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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 58

High-Temperature Heat Pumps

Task 4: Definition and Testing of Heat Pump Specifications

Recommendations for defining and testing of specifications for HTHPs in commercial projects

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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 programme 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 programme 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 programmes 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 in general 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 organised 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.
This report has been produced within HPT Annex 58. Views and findings in this report do not necessarily represent the views or policies of the HPT TCP and 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 policy makers in utilities, government offices and other organisations. 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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Further information about the Annex 58 can be found on the 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 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 national teams can be found on the Annex 58 homepage.

Participants and contributors to task 4 and authors of the report

The report has been prepared as a collaborative effort with contributions from various authors and has been coordinated by DTI. An overview of the contributors and their organization is shown in *Table 0-1*.

Table 0-1 - Overview of author contributors to Task 4 report.

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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 in the following 5 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 – 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).
- Develop strategies for the transition to heat-pump-based process heat supply (Task 3).
- Enhance the information basis 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.

This report documents the work of Task 4: Definition and testing of HP specifications – Recommendations for defining and testing of specifications for high-temperature heat pumps in commercial projects.

Executive Summary

The Annex 58 task 4 outlines guidelines and recommendations for defining heat pump specifications and performance, as well as for testing and validating this performance. The main results of the report are three sets of guidelines which are summarized below:

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 captaincy about the expectations for the heat pump design. As part of the discussion it is suggested to use performance maps.

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.

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. Lastly, a section is included on the use of simulation models in collaboration with on-site testing to expand the range of conditions that are covered.

Beyond the guidelines the report also describes the typical procurement process of a large-scale heat pump project, as well as describing the most relevant standards that currently exist for designing and testing industrial heat pumps, and specifically high temperature heat pumps.

In general, the task 4 report highlights the fact that there are many aspects that are important to consider during a large scale HTHP project. Early in the project, the tender must accurately describe the conditions that the heat pump will experience, to give the contractors the best chances at creating an accurate offer. The detailed design must carefully consider all safety, economic, and performance requirements. Finally, the testing phase must be as transparent as possible, preferably with a clear definition ahead of time of how the HP performance, if measured outside of the design points, is to be compared to the promised performance.

Hence, the developed guidelines can support both contractors and end-users in heat pump projects, as they can help to ensure that HTHPs meet performance requirements and industry standards, as well as promoting confidence in the technology and its adoption in various industrial applications and in the market in general.

Table of Content

1. Introduction and definitions

Most large-scale heat pumps are sold based on a guaranteed Coefficient of Performance (COP) that is to be obtained in the final application for specified operating conditions. However, there is no 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. Therefore, this task aims to establish recommendations for defining heat pump specifications and performance, as well as for testing and validating this performance. This is done to support both contractor and end-user in heat pump projects.

The report is split into 3 main parts to facilitate this discussion.

1) Chapter 2: Description of typical project process for a large-scale HP project. This includes descriptions of the typical processes for tendering, manufacturing, factory- and site acceptance tests (FAT/SAT).

2) Chapter 5: Development of guidelines for the definition of heat pump specifications to support the project management process, with focus on guaranteed performances at design and off-design conditions.

3) Chapter 6: Development of guidelines for testing of large-scale HPs, with a focus on the previously defined specifications.

In addition to this, a review of existing standards relevant for high-temperature heat pumps as well as selected projects examples and lessons learned for relevant industrial cases are included. These are contained in chapters 3 and 4, respectively.

The following terms, definitions, and abbreviations are used throughout this report:

Term	**Explanation**	**Unit**
Heating capacity	This refers the heat transfer rate on the sink side of the heat pump (hot side), typical identical to the thermal power at the condenser.	kW
Cooling capacity	This refers the heat transfer rate on the source side of the heat pump (cold side), typical identical to the thermal power at the evaporator.	kW
Heat pump load capacity	Part load fraction, relative to the nominal load of the heat pump. At full load, the heat pump load capacity is by definition 100 %.	%
Buyer	The entity who purchases the heat pump, and typically also operates the heat pump after hand-over	n/a
Contractor	The entity which manufactures and supplies the heat pump system.	n/a

The following abbreviations are used throughout the report:

Abbreviation	**Explanation**
COP	Coefficient of performance
CV-RMS	Coefficient of variation of root mean square error
DCS	Distributed Control System
EER	Energy efficiency ratio
EV stroke fraction	Expansion valve stroke/opening fraction
FAT	Factory acceptance test
HP	Heat pump
HTHP	High Temperature Heat Pump
HX	heat exchanger
MVC	Mechanical vapor compression
MVR	Mechanical vapor re-compression
PFD	Process flow diagram
RH	Relative humidity
SAT	Site acceptance test
TES	Thermal energy storage

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

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

2.1. Typical process for large scale heat pump projects

A stepwise process of establishing a large-scale industrial heat pump is described below and illustrated in Figure 2-1, representing the timeline from idea through initial feasibility study, permissions from contractor and authorities, tendering, design, implementation, commissioning, handover, and guarantees acceptance. It can be seen how the majority of the hours are used in the end of the project, and that typically 30 % of the hours are used in order to be able to make a CAPEX decision.

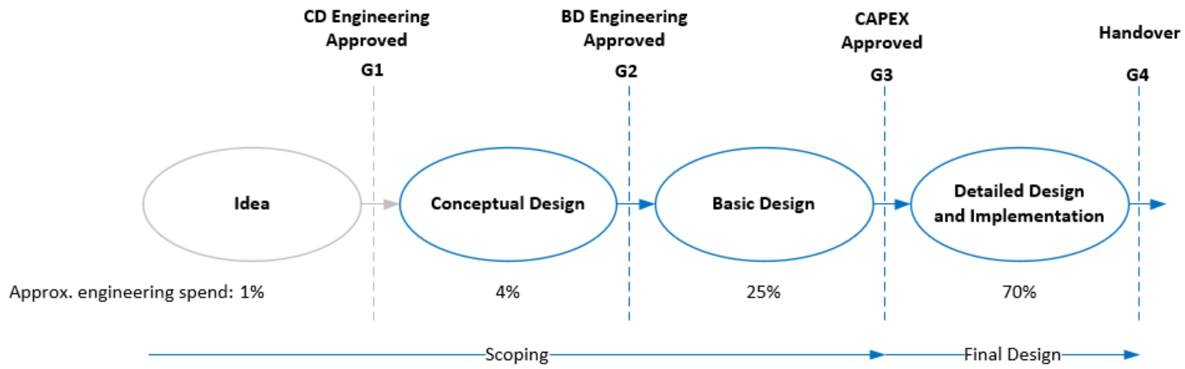

Figure 2-1 - Stages of the process of establishing a heat pump and the corresponding fraction of engineering hours spent.

Idea/conceptual brief (before G1 approval of conceptual design phase)
Based on a brainstorming session, or an otherwise derived idea, a conceptual brief can be made. Here, possibilities for a HTHP will be investigated further. The HTHP system will be either based on fulfilling a new heat demand, or the replacement of an existing heat source that most likely is based on fossil fuels. Based on the specific heat demand, along with prior experience with similar projects and assumptions about the operation of the HTHP, a conceptual brief can be made for a potential project, along with a budget estimate, that can lead to the approval of a Conceptual Design for further investigations. This initial brief will be associated with substantial uncertainty. There will not be any investment decision yet, only a decision for further investigation in this phase.

Conceptual design (before G2 approval of basic design phase)
The conceptual design will normally contain an energy mapping of the energy systems, and based on this, a feasibility study should be made to cover the economic potential of a HTHP project. The physical components of the HTHP system are determined, and a process flow diagram (PFD) is made for a system overview. Details and assumptions will be investigated to narrow down the uncertainties in the project. For the project budget, input from a potential contractor for the primary components is consulted to get a more certain project budget.
A timeline for the project is worked out to get an overview of the duration of the HTHP project. Values of the desired level of performance, COP, running time/up time, service and maintenance intervals, maintenance hours and overall lifetime will be estimated at this project phase.

Different information is needed at different stages. It's a good idea throughout this phase to keep a check list of what information the end-user needs to provide to further investigate the feasibility and business case of the project. A detailed specification of information early in the project helps to identify possible manufacturers and HTHP technologies that can best supply the desired product.

Basic design (before G3 approval of detailed design and implementation phase)

The basic design takes the conceptual design and details and specifies the system further. The components of the HTHP system are calculated and determined in detail for outlining the tender material and budget, and a P&ID of the system is made for the system design. Capacity and design figures are calculated. Quality, COP, time schedule, and uncertainties are defined for tender materials for the project. This work can be done in collaboration with one or more contractors.

The following is a list of key information that is important to the manufacturer to provide insights into suitable technologies and performance estimations for the customer. The most basic information is needed already in the conceptual phase, while the remaining information is needed in the basic design phase:

- Description of source side of heat pump:
    - Media (incl. possible contamination) to be cooled. If necessary, additional specification of the required heat exchanger material.
    - Design inlet temperature and description of occurring fluctuations (maximum and minimum, time profile)
    - Design mass flow and description of occurring fluctuations (maximum and minimum value, time profile)
    - Maximum allowed cooling or required cooling on the source side.
- Description of sink side of the heat pump:
    - Media to be heated
    - Design inlet temperature and occurring fluctuation (maximum and minimum value)
    - Design mass flow and description of occurring fluctuations (maximum and minimum)
    - Description of the desired outlet conditions (for example target temperature, steam pressure, steam temperature)
- List of operating points for which performance data is required for further evaluation. The possible fluctuations that can occur both on the sink side and on the source side should be taken into account.

Additional information on boundary conditions that are necessary for the feasibility of the heat pump integration, or that require additional equipment (e.g. a container for outdoor placement):
- Operating hours (Number of planned start-ups and shut-downs)
- Place of installation and environmental conditions
- Maximum allowed noise emissions
- Information on the electrical connection (e.g.: maximum available electrical connection power)

Additional general information:
- Rough time schedule of the heat pump project
- Standards and directives to be complied with
- Information about the automation system

List of the information provided by the manufacturer to start the next project phase, for example:
- Description of heat pump system (refrigerant, heat pump cycle, etc.).
- Performance data for specified operating points (incl. sound emissions).
- Allowed operating range of the heat pump
- Main dimensions and weight
- Maintenance recommendations
- List with requirements for the source and sink side
- List of included equipment
- Price
- Delivery time

Tender material for HTHP
Tender material is typical prepared and written in the end of the basic design period, based on the work, studies and analyses made during this phase.
When the Basic Design is approved at G3, the final decisions and choices are taken here. That will typically give the last details for the tender material, and the tender will normally be finished and send out as the first, when G3 is approved and the Detail Design period start.

