to perform, the method for determining maximum allowable deviations, recommended measurement uncertainties, as well as examples of the effect of measurement uncertainties, see Figure 12 which shows expected variation for the COP with a given uncertainty. Lastly, perspectives about using simulation models together with on-site testing for validating the performance of heat pumps in a wide range are described.

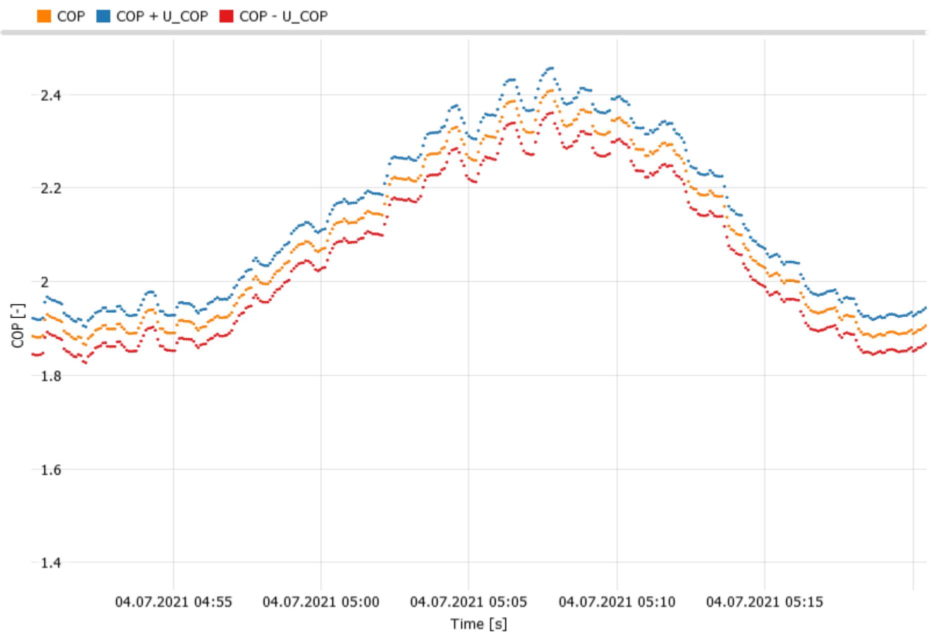


Figure 12: Example of COP derived from measurements and its calculated uncertainty (Source: AIT Austrian Institute of Technology GmbH).

Besides the three guidelines, the task 4 reports also include results about the following:

5.2.4. Heat Pump Standards

The most relevant heat pump standards used today are reviewed. These standards have typically been developed for space heating and air conditioning; meaning that these heat pumps are typically closed cycle compression heat pumps and operate at lower temperatures.

For industrial heat pumps, different temperature levels, cycle layouts, and refrigerants apply. In addition, industrial heat pumps may not be closed cycle reverse Rankine compression heat pumps, but can also be open cycle reverse Rankine, such as MVC or MVR, or be based on closed cycle reverse Brayton, reverse Stirling cycle or joule cycle. Furthermore, industrial heat pumps often have steam as output, requiring dedicated standardized measurement procedures.

In the task 4 report considerations about relevant standards for high temperature heat pumps are made, this includes design and safety considerations, and especially descriptions of test methods and test conditions.

5.2.5. Examples and lessons learned from industrial heat pump projects

A chapter with 5 examples of heat pump projects for process heating and district heating are included to include lessons learned from industrial heat pumps projects. The descriptions are made by the Danish energy consultancy company Viegand & Maagøe. The heat pump cases presented vary between 0.5 MW – 10 MW in capacity, and gives key insight into the tender evaluation, verification procedure, and lessons learned for various industrial heat pump projects. These lessons learned can also directly serve as inputs for guidelines about HTHP projects, for example with focus on how to handle performance variations depending on varying boundary conditions.