Detailed design and implementation phase (before G4 approval of handover)
When the CAPEX and budget is approved at G3, the tendering work can be completed, and the tender sent out to potential contractors for HTHP system, and the detailed design and implementation phase can begin. It here needs to carefully be considered what is “need to have” and what is “nice to have”. Reconsider “nice to have” does it give any value to the project or the final OPEX? Contractor should not require more functions than they need or will need from HTHP in the future. All extra requirements that are not needed, will cost extra maybe without any benefits.

The construction of the heat pump system typically follows the EN-378 standard, for instance about safety, construction, documentation, pressure/tightness testing, operation, and repair requirements. HTHP must fulfil legislation and requirements from authorities. Any extra safety requirements must be examined probably for its necessity because any extra safety requirement will also cost extra. Future developed HTHPs could deviate from conventional heat pumps and can demand new sections in EN-378 or a whole new standard.

The project plan is normally made in detail by the supplier, based on an overall time schedule from the tender material.

A part of this phase is to determine any potential requirements for FAT and SAT. A FAT can give some certainties for the delivery but comes with an added cost, that in the end the buyer needs to pay for. The FAT/SAT testing can refer to various performance tables, for instance regarding:

- Max. heat output
- COP in normal operating load
- Part load operation E.g., 40 % - 100 % capacity, and COP change in the tested points of the range

Regarding long term performance degradation there is limited references about long-term experiences with conventional HP performance and degradation. The present known experience regarding long term performance and degradation are:

- When a HP is commissioned and runs constantly, the present experience is that a HP runs with an almost constant performance and capacity with only small deviations from the commissioned performance and output, as long as the HP have all mandatory service during its operating lifetime.

- The most common reason for a HP-system degrade over time, is when heat exchangers on the HP-system are fouling. This type of degradation is sometimes possible to reverse by cleaning the heat exchanger plates. This cleaning can be implemented in the operation/service cycles so the efficiency of the HP-system can be maintained.

Before handover (G4) the testing must be according to the operating specifications in the tender requirements.

2.2. Tender specification and evaluation
In this section different aspects about the tender process are further outlined.

A subject tender is one possibility when making a tender specification. This normally requires more design work for the required tender material, and it can give unintentional limitations to the contractors bid solutions and component selection. The tender for the HTHP could also be a functional tender that opens the possibilities to gather different options for the component selection to fulfil a given task, e.g., to deliver a desired heat amount at an output temperature of 100 °C - 200 °C.

For a HTHP tender it is important to have a sufficient and well-defined heat source for the HTHP system. The exact border between what must be included in the tender and what remains the responsibility of the buyer of the HTHP, must be clearly defined in the tender material. This applies both to physical borders (identifiable on P&ID) and non-physical interfaces (internal process flow and functionality of the complete system). Even without detailed dimensions already prepared in e.g. a functional tender, the process requires in-depth technical knowledge to be able to evaluate the various proposals and compare the value of each of them.

It is important that the HTHP requirements are clarified, and finally determined in the tender material. Any change in and/or added demands/requirements to the tender materials, after sending out tender to bidders, will give the bidder worries about the project scope and requirements, and will often give higher uncertainties and in the end higher price.

Typical evaluation criteria for HP proposals consists of:
- CAPEX
- OPEX
- Performance (output, COP, Running time/up time)
- Service and maintenance (expected interval and price)
- Reservations and disclaimers (e.g. fixed time schedule)
- Contractor references for previous heat pumps/HTHP deliveries
- Availability (e.g. 720 hours test, that will also give a long-term COP)
- Project quality and execution plan

COP is normally a figure that are required in the tender material which are to be specified in the offer. This is used for evaluating offers from suppliers, and it is later used as a test requirement, that must be in accordance with the offers from the contractor. Typically, the tender requires a COP for e.g. at 100 % and 50 % HP load, and for two different and feasible temperature load cases. That is to ensure that there are given COPs in the offer, that can be used to verify the COP on the HP at SAT, because it is not always given that it is possible to make the SAT on a specific wanted load case that are given as the designing HP load.

The tender may be made flexible in terms of the exact heating/cooling capacity, since a proposed configuration could give significant financial and/or efficacy benefits by deviating slightly from the initially expected capacity due to the combination and number of compressor units, evaporators etc. The tender may for example have identified the option of installing extra capacity with a little extra cost to match a suitable combination of compressor units and evaporator units for a given case. With this approach the variety of potential components and units increases. In turn, the period for running-in and commissioning can be more time consuming than a tender with a predefined detailed design.

An example of the weighting ranges between the different economic criteria in the evaluation of the tender are shown below. Typically, it’s seen that the CAPEX cost has the highest weight:
- CAPEX (40 % - 60 %)
- OPEX (5 % - 15 %)
- COP (5 % - 15 %)
- Delivery time (0 % - 5%)

The indirect economical factors for an evaluation can for examples be weighted as the following:
- General quality (5 % - 15 %)
- HP supplier experience (0 % - 5 %)
- References and team (0 % - 5 %)
- Offered Service options (0 % - 5 %)

Penalties and compensation fines are typically part of the tender. This can deter contractors for bidding on the HTHP-tender and give the contractor a small number of bids to select from in the end. The fines are typically based on:
- COP being too low
- Can’t deliver the full heat output specified in tender
- Running time without service are not met

To encourage contractors to give a bid on a tender, bonuses can be helpful. Examples of results that can result in a bonus:
- Higher COP
- Higher heating output

Bonuses in the tender can make it more attractive for contractors to make a bid, and it can drive the contractors to do better than the minimum requirements described in the tender.

2.3. Warranty

Large heat pump systems are typically supplied by system contractors, that buy the heat pump machine from a heat pump supplier. This gives the heat pump system supplier the possibility for providing the HP system buyer the warranty originally given from the HP supplier.

If the HP system buyer requires a longer warranty period from the HP system supplier, the HP system supplier must take the risk, that is associated with the longer warranty period gives. And this will normally raise the price of the HP.

Typical warranty period on HP and HP system suppliers are 1-2 years. For some of the supporting parts to the heat pump system, such as pipe work and software an extended period is sometime seen.

2.4. Requirements for testing of heat pumps during heat pump projects

In this section the typical requirements for the FAT and SAT are described further.

2.4.1. FAT (Factory Acceptance Test)

Typical FAT requirements are stated as:

For mechanical, electrical and DCS equipment the Contractor shall prepare, organize, execute, and document Factory Acceptance Tests (FAT) in the presence of subcontractors and other contractors. For the Electrical and DCS FAT, the FAT test procedure shall be approved by the Buyer. Basis for procedures is described in "IEC 62381 Automation systems in the process industry – Factory Acceptance test (FAT), site acceptance test (SAT) and site integration test (SIT)".

Before the above-mentioned tests, the Contractor must also perform (according to EN 378-2:2016 and the included sub-standards):

1. *Strength pressure test*
2. *Tightness test*
3. *Functional test of safety devices for limiting the pressure*
4. *Conformity test of the complete installation*

The Buyer reserves the right to participate in any FAT tests carried out before shipping of components/machines. The Buyer shall be informed about the relevant tests and dates in the Inspection and Test plan.

If a FAT is found relevant and required by the Buyer, typical FAT requirements are given in an *"Appendix – Heat Pump Performance Table",* this will normally be the same requirements as there will be for the later SAT, see next section.

2.4.2. SAT (Site Acceptance Test)

Typical SAT requirements can for example include text in the following form:

In general, all parts of a system must be tested under conditions corresponding to the nominal ones indicated in "Appendix – Heat Pump Performance Table". Testing includes functional tests of operating and safety automation, capacity tests, sound measurements, and leak tests.

The Contractor submits a plan for testing the heat pump at least a month before the test and the Buyer's operating staff is informed of the schedule and invited to participate in all tests. All transmitters, signals and alarm limits that can be tested during standstill are tested before start-up. Then operating equipment is commissioned, compressors are tested for rotation, signals, monitoring, and alarms.

When all tests have been completed and documented with satisfactory results, commissioning and balancing begins. At least 14 days before commissioning, the contractor submits a timetable for commissioning and balancing. The Employers operating staff are invited to participate in commissioning and balancing.

Before the start of commissioning and balancing, all building materials, tools, and temporary installations must have been removed and the installation must be cleaned so that the access and escape routes of *the installation can be used safely without danger to installations and people.*

The trial operation is performed after Cold commissioning and SAT and shall be performed with a duration of e.g. 720 hours. The HTHP system are inspected min. once a week by contractor and irregularities are noted and corrected.

"Appendix – Heat Pump Performance Table", must be based carefully on what is the buyer's individual needs to the given HTHP.

3. Standards

This chapter introduces the most relevant heat pump standards used today. 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, since steam power is not fully characterized by flow and temperature, but requires the steam quality as well.

The design, construction and testing of a heat pump falls under a wide range of relevant standards. A high temperature heat pump can include both electrical systems, pressurized systems, pipes, welds, flammable substances, high temperature surfaces, lubricated surfaces and joints, etc. All of these fields are governed to some extent by standards, that are not necessarily specific to heat pumps. This section will focus mostly on the existing standards that in some way describe heat pump-specific considerations that are relevant for high temperature heat pumps, such as design and safety considerations, and especially descriptions of test methods and test conditions.

3.1. Relevant standards in Europe

To give an understanding of the extent to which the design and construction of heat pumps is governed by European standards, Table 3-1 summarises a list of relevant standards.

Local standards shall be applied if the requirements of the local standards are stricter than those of the relevant standards specified below. The standards used shall always be the most recent versions.

Table 3-1 - Overview of heat pump related standards.

Standard	Description
	General electric components
CE marking	An EU CE marking (modules as well as inverter) is mandatory. This refers only to compliance with the Low Voltage Directive, nothing about efficiency and no testing
EMC Directive	An EU directive
EN 50160	Voltage characteristics of electricity supplied by public electricity networks
EN 60038	CENELEC standard voltages
EN 60076	Power transformers
EN 60364	Electrical Installations for Buildings
EN 60364-5-52	Low voltage electrical installations – Part 5-52: Selection and erection of electrical equipment – wiring systems
EN 60529	Degrees of protection provided by enclosures (IP code)
EN 60664-1	Insulation coordination for equipment within low voltage systems – Part 1: Principles, requirements and tests
EN 61000	Electromagnetic compatibility (EMC)
	IEC TR 61000-3-6 EMC limits. Limitation of emissions of harmonic currents for equipment connected to medium and high voltage power supply systems.
	IEC TR 61000-3-7 EMC-limits. Limitation of voltage fluctuations and flicker for equipment connected to medium and high voltage power supply systems.
	IEC 61000-3-11 Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤ 75 A and subject to conditional connection.
	IEC 61000-3-12 Electromagnetic compatibility (EMC) – Part 3-12: Limits – Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current >16 A and ≤ 75 A per phase.

Standard	Description
	IEC/TR 61000-3-13 Electromagnetic compatibility (EMC): Limits – Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems.
	IEC/TR 61000-3-14 Electromagnetic compatibility (EMC): Assessment of emission limits for harmonics, interharmonics, voltage fluctuations and unbalance for the connection of disturbing installations to LV power systems.
	IEC 6100-4-15 Electromagnetic compatibility (EMC) – Part 4-15: Testing and measurement techniques – Flickermeter – Functional and design specifications
	IEC 61000-6-2 Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity for industrial environments
	IEC 61000-6-4 Electromagnetic compatibility (EMC) – Part 6-4: Generic standards – Emission standard for industrial environments
EN 61439	EN 61439-1 Low-voltage switchgear and control gear assemblies – Part 1: General rules
	EN 61439-2 Low-voltage switchgear and control gear assemblies – Part 2: Power switchgear and control gear assemblies
EN 62271-200	High-voltage switchgear and control gear – Part 200: AC metal-enclosed switchgear and control gear for rated voltages above 1 kV and up to and including 52 kV
EN/TR 61850-90-7	Object Models for power converters in distributed energy resources (DER) systems
Low Voltage Directive (LVD) (2014/35/EU)	EU directive.
Cables and connectors	
EN 62275	Cable management system – cables ties for electrical installation
EN 62852	Connectors for DC-application in photovoltaic systems - Safety requirements and tests
Piping, mounting system, and mechanical loads	
ASCE 7-05	Minimum Design Loads for Buildings
DIN 1055	Actions on structures
EN 1090	Execution of steel structures and aluminium structures
EN 1993	Design of steel structures
2006/42/EU	Machinery directive
2014/68/EU	PED (Pressure Equipment Directive)
EN 13136: 2013 + A1:2018	Refrigerating systems and heat pumps - Pressure relief devices and their associated piping - Methods for calculation
EN ISO 10113:2020	Metallic materials. Sheet and strip. Determination of plastic strain ratio
EN 13480	Metallic Industrial Piping
EN ISO 5817:2014	Welding — Fusion-welded joints in steel, nickel, titanium, and their alloys (beam welding excluded) — Quality levels for imperfections
EN/ISO 12241	Thermal insulation for building equipment and industrial installations. Calculation rules
Testing, system design and measurements	
EN 378-2	Refrigeration systems and heat pumps – Safety and environmental requirements – Part 2: Design Construction, testing, marking, and documentation
EN 12900	Refrigerant compressors ‐ Rating conditions, tolerances and presentation of manufacturer's performance data
EN 14511	Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors
EN 14825	Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance
EN 13771	Compressors and condensing units for refrigeration – Performance testing and test methods
ISO 916	Refrigerating units using positive displacement compressor, condensing units and evaporator-condenser

Standard	Description
Fire prevention, electrical protection, and safety	
EN 13501-1	"Fire classification of construction products and building elements"
2014/34/EU	ATEX directive
EN 60754-1+2	Test on gases evolved during combustion of materials from cables – Part 1 and 2
EN 61034-1+2	Measurement of smoke density of cables burning under defined conditions – Part 1 and 2
EN 61557	Electrical safety in low voltage distribution systems up to 1 000 VAC. and 1 500 VDC. - Equipment for testing, measuring, or monitoring of protective measures - Part 1: General requirements
EN 61557-1	Electrical safety in low voltage distribution systems up to 1000 V AC. and 1500 V DC. – Equipment for testing, measuring, or monitoring of protective measures – Part 1: General requirements
EN 62305-1 to 3	EN 62305-1 Protection against lightning
EN 378-3	Refrigeration systems and heat pumps – Safety and environmental requirements – Part 3: Installation site and personal safety

3.2. Evaluation of existing standards for characterization of performance for high temperature heat pumps

In this section the most relevant EN and ISO standards for characterization of the performance and design in relation to high temperature heat pumps are discussed. These are estimated to be:

- EN 14511
- EN 14825
- EN 13771
- EN 12900
- EN 378
- ISO 916

EN 378: Refrigeration systems and heat pumps - Safety and environmental requirements

This standard focuses on safety hazards, safety requirements, component requirements and safety testing, personal protection, operation and maintenance. The standard specifies the different hazard classes such as mechanical hazards (cuts), electric hazards (shock), thermal hazards (burns), substance related hazards (inhalation, explosion) and environmental hazards (pollution, lack of oxygen). It describes norms that the manufacturing of the components must comply with, as well as tightness testing, materials requirements and pressure and fatigue testing. Furthermore, design should include safety issues related to unusual conditions such as high transport temperatures, persons climbing the equipment, external fire, as well as conditions that can result in excessive internal pressure. Furthermore, safety devices, access devices and controls should be designed in a way that prevents damage in case of human mistakes.

The general approach in this standard is directly applicable to industrial heat pumps as well. In industrial heat pumps, conditions will frequently be more severe, and pressures, temperatures and volumes will often be higher, but this is largely covered by the standard, which also includes procedures for conditions >200 °C in the pressure testing description.

EN 14511: Air conditioners, liquid chilling packages and heat pumps for space heating and cooling and process chillers, with electrically driven compressors

The most extensive and most relevant existing standard for heat pump testing is EN 14511. This standard describes the performance testing procedure for heat pumps and air conditioners (AC) for space heating and cooling. However, since it is specific for AC and space heating, the temperature range is a lot lower than what is relevant for HTHPs. The procedures are, however, sound and can be expanded upon for HTHP specific applications.

This standard specifies the performance testing procedure for electrically driven heat pumps and air conditioners under stable conditions, using either an air or liquid flow as heat transfer medium for either the source or the sink.

Part 2 specifies the test conditions, specifying ambient temperatures and source temperature and humidity ranges, as well as sink temperature and humidity. Because of the focus on space heating and tap water heating, the heating mode sink temperatures are in the range of 20 °C (LT space heating) to 65 °C (HT tap water heating). For the cooling mode, sink temperatures are specified in the range of 7-18 °C. Obviously, for industrial heat pumps, other temperature levels must be specified, which are related to the process conditions under which these heat pumps have to run.

Part 3 specifies the test methods. In particular, corrections are specified for thermal power and electric power, related to the fan performance and lab conditions. Also, other effects influencing the performance measurements are mentioned, such as pressure drop by orifices. Conditions should be measured under steady-state, typically over 35-60 minutes. A listing of Key Performance Indicators (KPIs) is also specified, such as electrical power, thermal power and COP, in heating mode, and cooling mode, and for the electricity also in standby mode and off-mode.

Part 4 specifies requirements to be specified by the manufacturer, such as the range of operation, type of oil, filling of refrigerant etc., as well as other instructions for the installer. Also, start-up performance should be tested, related to e.g. restart after power blackout, and noise level and startup current should meet the corresponding norms.

Whereas part of the standards clearly applies for HTHP, other aspects have to be modified. The most obvious one is the temperature ranges specified for the testing, max. at 65 °C on sink side for water-water testing. Furthermore, aspects like start-up current or noise production are completely different in an industrial environment as compared to domestic application.

EN 14825: Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance
This standard is somewhat similar to the previous EN 14511 but specifies the performance testing procedure for electrically driven heat pumps and air conditioners under part load and means to characterize seasonal performance characteristics. The performance is measured under part load ratios. Furthermore, calculation methods for the seasonal Energy Efficiency Ratio (EER) and COP are presented.

EN 13771: Compressors and condensing units for refrigeration – Performance testing and test methods
This focuses on testing of compressors and condenser units. A condenser unit is defined as the combination of a compressor, a condenser/gas cooler, along with other required components – so essentially a heat pump, but with focus solely on the sink side. The standard provides test methods for testing compressors and condensers, for determining condenser capacity, compressor power, refrigerant mass flow, isentropic efficiency and COP. It also describes the maximum allowable deviation of test conditions during the testing, and the maximum allowable measurement uncertainty.

Part 1 specifies testing of compressors and part 2 specifies testing of condenser units. Neither standard specifies specific temperatures that the tests must occur under, they only specify different test methods, and the allowable measurement uncertainties. The standard can thus also be relevant for HTHPs.

EN 12900: Refrigerant compressors – Rating conditions, tolerances and presentation of manufacturer's performance data
This standard describes the testing conditions and test condition tolerances for refrigerant compressors. The conditions described in the standard are partially temperature independent, as it depends on the inlet condition, which for applications not described as 'Household and similar refrigerators/freezers' can be specified as a superheating temperature, instead of an absolute temperature. This standard could thus be relevant for testing of compressors intended for HTHPs.

ISO 916 Part 2: Refrigerating units using a positive-displacement compressor, condensing units and evaporator-compressor
This standard describes test methods for determining the capacity of heat pumps with positive displacement compressors. The standard provides descriptions of test methods of which two must be performed preferably simultaneously. The test results of the different test methods are then compared, and the mean value is taken as the final result. The test is invalidated if the test method results deviate more than a certain percentage from each other. The standard also provides maximum allowable deviations

of the test parameters. The standard is not specific to a certain temperature range, and can also be relevant for HTHPs.

3.3. Relevant standards in Japan

Table 3-2 lists existing standards that would be relevant for high-temperature heat pumps in Japan. JIS is an abbreviation for Japan Industrial Standards, which is a national standard for industrial activities in Japan and is published through the Japanese Standards Association (JSA). In contrast, JRA is an industry standard of the Japan Refrigeration and Air Conditioning Industry Association (JRAIA). There are no specific standards directly for high-temperature heat pumps. Both JIS B 8613 and JIS B 8621 focus on space heating and cooling application, and JRA 4060 is for hot water supply applications. JIS B 8222 is a standard for boilers, not heat pumps. However, the boiler standard would serve as a reference for steam supply heat pumps.

Table 3-2 - Existing standards for heat pumps and boilers in Japan.