5.2.6. Description of typical process for large-scale industrial heat pump projects

Finally, a chapter describing the typical heat pump project phases from idea to heat production, based on conventional industrial heat pumps, is included. These typical processes for a HP project are assumed to also be applicable to HTHP projects. The focus in this chapter is on system design, tendering and testing demands.

5.3. Conclusion

The task 4 report highlights the fact that there are many aspects that are important to consider during a large scale HTHP project. The main result are the three guidelines as described in the report:

- Guideline for definition of heat pump specifications
- Guideline for laboratory testing conditions
- Guideline for site testing

End-users and contractors should collaborate closely to define clear specifications and testing procedures, ensuring that HTHPs are tailored to specific project needs. Early in the project, the tender must accurately describe the conditions that the heat pump will experience, to give the contractors the best chance of creating an accurate offer. However, it is important not to describe the design of the heat pump allowing manufacturers room to offer their best solution. The detailed design must carefully consider all safety, economic, and performance requirements.

Consideration should be given to both laboratory and site testing, with an understanding of the limitations and benefits of each approach. The testing phase must be as transparent as possible, preferably with a clear definition ahead of time of how the HP performance. Simulation models should be leveraged to complement physical testing and provide deeper insights into HTHP performance under varying conditions. This is especially important if the heat pump performance is evaluated at other conditions than the design points.

These guidelines serve to help with the most important aspects of a large-scale heat pump project; specifying the design, performance, and non-functional requirements of the heat pump, testing the heat pump in a laboratory, testing the heat pump on-site, and ensuring that the performance of the heat pump can be validated.

6. Task 5 - Dissemination

Annex 58 collects, develops and communicates valuable information related to high-temperature heat pumps. This chapter provides an overview of the latest communication activities related to the project. The dissemination activities include reports, presentations and workshops at conferences, articles in magazines and online webinars. Most of the dissemination material can be found on the Annex 58 homepage: https://heatpumpingtechnologies.org/annex58/.

6.1. Task Reports

Annex 58 is organized in four main tasks with the technical focus, of which each are documented by a report:

- Task 1 – Technologies
- Task 2 – Integration Concepts
- Task 3 – Applications and Transition
- Task 4 – Definition and Testing of Heat Pump Specifications

6.2. Workshops and selected presentations at international conferences

Annex 58 has contributed to a number of international conferences with workshops and presentations. An overview of selected contributions is given in the following:

- 29.03.2022 – IEA HPT Annex 58 about HTHPs – State of the art review, demonstration cases and development perspectives at the 3rd High-Temperature Heat Pump Symposium in Copenhagen by B. Zühlsdorf, Jonas Lundsted Poulsen & Florian Schlosser

- 26.10.2022 – High-Temperature Heat Pumps for Industrial Applications – New Developments and Products for Supply Temperatures above 100 °C at China Heat Pump Conference 2022

- 25.04.2023 – Annex 58 Workshop at DTI in Aarhus with country presentations including an overview of national HTHP industry, an overview of national HTHP market and perspectives, development perspectives for HTHP technologies and selected RD&D projects by the following countries:
    - Denmark
    - Austria
    - Belgium
    - Canada
    - Finland
    - Germany
    - Japan
    - Netherlands
    - Norway
    - Switzerland

- 15.05.2023 – Workshop about *Decarbonizing process heating with HTHPs – How to exploit the potential?* at the 14th IEA HP Conference in Chicago by B. Zühlsdorf, Steven Lecompte & Jonas Lundsted Poulsen

- 24.08.2023 – Workshop about *Annex 58 – HTHPs for Decarbonization of Industries* at the International Congress of Refrigeration 2023 in Paris by B. Zühlsdorf and C. Arpagaus

6.3. Articles in magazines

The participants of Annex 58 have contributed with a number of articles to the IEA HPT Magazine Vol. 41 No 1/2023 about Industrial Heat Pumps – Opportunities to Unlock their Full Potential.