Standard	Scope	Application
Water chilling units JIS B 8613: 2019	• This standard specifies water chilling units that consist of refrigeration cycles with electric-driven positive displacement compressors, evaporators, and condensers to cool or heat water. • This standard applies to items used for air conditioning, and does not apply to items used for drinking, industrial use.	Space heating
Centrifugal water chillers JIS B 8621: 2019	• This standard specifies centrifugal chillers for cooling or heating water, which consist of refrigeration cycles with centrifugal compressors, electric motor for driving the compressors, evaporators, condensers. • This standard specifies chillers whose cooling capacity or heating capacity according to the standard rating is 150 kW or higher. • This standard applies to chillers that use practical refrigerants with the saturated vapor pressure of 3 MPa or less at a temperature of 35 °C. • This standard does not apply to items used for drinking purposes.	Space heating
Commercial heat pump water heaters JRA 4060: 2018	• This standard specifies water heaters designed and manufactured for use in hot water supply systems for sanitary purposes such as washing, bathing, and cleaning in commercial buildings. • This standard specifies electric-driven heat pumps using carbon dioxide (CO_2) or hydrofluorocarbons (HFCs) as the refrigerant. • Commercial heat pump water heater usually consists of a heat pump unit, a hot water storage tank, and their auxiliary equipment.	Hot water supply
Heat balance of land boilers JIS B 8222: 2023	• This standard specifies general heat account methods for the testing of land boilers using solid, liquid and gaseous fuels between delivery parties. • Land boilers mean stationary boilers, excluding boilers installed on ships, locomotives, etc.	Steam or hot water production

Table 3-3 shows the list of performance test conditions of water-to-water heat pumps in the existing standards. The heat source inlet temperature is specified at 15 °C or 12 °C. This is because the heat source is assumed to be geothermal heat, river heat, or chilled water. The use of waste heat as the heat source is not assumed. On the other hand, the heat sink outlet temperature is specified at 45 °C for space heating or 65 °C for hot water supply. It is not intended for application to industrial heating processes.

Table 3-3 - Performance test conditions of water-to-water heat pumps in existing standards in Japan.

Standard	Application	Heat source inlet	Heat source outlet	Heat sink inlet	Heat sink outlet
JIS B 8613	Space heating	15 °C	7 °C	40 °C	45 °C
JIS B 8621	Space heating	12 °C	7 °C	40 °C	45 °C
JRA 4060	Hot water storage	15 °C	Not specified	24 °C	65 °C
JRA 4060	Hot water storage	15 °C	Not specified	17 °C	65 °C
JRA 4060	Hot water storage	15 °C	Not specified	9 °C	65 °C
JRA 4060	Hot water storage	15 °C	Not specified	5 °C	65 °C
JRA 4060	Heat retaining	15 °C	Not specified	60 °C	Not speci-fied

Table 3-4 shows the measurement methods for physical quantities related to steam production in JIS B 8222. In this standard, produced steam flow rate shall be calculated based on measured feed water flow rate. The tolerance of the measurement of the feed water must be ±1.0 %.

Table 3-4 - Measurement methods for physical quantities related to steam production specified in JIS B 8222.

Physical quantity	Measurement method
Feed water flow rate	• This flow rate is measured with flow meter such as weight tank type, capacity tank type, volumetric type, or differential pressure type. • Tolerance of the measurement is ±1.0 %.
Produced steam flow rate	• This flow rate is calculated based on feed water flow rate. • Even if a steam flow meter is installed, its measured value is used for reference.
Produced steam pressure	• The pressure of saturated steam is measured at the boiler shell or its equivalent part. • The pressure of superheated steam and reheated steam is measured at the location where their temperature is measured.
Quality of steam	• The quality of steam is measured at a location close to the boiler shell outlet or at a location equivalent to it. • Detailed measurements described in an appendix.
Blow water flow rate	• This flow rate is measured by installing a flow meter after the blow water cooler. • If not measured using a flow meter, calculate using the method shown in the standard.

Finally, some comments are introduced toward the future establishment of performance test methods for high-temperature heat pumps:

- For hot water supply heat pumps, the test methods described in the existing standards can be used to test the heating capacity and calculate the COP. However, the existing standards focus on space heating or hot water supply in the building sector, and therefore do not cover the wide range of temperature conditions of various heating processes in industrial sector.
- For hot air supply heat pumps, there are no descriptions how to measure air flow rate in the existing standards. It would be necessary to determine a method for measuring the flow rate of hot air.
- For steam supply heat pumps, existing standards for boilers are also helpful. In the existing standard for boilers, steam flow rate is calculated based on the measured value of feed water flow rate. However, some steam supply heat pump systems, especially when installing steam compressors with water injection on the top of the system, have a larger steam supply flow rate than the feed water flow rate. Direct measurement of steam flow rate would also be an option to test the heating capacity.

For performance indications:

- There are various temperature conditions for industrial heat pumps. Therefore, it would be preferable to indicate a performance map within the operable range of each heat pump without specifying specific temperature conditions.
- It would be better for end-users to have some standard for indicating the performance of MVR systems.

4. Examples and lessons learned from industrial heat pump projects

This chapter outlines 5 examples of heat pump projects for process heating and district heating, which the Danish energy consultancy company Viegand & Maagøe has been part of. 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 examples with focus on how to handle performance variations depending on varying boundary conditions.

4.1. Case 1: Surplus heat from distillation process to district heating

Case 1 involves a project where surplus heat from distillation processes was utilized for producing district heat for the local district heating company.

4.1.1. Introduction to the case 1

The heat was recovered at a temperature of 75°C and the district heating required a temperature between 75 °C and 85 °C. The system was constructed with a hot water loop with a cooler and a stratified buffer tank to balance both the cooling and heating demands. The district heating water was heated in two steps. The first step by direct heat exchange from the water loop and then indirectly, also from the water loop, by two heat pumps.

By having this setup, the "system efficiency COP" was in the range of 60 due to high share of direct heat exchange. The COP for only the heat pump part was in the range of 8-10. The high COP is due to the high source temperature and thus the relatively small temperature lift.

The heat pumps were installed in 2018 and the design conditions are summarized in Table 4-1.

Table 4-1 - The design conditions of the heat pump.

Sink max. out temp. [°C]	Sink avg. out temp. [°C]	Sink in temp. [°C]	Heat power [kW]	Source in temp. [°C]	Source out temp. [°C]	COP
85	85 - 75 (winter-summer)	70	3,000	75	60	9.5 ("direct", winter-summer)

4.1.2. Tender evaluation

The tenders in this project were evaluated on the following criteria:

- Budget
- COP
- References
- Service and maintenance
- Lifetime

4.1.3. Description of how tests were planned (FAT/SAT)

Below are examples of two paragraphs from the tender document. Both the FAT and SAT tests were to be performed based on the same set of requirements that were stated in the tender document.

<u>Examples from the tender document:</u>

1. **FAT**
   A FAT must be carried out for both heat pumps. This test must at least demonstrate the requirements specified in the tender document, i.e.:
   - Cooling and heating performance at 100 %, 75 %, 50 %, and 25 % capacity
   - COP factor at 100 %, 75 %, 50 %, and 25 % capacity
   - Motor efficiency at 100 %, 75 %, 50 %, and 25 % capacity
   - Frequency converter efficiency at 100 %, 75 %, 50 %, and 25 % capacity
   - How the compressor starts and how it regulates up to 100 % capacity and then down to minimum again.
   - Measurement of starting and full load current

- Measurement of vibrations for the entire machine in its entire control range
- Measurement of flow and temperatures in/out of process cooling water, evaporator
- Measurement of flow and temperatures in/out of remote cooling water, condenser
- Measurement of suction and condensation pressure

The test must be documented in a report.
The heat pumps must not be sent to the construction site before this FAT report has been approved.

2. **General requirements for control**
   A FAT is carried out on the control side of the heat pump system, as well as components.
   The test must be attended by the client or his supervisor.
   During the FAT, it must be proven:
   - How the heat pump regulates up and down, with increasing and decreasing loads.
   - That the machine and electrical panels comply with specifications and have been executed correctly.

4.1.4. Description of test results

The FAT test was performed at an independent institute, that had the capacity required for testing the two heat pumps. The test centre could only test one heat pump at a time, hence the full serial setup was not tested. Each individual heat pump was then tested with the conditions for the serial setup, representing the setup on site.

The test was successful conducted, and the test report was approved.

The test was overseen by representatives from the client (future owner), the consultant, the heat pump contractor and the test centre performing the test.

4.1.5. Description of how test results and deviations have been handled

There were however some problems during the FAT with keeping up the high load during the test period. This was handled by making a comment in the FAT report stating that an additional test must be performed during the SAT test.

Due to a lack of capacity on the FAT site, the actually serial setup of the heat pump set up was not made during the FAT, but the heat pumps were tested individually simulating the serial setup. Due to the lack of the test capacity, it was noted in the test reports that the serial test setup must receive special attention during the SAT.

During the SAT test problems related to the oil system occurred and these problems needed to be solved on site during operation.

4.1.6. Warranty in case 1

On the heat pump there was given a 1-year warranty on defects.

4.1.7. Lessons learned from case 1

It is hard to say whether the FAT test was “overkill” or not. Because of the positive outcome of this test, one could argue that the test was redundant, but if the test has shown severe problems, then the test would have paid off. Due to the maturity of the heat pump technology compared to 6 years ago, a FAT test could most likely be excluded today for this type of heat pump. But if the heat pump were to operate under special conditions, the test could be advisable.

It is hard to tell if the issues with oil seen during SAT could have been detected during a FAT test. If the problems were to be detected, then the duration of the FAT test had to be significantly longer, which would have increased the cost related to the test. If this should have been prevented, the client/consultant should have studied all the different weaknesses of the possible heat pump solutions before asking for an offer. It would not be possible to foresee all potential problems, hence the client/consultant has to rely on the contractor's experience and guarantees. The client/consultant can setup a penalty scheme that compensates for any unforeseen issues. However, large penalty schemes could also have had the effect that contractors would not have chosen to make an offer on the project.

4.2. Case 2: Surplus heat from data center cooling to district heating

Case 2 is a project where surplus heat from data center cooling was utilized for producing district heat for a local district heating company.

4.2.1. Introduction to the case 2

The heat was recovered at a temperature of 14 °C and the district heating required a temperature between 65 °C and 75 °C. The heat pump system was built on an existing cooling system based on a closed water/glycol system. The existing cooling consisted of free-air cooling or machine cooling. The water/glycol was taken out on the return loop to the HP, and returned before the cooling tower, that worked as backup/safety-cooling. The client didn't want to build HP system on top of the existing machine cooling, as they wanted to keep their existing cooling system in place as a safety precaution.

The HP is a 2-stage HP, both using piston compressors with NH_3 as refrigerant. The heat pumps were installed and commissioned in 2019 and the design conditions are summarized in Table 4-2.

Table 4-2 - The design conditions of the heat pump

Sink max out temp. [°C]	Sink avg. out temp. [°C]	Sink in temp. [°C]	Heat power [kW]	Source in temp. [°C]	Source out temp. [°C]	COP
75	75 - 65	45	1,896	14	9	3.67-3.99

4.2.2. Tender evaluation

Tenders ware evaluated on the following criteria, and with a selection weighting give in %:

- Budget: 50 %
- Options: 5 %
- Quality: 20 %
- COP: 20 %
- References: 5 %

4.2.3. Description of how tests were planned (FAT/SAT)

Both FAT and SAT were planned and described in the HP contract. FAT was carried out before shipment of HP and SAT was carried out after installation and commissioning.