6.4. Deep Dives

Within Annex 58, a number of Deep Dives on selected topics have been arranged and were typically held as online webinars of 2 h. These Deep Dives involved invited speakers and were open to all interested participants.

The following Deep Dives have been arranged as part of Annex 58:

- **Process Integration** – 16.03.2023
    - “Heat pump integration for decarbonizing industrial energy systems (incl. short introduction to process integration)”, Prof. François Maréchal, EPFL – 30 min incl. questions
    - “Process Integration of High-Temperature Heat Pumps”, Florian Schlosser, University of Paderborn – 20 min incl. questions
    - “The impact of process changes to a heat pump’s performance”, Brendon de Raad, Rotterdam University of Applied Science – 20 min incl. questions
    - “Development integrated analytical simulation technology for heat pumps”, Shunsuke TOYODA, JRCM (The Japan Research and Development Center for Metals) – 20 min incl. questions
    - Open discussion about the applicability of process integration methods and the practical implementation of the results from process integration studies
- **Application potential for high-temperature heat pumps** – 15.12.2022
    - Application potential of industrial heat pumps, Alexandre Gouy & Fabian Voswinkel, IEA
    - The talk will present results from Net Zero by 2050 – A Roadmap for the Global Energy Sector and a The Future of Heat Pumps.
    - Potentials for HTHPs and market analysis, Cordin Arpagaus, OST
    - An estimation of the European industrial heat pump market potential, Simon Spoelstra, TNO
    - The talk will be based on the article An estimation of the European industrial heat pump market potential published in 04/2021 in the Journal for Renewable and Sustainable Energy Reviews.
    - Industry perspectives and growth potentials within industrial heat pumps, Thomas Nowak, EHPA
    - Common discussion with presenters about the application potentials and how they can be exploited
- **Heat-driven heat pump technologies** – 03.11.2022
    - Introduction to heat driven heat pumping technologies – Principles, applications and state of the art, Steven Lecompte, University of Ghent
    - Gas-Solid Reactions for thermochemical energy storage and conversion, Marc Linder, DLR
    - Thermal compression heat pumps, Kashif Nawaz, ORNL
    - Heat transformer technology for high-temperature applications, Wouter Ducheyne, CEO and Co-founder, QPinch
- **Working fluid and cycle optimization** – 29.22.2021
    - Working fluid and cycle optimization – Performance improvement potentials and how to exploit them, Benjamin Zühlsdorf, DTI

  - Heat pumps based on gas cycles – Technologies, working fluids, applications and perspectives, Panagiotis Stathopoulos, DLR
  - Hybrid compression-absorption heat pumps using water & ammonia – State of the art and ongoing developments, Marcel Ahrens, NTNU
  - Working fluids for high-temperature heat pump systems, Alexander Cohr Pachai, Johnson Controls
  - Thermodynamic analysis of potential refrigerants for high temperature heat pump applications, Valerius Venzik, RWTH Aachen University
- **Steam Generation and MVR** – 30.08.2021
  - Analysis of a steam generating high temperature heat pump for industrial waste heat recovery, Sabrina Dusek, AIT
  - Theoretical investigation of HTHP cycles for steam generation, Cordin Arpagaus, OST
  - A steam supply heat pump system, Takenobu Kaida, CRIEPI
  - Overview and developments for steam compression and MVR, Michael Bantle, SINTEF
- **Medium-scale HTHP systems** – 08.07.2021
  - Development of high-temperature heat pumps, Tim Hamacher, SPH Sustainable Process Heat
  - Unlocking low carbon heating in high temperature applications, Star Refrigeration, David Pearson
  - Function, design and possible applications of a Rotation Heat Pump at high temperatures, Andreas Längauer, ECOP
- **Medium- and large-scale HTHP systems** – 19.05.2021
  - Development of large-scale heat pump systems, German Aerospace Center, Panagiotis Stathopoulos
  - MAN ETES System including tests from pilot plant, MAN Energy Systems, Emmanuel Jacquemoud
  - Application-specific designed large-scale heat pump systems, Andrea Barbon, Turboden
  - Multi-stage steam compression systems, Kjetil Evenmo, EPCON
  - High-Temperature Heat Pumps based on hybrid absorption compression principles, Hybrid Energy
  - High-Temperature Heat Pump based on Sterling principle, Olvondo