4.2.4. Description of test results

FAT was carried out according to the contract and was done at the HP contractors own test facility, and the FAT result was found OK/over the tender specification.

SAT was carried out with the current load on system. The data center was not fully built according to the given HP spec, so the SAT could not be carried out with full load on HP system. The HP system was accepted according to the SAT made on the actual cooling load possible.

4.2.5. Description of how test results and deviations have been handled

The COP was found over specification, and the cooling load was a little under specification.
Both deviations were inside the contractual dead band, and no contractual penalties were applied.

4.2.6. Warranty in case 2

The delivery in case 2 was based on conditions according to ABT18, that require a bank guaranty at 10 % of the prices for the first year of service, this is reduced to 2 % after the first year of service and will expire after 5 years. This bank guaranty is made to ensure the coverage of any defects and malfunctions on the scope of delivery for the heat pump.

4.2.7. Lessons learned from case 2

District heating should have had a start-up shunt for the HP system, to avoid cold water going into the DH pipe system during start up.

4.3. Case 3: Surplus heat from process cooling to district heating

Case 3 involves a project where surplus heat from process cooling was utilized for producing district heat to the local district heating company.

4.3.1. Introduction to the case 3

The heat was recovered at a temperature of 25 °C and the district heating required a temperature between 73 °C and 85 °C.

The system was constructed on the existing cooling water system, that originally was cooled by an open cooling tower. This open cooling tower system was directly connected to the HP system. The relative high temperature lift (25 °C – 85 °C) was done with two stage NH_3 HP systems, and the system was built up with two units of HPs with two stages of compression.

Water was taken out before the cooling tower to the HP and lead back over the cooling tower to ensure the cooling of the water. The heat pumps were installed in 2019. The design conditions are summarized in Table 4-3.

Table 4-3 – The design conditions of the heat pump.

Sink max. out temp. [°C]	Sink avg. out temp. [°C]	Sink in temp. [°C]	Heat power [kW]	Source in temp. [°C]	Source out temp. [°C]	COP
85	73.5	49	3,587	25	18	3.88

4.3.2. Description of how tests were planned (FAT/SAT)

Both FAT and SAT were planned and described in the HP contract.

4.3.3. Description of test results

FAT was carried out before shipment of HP at the HP contractor. FAT was carried out during the Corona pandemic and verified in online meetings.

SAT was carried out after the installation and commissioning. Results from the SAT was on the limit of the tender specification. This was because of fouling in the heat exchanger to the HP system. The fouling originated from the open cooling tower, that collects dirt in the air, which accumulates as fouling in the heat exchanger.

The water loop was equipped with a filter to remove the dirt and avoid fouling. But the fouling could not fully be avoided, so the system ended up with negative deviation on COP and cooling capacity.

4.3.4. Description of how test results and deviations have been handled

The COP and cooling capacity were found under specification which were concluded to be due to the fouling in the heat exchanger.

Both deviations were not according to the contract, but due to the fouling from the cooling water, which was stated as clean in the tender, no contractual penalties were applied.

4.3.5. Warranty in case 3

The contract and warranty periods are unknown for this case.

4.3.6. Lessons learned from case 3

Water systems connected to HP system must be clean and must not cause any fouling. An open water system with an open cooling tower cannot be used directly connected to a HP system without fouling issues. A water filter before the HP system is not a guarantee that there will be no fouling.

The issues seen with fouling show it is important to consider this beforehand, both regarding the design of the heat pump system and the verification testing of the heat pump. This issue could be taken into account in the tender material, as this can heavily impact the heat transfer in the heat exchangers, and hence the performance of the heat pump.

4.4. Case 4: Surplus heat from process cooling to process heating

Case 4 involves a project where surplus heat from process cooling was utilized for process heating in a hot water system.

4.4.1. Introduction to the case 4

The heat was recovered at a temperature of 35 °C and delivered to the hot water system at a temperature of 65 °C. The system was constructed with a hot water loop with two buffer tank both to even out the cooling and heating demands.

The heat pump was installed in 2022 and the design conditions are summarized in Table 4-4.

Table 4-4 - The design conditions of the heat pump.

Sink max. out temp. [°C]	Sink avg. out temp. [°C]	Sink in temp. [°C]	Heat power [kW]	Source in temp. [°C]	Source out temp. [°C]	COP
65	65	53 (45, design)	535	35	25	5.32

4.4.2. Tender evaluation

Tenders were evaluated on the following criteria:

- Solution Quality
- Budget
- Items not included which otherwise are included in the tender.
- Reservations and Conditions
- COP – Business Case Assessment

4.4.3. Description of how tests were planned (FAT/SAT)

FAT was not part of the contract but was planned by the HP contractor before shipment from factory. SAT was planned to be done on site after installation and commissioning.

4.4.4. Description of test results

FAT was done by the HP contractor on the SAT specifications. The SAT was carried out and it was found that the HP was delivering inside the tender specification dead band when the system values was adjusted due to deviating operation conditions.

4.4.5. Description of how test results and deviations have been handled

The COP was adjusted due to the higher sink inlet temperature from 45 °C to 53 °C. COP for this point was calculated by HP-contractor during tender phase, and it was agreed that this point was used as guaranty-point in the SAT.

4.4.6. Warranty in case 4

The delivery in case 4 was based on conditions according to AB18 (Danish general conditions for building and construction works and supplies), that require a bank guaranty at 10 % of the prices for the first year of service, this is reduced to 2 % after the first year of service and will expire after 5 years. This bank guaranty is made to ensure the coverage of any defects and malfunctions on the scope of the delivery of the heat pump.

4.4.7. Lessons learned from case 4

Industrial hot water systems, heated by a HP, require a buffer capacity to even out a varying heat consumption to an almost constant heat supply from the HP. In this project the buffer system was well dimensioned, so the system is working well with the varying heat consumers supplied with heat from a HP.

Due to the deviating sink inlet temperature, it is recommended to require COP in different operating points, with different sink in temperatures, during the tender phase. This will give more possibilities to get operating conditions that can fulfil a SAT.

4.5. Case 5: Surplus heat from process cooling to process heating

Case 5 involves a project where surplus heat from process cooling is utilized for process heating in a hot water system.

4.5.1. Introduction to the case 5

The heat was recovered at a temperature of 7.5 °C and delivered to the hot water at a temperature of 90 °C - 93 °C. The system is constructed with a two-stage compressor system in order to overcome the high temperature lift. The design conditions are summarized in Table 4-5.

This project is still ongoing, and the heat pumps are in the ordering phase at this point in time (start of 2024).

Table 4-5 - The design conditions of the heat pump.

Sink max out temp. [°C]	Sink avg. out temp. [°C]	Sink in temp. [°C]	Heat power [kW]	Source in temp. [°C]	Source out temp. [°C]	COP
93	90	50 - 60	10,000	7.5	1	5.7 (on proposed HP)

4.5.2. Tender evaluation

Tenders were evaluated on the following criteria, and with a selection weighting give in %:

- Budget: 50 %
- OPEX: 20 %
- Highest availability: 15 %
- Service and maintenance: 10 %
- Time schedule and project approach: 5 %

4.5.3. Description of how tests were been planned (FAT/SAT)

For this system there will only be SAT of the complete system because the system is built directly on site. The compressors are tested individually from the factory, but not in combination, and at the design loads as a FAT normally would constitute.

4.5.4. Description of test results

When heat pump system is installed and commissioned, the tender states what availability, capacity, and efficiency the heat pump system should be tested according to. The test will be performed over a defined time given in tender.

4.5.5. Description of how test results and deviations have been handled

The HP is not produced yet. This large heat pump system will be built and assembled on site, so it will not be possible to have a FAT.

4.5.6. Warranty in case 5

In case 5 there are specified different warranties points with different warranty periods for the heat pump system:

- The heat pump itself has a 2 year warranty on defects and malfunctions (wear parts however omitted as specified in service documentation).
- Piping work have a 5 year warranty on defects.
- Process function have 6 year warranty
- Software have 5 years warranty

4.5.7. Lessons learned from case 5

One of the heat pump contractors supported the project with the basic design phase, and identified a HP system layout, that was suitable for the tender material. However, in the quote from the same contractor, they offered a different type of HP system.

It is preferable, that the tender material is not made with a pre-determined HP system design, so the bidding companies can work on different system designs, to get most efficient HP system for the upcoming quotes.

5. Guidelines 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 this chapter certain parameters, performance metrics, safety and testing procedures to be included in such 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 captaincy about the expectations for the heat pump design.

5.1. Definition of specifications

Boundary conditions for temperature and humidity for the heat pump:

- Sink inlet temperature: Definition of the inlet temperature of the media to be heated up on the sink side of the heat pump in the entire application area of the heat pump, and in all operating conditions, including expected variations.
- Sink outlet temperature: Definition of the target temperature of the heat sink, after the heat transfer process from the heat pump to the media to be heated up. Needs to be given in the entire application area of the heat pump, and in all operating conditions.
- Source inlet temperature: Definition of the inlet temperature of the media to be cooled down on the source side the heat pump in the entire application area of the heat pump, and in all operating conditions, including expected variations.
- Source outlet temperature: Definition of the maximum temperature decrease in the heat source (if any), after the heat transfer process from the heat pump to the media to be cooled down. Needs to be given in the entire application area of the heat pump, and in all operating conditions.
- Relative humidity: Specification of the target humidity percentage for both the heat sink and heat source sides, in case humidity control is important.
- Ambient temperature in the environment for the location of the heat pump.

Boundary conditions for flow on secondary sides of the heat pump including pressure drop:

- Definition of the flow conditions on both the source and sink side of the heat pump. Including expected variations and availability.
- Definition of the maximum foreseen pressure drop on both the sink and source sides of the heat pump at certain flow rates. E.g. pressure drop ≤ 0.1 bar at a flow rate of 10 m^3/h.
- Media on secondary sides needs to be specified, including expected fouling characteristics and information about composition, e.g. inert gases.

Heat pump performance:

- Heat transfer rate on sink side: Definition of the minimum heat transfer rate on the sink side of the heat pump, typically expressed in megawatt (MW), in the application area of the heat pump.
- COP: Specification of the minimum COP for the heat pump in the application area, including whether the COP calculation includes auxiliary equipment. It is recommended to use performance maps, as discussed in section 5.2.
- Specification of the needed standstill power for the heat pump to assess the system's efficiency over an entire heating period/production campaign.

Availability:

- Availability: Set a minimum required availability percentage for operation with the heat pump over a 30/day period. Consider any factors that may influence availability, such as manufacturer delivery margin, heat source activity, etc.
- In some applications system solutions are highly relevant where there is much focus on availability, redundancy, storage, and flexibility. In some of these cases it might make sense for the end-user to specify a “heat as a service” business model.

Refrigerant type:

- Clear indication of the type of refrigerant used in the heat pump, along with its global warming potential (GWP).

- Assurance for compliance with environmental regulations regarding refrigerants and GWP limits.

Permissible noise & vibration levels:
- Sound power level: Definition of the maximum permissible noise levels produced by the heat pump during operation, expressed in decibels (dB), For example, noise level ≤ 75 dB in all operating conditions.
- Vibration Impact: Consideration of vibration levels that may influence neighbouring buildings and equipment and set acceptable vibration limits for the heat pump. For example, vibration level ≤ 0.5 mm/s.

Compressor type & technology:
- Definition of the type of compressor used in the heat pump (e.g., scroll, reciprocating, screw, centrifugal) and any advanced compressor technology employed.
- In case of suggested multi-stage compression, the different pressure/temperature stages must be clearly defined.
- What is the operating range (max/min allowable temperatures, RPM, etc.)

Operating modes and control features:
- Listing of the available operating modes (e.g., heating, cooling, defrost) and control features, such as thermostatic control, variable-speed control, and smart control capabilities.
- Startup and shutdown times needs to be stated.
- Capacity ramping rates need to be specified.

Test standards and protocols:
- Reference of industry standards and protocols for performance testing, such as these discussed earlier in chapter 3, to ensure accurate and standardized testing procedures.
- FAT testing: A FAT and the operating points to be tested must be careful considered. Is this necessary and/or if this makes sense with the possibilities for testing there is for the contractor. Sometimes the heat pump will be built directly on site making a FAT hard. It can be costly to make facilities to be able to run any efficiency and capacity test with given test points for the HTHP in a contractor factory set-up, especially if the contractor doesn't have these test facilities and capacity already in their factory. The cases where it is most relevant is for new technologies where there is a lower experience, and where the FAT test can be used to test operating points which is hard to get on the site. Is should be noted that the FAT test can act as kind of insurance for the buyer, however it will also come with an added cost, and might not identify issues only seen in full scale on site after a longer period of operation. An advice is to get an optional price for the FAT in order to estimate if the extra cost brings value for the project.
- A SAT must be included: Here it needs to be specified how steady-state is defined, what operating points that needs to be tested, how nonconformities will be handled, including the heat pump side, but also any deviances in the site conditions the buyer is responsible for. If interpolation/extrapolation performance curves are used it is strongly advised to specify the approach before the SAT. See also chapter 6.2 for further discussion. It is however, also recommended to avoid to many design points in the tender material (overspecification), as this can cause some contractors to deselect prequalifying or making an quotation for the project.

Safety aspects:
- Specification of safety features incorporated into the heat pump system, such as high-pressure protection, low-pressure protection, Atex design consideration, and temperature limitations.
- Design specifications in compliance with national legislation and EN-378.

Certification requirements:
- Clear specification of any certifications or approvals required for compliance with safety, environmental, or energy efficiency regulations.

Electrical supply requirements:
- Clear statement of the required electrical supply specifications, including voltage, phase, and frequency.
- Electrical noise & harmonic filters: Consideration of whether harmonic filters are needed to control electrical noise, both internally for the heat pump and for its connection to the grid.

Material requirements and types:

- Requirements for materials needs to be specified, e.g. if any parts of the heat pump system needs to be in stainless steel.
- Requirements for oil needs to be specified, e.g. if it is needs to be food grade type of oil.

Warranty and service requirements:

- Clearly outline the warranty terms and conditions, including the duration of coverage and what is included/excluded from the warranty, e.g. if there are any differences in warranty for the system components. Provide information about required service parts, intervals, and maintenance procedures to ensure optimal performance.
- Included training of end-user staff needs to be specified.

Documentation and reporting:

- Establishment of requirements for documentation and reporting of test results, performance data, and system specifications.

System design:

- Consider if buffer capacity is needed to both smooth out deviations in fast changing boundary conditions to the heat pump, and also if energy storage is needed to accommodate a more constant heat supply for the heat pump during varying heat consumers.
- Are intermediate loops required on the sink or source side to remove the risk of leaks to the process?
- Is a startup heat exchanger (HX) required to ensure no liquid in the compressor during startup?
- Is oil cooling required, and if so, can this heat be used in the process?

5.2. Performance maps

The performance of a heat pump calculated at a few design points only promises the performance in these points. When the heat pump is installed at the end-user's site, it might end up experiencing operating conditions that are not on the design points for most of the operating hours. This can bring up the question of what performance the contractor is accountable for, in these off-design conditions. It can be argued that if the actual boundary conditions are deviating from the design boundary specified it is the fault of the end-user. But a grey area of operating conditions exists where the promised performance and accountability is more uncertain.

To mitigate this problem, a performance map of the heat pump is suggested to be agreed upon between the buyer and the contractor. This can for example be specified with a given range of sink and source inlet and outlet temperatures where a map of expected COPs is shown. This is a multidimensional map, with the sink and source temperatures as parameters. Within some reasonable boundary and safety margins that both the contractor and buyer are confident in. This map can be generated for several points using simulation models, and the values in-between the points can easily be interpolated. This would make it clear what performance is promised by the contractor, and it is up to the end-user to ensure operating conditions inside the map, e.g. by ensuring the correct flow and fouling conditions on the secondary sides of the heat exchangers.

Figure 5-1 shows an example of a performance map, based on the sink and source outlet temperatures with various temperatures glides. Of course, there are also other factors that affect the COP than the temperature, like the capacity setpoint, or whether there is any oil cooling, and if this oil cooling is utilized in the process to add to the heat output. Thus, the performance map requires many parameters, and it is not easily visualized when including all these parameters. However, in many cases, these parameters would be fixed by the design of the heat pump, and not change during operation. The performance map is a function depending on with multiple parameters such as seen in the following equation, each with needs to be specified or assumed for the given performance map:

$$\mathrm{COP} = f(\mathrm{T_{sink,in}}, \mathrm{T_{sink,out}}, \mathrm{T_{source,in}}, \mathrm{T_{source,out}}, \dot{\mathrm{Q}}_{\mathrm{setpoint,}}, \text{oil cooling, fouling, flow rates, heat losses, …})$$

Similar functions can be made for describing the maximum heat capacity, or any other interesting characteristics of the heat pump.

To create these functions, a certain number of data points are required, such that sufficiently accurate interpolations can be made between them. To gather these data points, a test stand could be used. However, this is likely expensive and time consuming, so an alternative is also a well validated simulation model of the heat pump design. Especially for serially produced heat pumps and compressors such performance maps are suitable where test data from other existing examples and heat pump design already exists, which can be used for validation for such simulation models.

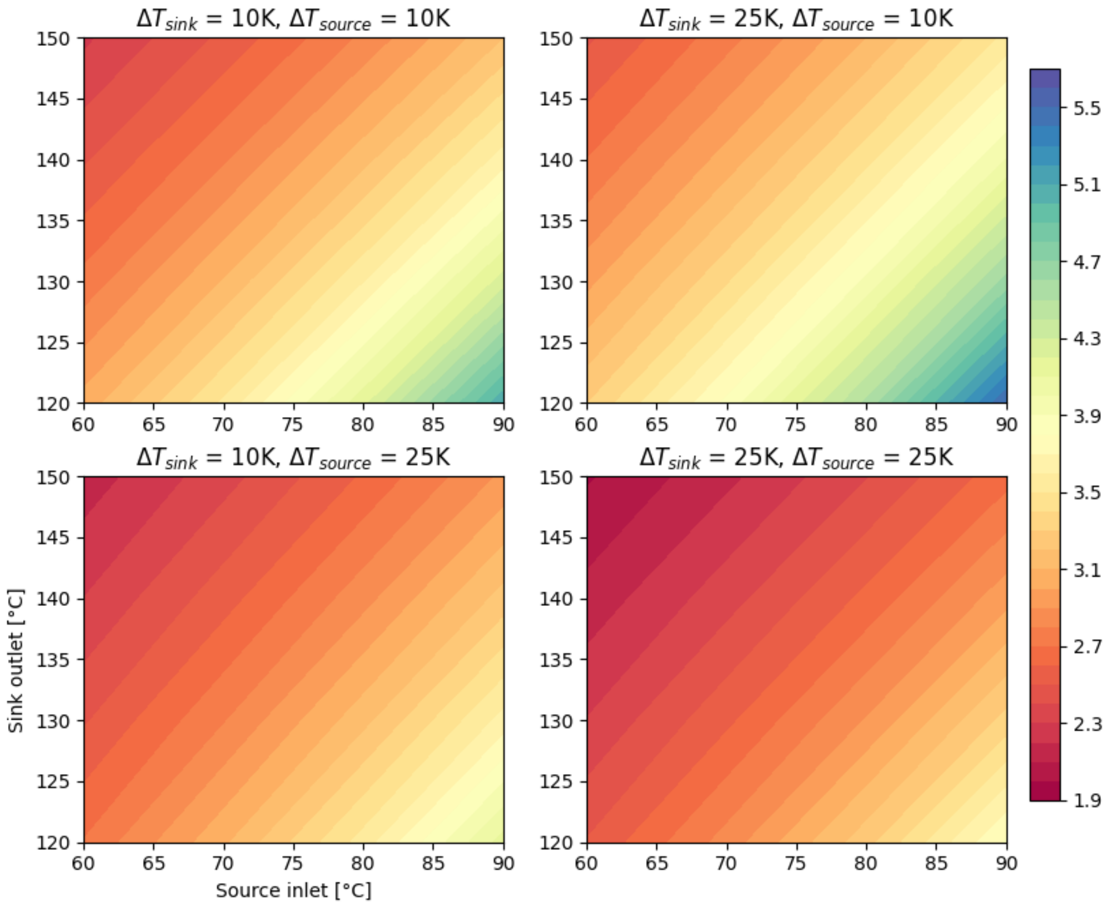

Figure 5-1 - An example of four performance maps for the COP, each valid for their own temperature range and sink- and source temperature glide.

5.3. Using penalties and bonuses in the tender process

In tender documents it is possible to include the option of both penalties and bonusses if the final heat pump system turns out to perform worse or better than initially promised, hence it can serve as an incentive to increase the quality of the heat pump, where a few percentage change in capacity and COP can have a high impact on the business case in the lifetime of the heat pump.

Penalties must be limited with maximum values, since the contractors are not willing to accept a risk for a substantial financial penalty compared to the actual value of the delivery. Hence, the buyer has to accept a certain risk in the project. Similarly, a bonus should have an upper limit.

An uncertainty range (dead band) with no penalty or bonus may be relevant to include in order to take measurement uncertainties into account. Uncertainty range and the calculation method must be clearly described already in the tender documents to reduce risk of disagreements on a financial penalty (or bonus).