6.5. Final webinar

After the conclusion of the Annex activities and the finalization of the task reports, the findings were shared in the two-hours webinar “Outcomes on HPT Annex 58 - High Temperature Heat Pumps” that took place on 23.04.2024. The agenda included a presentation of the findings of Task 1, 2, 3, and 4. The webinar was open to everyone and over 230 people participated.

7. Overall conclusions and perspectives

The findings of Annex 58 offer valuable insights into the availability, future development, and challenges of high-temperature heat pumps (HTHP). This work highlights the significant potential of this technology and the necessity for further efforts to develop a broader range of solutions to meet decarbonization targets.

A technology review of 34 commercially available and emerging technologies was conducted across a broad selection of manufacturers, geographies, supply temperatures, and capacities showing a growing, global effort to develop high-temperature heat pumps. Fifteen descriptions of demonstrations across various industrial sectors were collected highlighting successful implementations of high-temperature heat pumps with supply temperatures between 115 °C and 240 °C. Based on the review, it is anticipated that increasingly more high-temperature heat pump technologies will become commercially available with supply temperatures up to 120 °C during 2024, up to 160 °C during 2025, and for even higher temperatures soon after. The database based on the technology review was found to provide valuable information for a variety of stakeholders, and it is expected to become even more important to facilitate the knowledge exchange between solution providers and end-users to support a rapidly growing market.

However, market deployment is influenced not only by technological advancements but also by the ease of integration into existing systems. Twelve in-depth investigations of representative processes were conducted where the integration of high-temperature heat pumps is particularly promising. These include processes such as baking, drying, and distillation which are responsible for a large portion of industrial energy use. It was observed that processes with similar characteristics typically benefit from the implementation of the same heat pump technologies, allowing for the development of blueprint solution for selecting heat pump concepts for specific applications, thereby reducing developmental efforts. Nonetheless, the prevailing regulatory and economic conditions, such as electricity prices and available subsidy schemes continues to play a crucial role.

Key aspects of large-scale heat pump projects, from procurement to testing, were analyzed. The typical process for such projects was described, existing standards reviewed, and guidelines developed for defining heat pump specifications and testing both in the laboratory and on-site. These guidelines serve to help with the most important aspects of a large-scale heat pump project; specifying the design, performance, and non-functional requirements of the heat pump, testing the heat pump in a laboratory, testing the heat pump on-site, and ensuring that the performance of the heat pump can be validated.

Furthermore, guidelines were provided for developing strategies to decarbonize process heating. Key elements of creating an effective strategy involve defining overarching goals, establishing a realistic timeline, gathering data, and assessing conceptual solutions while being aware of the technologies currentlyt available and in the near future. This process should culminate in a roadmap outlining milestones, targets, required actions and the necessary expertise to reach the overall goal of decarbonization.

Looking ahead, the development and deployment of HTHPs are expected to accelerate significantly, driven by technological advancements, increasing industrial demand for sustainable energy solutions, and supportive regulatory environments. Technology developments, end-user adoption, and boundary conditions are mutually dependent with one increasing with the other. By 2030, HTHPs are projected to be a key technology in industrial process heating, with advancements leading to increased efficiencies, reduced costs, and broader industry adoption. Collaboration among technology providers, end-users, policymakers, and R&D organizations will be crucial in overcoming existing barriers and ensuring the successful integration and operation of HTHPs across various industrial sectors. Thus, there is an increasing potential in gathering, coordinating, and disseminating information about HTHPs between the different groups of stakeholders to support increased installations and consequently accelerating the decarbonization of the industry.

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