It is recommended to include daily penalties for delay in the projects. The size of fine here can be calculated as lost production incomes or lost value for energy savings for the time period the heat pumps is not running. Again, this needs to have an upper limit, and needs to reflect a realistic loss for the end-user.

It can also be considered to hold back a smaller amount of the payment and make it depended on 1 year/5 years inspection or testing of the heat pump.

6. Guidelines for testing of large-scale HTHPs

This chapter outlines guidelines for testing and rating HTHP's. The chapter is split in three parts:

- Guideline for laboratory testing conditions
- Guideline for site testing
- Using simulation for heat pump rating.

6.1. Guideline for laboratory testing conditions

The characterization of a heat pump system can take place in a laboratory when characteristics such as the size, capacity and configuration allow for testing in a laboratory, which for large heat pumps can be limited. An updated overview of the high-temperature heat pump test capabilities for selected RTO's and universities which are involved in the Annex 58 can be seen in Table 6-1. These test facilities could be used for third party testing if the size of the heat pump fits the size of test facility.

Table 6-1 - Selected and recent test facilities for medium and high-temperature heat pumps.

Organization	Country	Year	Source type	Sink type	Sink temp. [°C]	Capacity [kW]	Note
AIT	Austria		Water	Water	95	100	
			Brine	Water	95	100	
			Air	Water	95	50	Air temperature from -25°C
			Water	Oil	250	15	
			Brine	Oil	250	15	
			Air	Oil	250	15	Air temperature from -25°C
		TBD	Air	Water	95	100	Air temperature from -25°C
TU Graz - IWT	Austria	2018	Water	Water	160	700	
DTI	Denmark	2023	Water	Water	180	1500	
			Air	Water	180	700	
EDF	France	2010	Water	Water	140	1000	
				Steam	200	1000	
DLR	Germany	2024	Air	Air	230	60	
CRIEPI	Japan	2013	Water	Water	95	600	
				Steam	200	600	
				Air	200	200	
			Air	Water	95	350	Air temperature from -20 °C to 50 °C
KRAAC	Korea	2012	Water	Water	80	1050	
				Air	80	1050	
			Air	Water	80	175	Air temperature from -20 ℃ to 70 ℃
			Air	Air	60	140	
		2023	Water	Water	60	1750	
TNO	Netherlands	2020	Water	Steam	200	2000	
		2023	Water	Steam	200	300	
OST-IES	Switzerland	2018	Water	Water	160	12	
		2022	Water	Water / Steam	120	120	
		2024	Water	Water	200	60	

Ghent University	Belgium	2010	Therminol 66	Water - glycol	90	480	
		TBD	Therminol 66	Therminol 66	200	100	

For heat pumps that can meaningfully be tested in a laboratory, all the external conditions affecting the operation of the heat pump must be controlled. The type of tests needed to characterize the heat pump's performance under laboratory conditions are:

- Full load test
- Partial load test
- Ramping tests
- Stand-by test
- Off-mode test

Which are described in the following sections.

The uncertainty of the measuring devices to consider has been defined in standard EN-14511:3-2022. It is recommended that the uncertainties of the measured values shall not exceed the values listed in Table 6-2.

Table 6-2: Uncertainties of measured values based on 14511.

Measured quantity	Uncertainty of measurement	Unit
Liquid		
Temperature difference	± 0.15 K	K
Temperature inlet/outlet	± 0.15 K	°C
Volume (mass) flow	± 1 %	m^3/s (kg/s)
Static pressure difference	± 1 kPa (Δp≤20 kPa) or ±5 % (Δp>20 kPa)	kPa
Air		
Dry bulb temperature	± 0.2	K
Wet bulb temperature	± 0.4	K
Air volume flow	± 5 %	m^3/s
Static pressure difference	± 5 Pa (Δp≤100 Pa) or ± 5 % (Δp>100 Pa)	Pa
Refrigerant		
Pressure at compressor out-let	± 1 %	kPa
Temperature	±0.5 K	°C
Concentration (in volume)		
Heat transfer medium	±2	%
Electrical quantities		
Electric power	±1 %	W
Voltage	±0.5 %	V
Current	±0.5 %	A
Compressor rotational speed (for open type com-pressors)	±0.5 %	min^{-1}

6.1.1. Full load test

For the full load tests the performance of the heat pump under steady state conditions is measured and the average of each value over time is used for its performance characterization. These results will provide information on the performance of the heat pump at different operating conditions.

The data considered belongs to the "data collection" period. For better results the data collection period must follow a "preconditioning period" in which the heat pump operates for a minimum required period of time. This period must be enough to allow all components to reach thermal equilibrium before the data collection period starts.

The heat pump operating conditions are defined by the manufacturer. The operating temperatures of the heat pump are basically the temperatures that the system can operate in for the heat source and the sink side. For the characterization it is advised to select a minimum of five operating conditions at the heat source and sink sides, within the range provided by the manufacturer. The specific temperature conditions could be equally spaced and spread within the operating range of the heat pump. In this way, the performance of the heat pump can be evaluated for different type of applications and conditions applicable to different process requirements and temperature lifts.

For example, the testing plan for a heat pump with operating range of conditions of 60 to 80 °C in the heat source side, and 100 °C to 140 °C on the sink side the full load test conditions in Table 6-3 could be considered. In some operating points the pressure ratio could exceed the maximum of the heat pump, for example in the case of 60 °C source/140 °C sink. For those case scenarios the testing point are not considered.

Table 6-3 - Testing matrix example for a HTHP

Heat source inlet temperatures [°C]	**Heat sink outlet temperatures [°C]**				
	100	110	120	130	140
60	X	X	X	X	X
65	X	X	X	X	X
70	X	X	X	X	X
75	X	X	X	X	X
80	X	X	X	X	X

The flow rates in the source and the sink side could be set as stable under a "nominal operating condition". Considering the example testing matrix of Table 6-3, the flow rate could be fixed for the case of heat source inlet temperature 70 °C and heat sink outlet temperature 120 °C. For the rest of tests, the flow rate will remain equal and the temperature difference in the source and sink sides of the secondary flows will change accordingly.

6.1.2. Partial load test

For heat pumps that are capable of operating under partial loads it is necessary to characterize their performance under partial load operation. There are more than one method to control the heating capacity of a HTHP, which could be via the electric input, the internal valves of the compressor, by-passing vapor, or other methods. Every type of capacity control has a range of operation considering the lowest as the "minimum load" and the highest capacity as the "maximum load".

For partial load tests it is suggested that the heat pump operates at a minimum of three (3) different capacity loads. The range of loads differ from manufacturers therefore the values can be adapted according to each HTHP system. An "intermediate capacity load" can be considered to provide an intermediate operating performance. For each load, three temperature lifts can be considered to provide further performance curves. In addition, it needs to be considering that the full load tests might already have been tested in the "full load testing" campaign, therefore it might not be necessary to repeat these tests. An example of the suggested tests and the way they could be presented is illustrated in Table 6-4.

Table 6-4 - Example of partial load testing conditions.

Capacity load	**HP temperature lift [K]**	**COP [-]**
Maximum load	50	3.2
	40	4.9
	30	6.0

Intermediate load	50	3.0
	40	4.5
	30	5.5
Minimum load	50	2.5
	40	3.8
	30	4.5

6.1.3. Ramping tests

The gradual increase or decrease of the compressor speed (RPM) is defined as a “ramp”. To estimate the response of the heat pump to the thermal load variations, ramping tests are also suggested. These tests show the performance of the HTHP during sudden high load changes that could happen during start-up and shut-down phases of the system, and might also provide insights to have the heat pump can provide possible ancillary services for the electricity grid.

For the ramping tests the HTHP basically starts from stand-by mode, and it is set to deliver the load at the required temperature in the sink side. The time to reach the required conditions could differ depending on the heat pump type, the set points and the internal control parameters. The operation of the HTHP and the time is monitored until it reaches a demanded load (ramp-up).

The same strategy when applied inversely where the heat demand drops is called ramp-down test. The time needed to get from stand-by mode to a required T_{HPlift} is measured providing an overview of the reaction time of the heat pump under maximum operation requirements (see Figure 6-1). In cases where the heat pump follows a ramp down pattern during shut-down, it is important to measure the time needed, since the energy consumed during this period of time is considered as losses. This amount of energy lost can be substantial when the heat pump operates in large number of cycles during the year.

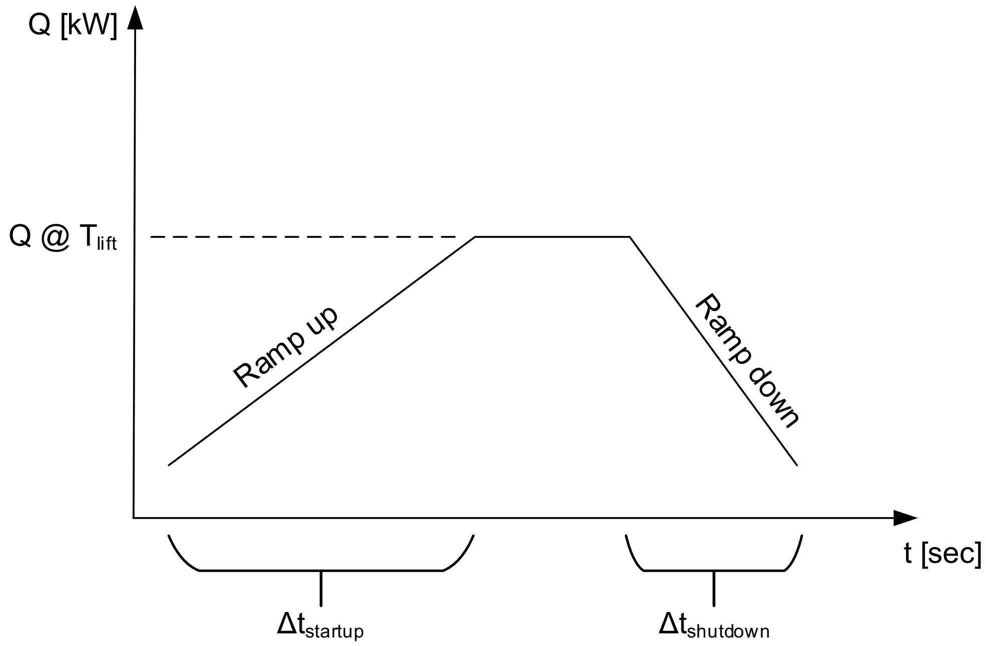

Figure 6-1 - Graph showing the ramping tests delivered at minimum and maximum HP temperature lifts and the time reaction of the HP.

6.1.4. Stand-by test and off-mode test

The stand-by test is intended to evaluate the energy/power consumption of the heat pump during its stand-by phase. Heating elements, circulation pumps for internal loops or electronic devices could be responsible for auxiliary energy consumption during the stand-by phase of the heat pump. This type of energy consumption could have an important impact on performance if the consumption is substantial.

The off-mode test includes the measurement of the power consumption of the heat pump during off-mode phase. This could involve any type of systems that are meant to protect or monitor the heat pump system during long term off mode periods. They could be heating elements, any consumption of the cabinet, etc.

6.1.5. Test apparatus and procedures

6.1.5.1. Measurements

The measurements that must be considered for high temperature heat pump testing are shown in Table 6-5.

Table 6-5 – Measurements for HTHP testing

Ambient site conditions	- Air temperature (°C) (inside the testing room) - Humidity - Atmospheric pressure (kPa) - Ventilation rate
Electrical quantities	- Voltage (V) - Total Current (A) - Total Power input (kW)

Thermodynamic values	- Working fluid loop(s):
	    o Temperature (°C)
	    o Pressure (kPa)
	    o Non-intrusive mass flow rate (kg/s)
	- Secondary loops:
	    o Temperature (°C)
	    o Pressure (kPa)
	    o Mass flow rate (kg/s)

Noise	- From enclosure of HP
Vibration	The vibration coming from the enclosure of the heat pump or from the metallic frame of the setup could be measured. The reason is to ensure that the location is safe for the heat pump installation. The values to be measured could be: - From the enclosure Amplitude (g's) - Frequency (Hz)

6.1.5.2. Calculated values

The values to be calculated are listed below:

- *Heating capacity.* This refers the heat transfer rate on the sink side of the heat pump (hot side), typical identical to the thermal power at the condenser.
- *Cooling capacity*. This refers the heat transfer rate on the source side of the heat pump (cold side), typical identical to the thermal power at the evaporator.
- *Coefficient of performance* (COP)
- *Lorenz efficiency.* The Lorenz efficiency is defined as the ratio of the actual heat pump COP and the Lorenz COP for a specific heat source and heat sink. The Lorenz COP is the maximum

achievable performance for a heat pump device working between two temperature reservoirs.
- *Heat pump temperature lift* (T_{HPlift}). Defined as difference in heat sink outlet temperature and heat source inlet temperature.
- *Steam superheating degree*

6.1.5.3. Other additional optional values

- Isentropic efficiencies
- Volumetric efficiency
- Steam quality % (in case of a steam generating HTHP)
- Oil data (moisture, acidity, viscosity – minimum operating period must be defined)
- Refrigerant data (water content, oil content, impurities)

6.1.5.4. Measurement points and procedure

The points to measure in the HTHP setup are illustrated Figure 6-2. For the secondary loops (water/air/other) the measurements of temperature, pressure and mass flow rate at the heat source (evaporator) and heat sink (condenser) must be considered. If additional heat exchangers require secondary flows (subcooler, etc.) their temperature, pressure and mass flow rate must be measured as well.

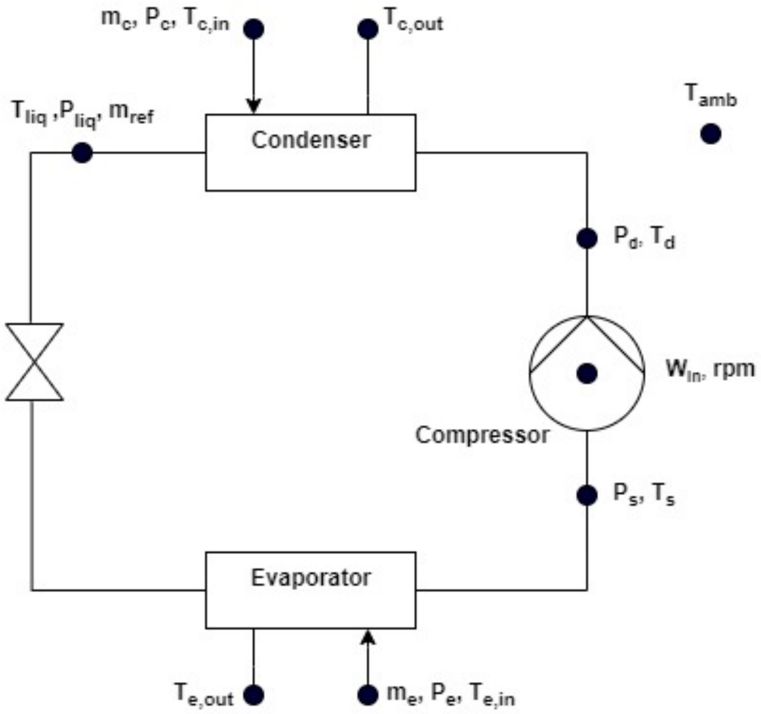

Figure 6-2 - Schematic of a basic heat pump layout with the required sensors shown.

On the refrigerant side, suction and discharge temperatures and pressures are measured near the compressor ports. The compressor electricity consumption and speed must be also measured. The temperature of the condensed liquid at the condenser/subcooler outlet as well as the mass flow rate is important to be measured. Finally, the ambient temperature conditions are also monitored to define the losses of the setup.

The measurements needs to be noted when the system is in steady-state. According to EN 14511-3: 2018, there are several steps to follow to identify whether the heat pump operates in steady state conditions, which can be used as a reference for this guideline.

The preconditioning period ends when the test tolerances specified in Table 4 of EN 14511-3: 2018 are attained for at least 10 minutes and is followed by an equilibrium period of one hour in which the tolerances should be met.

Hence, the data collection period lasts a minimum period of 70 minutes, in which data must be sampled at equal intervals of 30 seconds or less. For each interval of 5 minutes during the data collection period, an average temperature difference shall be calculated ΔTᵢ (t). The average temperature difference for the first 5 minutes of the data collection period ΔTᵢ (t = 0) is used for calculating the following percent change:

$$\%\Delta T = \left[\frac{\Delta T_i(\tau = 0) - \Delta T_i(\tau)}{\Delta T_i(\tau = 0)}\right]$$

If during the data collection period the $\%\Delta T$ of the measured values do not exceed 2.5 % and the test tolerances specified in in Table 4 of EN 14511-3: 2018 are satisfied, the operation is considered steady-state.

6.1.6. Test results

Looking at the key test results, they could include:

- COP
- Heating capacity [kW]
- Cooling capacity [kW]
- Required electricity consumption
- Response time

The results can be used for making a performance label, which potential could look as shown in Table 6-6, showing the performance in the various operating conditions and the noise and vibration measured values.

Table 6-6 - Presentation of lab test results.

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/s²]				

In this example, the heating capacity is shown in certain intervals for the average temperature lifts, and the response time is calculated from stand-by mode and ends when the heating capacity are in steady state, as defined in the above section *Measurement points and procedure.* In addition to this the losses are shown, which can be multiplied by the time to find the total energy loss in stand-by and off-mode in a given time interval.

6.2. Guideline for site testing

During site testing, and SAT, the heat pump experiences real operating conditions from start-up to full load, hence there are naturally more fluctuating boundary conditions and changes in ambient conditions around the heat pump compared to testing in the laboratory. At the same time, there are most likely a series of constraints to the possibility of changing these boundary conditions, leading to a limited operating area for the heat pump.

The purpose of this chapter is to describe a site testing guideline that can be used to ensure the buyer has a purchased a well-functioning heat pump that lives up to the specifications agreed upon together with the contractor, as specified in chapter 5. Testing on-site allows one to test the heat pump with the capacity that the heat pump was designed for, without the limitations that a laboratory may have. Moreover, the site has the correct electrical installation prepared for the heat pump.

6.2.1. Specification of site testing

Under the specifications agreed upon, the test procedure is recommended to focus mainly on verifying the:

- COP
- Temperature values and glide for the sink and source side
- Thermal output power
- Electrical power

The following is a general checklist of measurements to be performed during the SAT:

- Thermodynamic values of the process
    - Sink and source flows (including all sub-flows such as injection water for desuperheating steam, any flows that the sink or source might be split into, flows for open systems where part of the sink flow is lost to the process, etc.)
    - Auxiliary flows (water for oil cooling, steam used for a startup heat exchanger, etc.)
    - Inlet and outlet temperature on sink and source
    - Inlet and outlet pressure on sink and source
    - For steam generation and vapor condensation determine the outlet quality
    - For humid air determine inlet and outlet humidity
    - For bulk products in drying processes it can in some cases be necessary to determine the inlet and outlet temperatures and also inlet and outlet water content
- Ambient/site conditions
    - Temperature
    - Humidity
- Electrical data as consumed by the entire HP system
    - Voltage
    - Current
    - Power
- Data collection period
    - Length of measurement period that values are averaged over
    - Sampling rate
    - Maximum deviations of measurement values
    - Standard deviation of measurement values
    - Mean values of measurement values

Besides the performance testing, it is also recommended to include a functionality test of the heat pump system, which checks that the requirements for noise, vibration levels, and potential Atex equipment in the various operating conditions are fulfilled. Furthermore, leakage and pressure testing according to EN-378 also needs to be made.

The suggested method for performance testing matches closely with the procedure described in ISO 916:2020, related to performance warranties for refrigerating systems, which can therefore be used for inspiration for site testing. In the ISO916 standard, the following specification is given: “Only the characteristics essential to the economic efficiency and the operation of refrigerating systems and verifiable by usual measurement methods shall be the subject of performance warranty. This requires allowances for the variations of operating conditions which are hardly avoidable in practice (ISO 916:2020).” The standard therefore focuses on cooling capacity, electrical power uptake by the compressor, electric power uptake by the entire system and the calculation of the COP. The standard refers to performance in steady state for operating conditions as agreed previously, taking into account allowed tolerances in operating conditions and sensor uncertainty.

The measurement deviations and uncertainties that can be accepted for the site test, must be agreed upon before a test result can be noted in a given test point. The expected deviation can depend on both the heat pump technology and the given application. Various tables for such expected tolerated deviations can for instance be found in ISO 916:2020 and EN-13711. It is in this guideline recommended to specify the acceptable deviation for selected key measurements. The choice of the key measurements will depend on the given application and the heat pump type but could for example be as listed in Table 6-7. If the variability of the measurements is not known beforehand, the site test should span a period long enough to establish this variability. Once this is done, a time period of minimum 30 min can be selected where the variability is within the acceptable deviations. This period is then defined as steady-state mode.

The test measurements must then be taken as the mean values across this time period, with a sample rate of e.g. 1 minute. The test parameters must also be noted, as these are the conditions under which the performance is measured, and the conditions that must be used for comparison with the performance map given by the HP supplier, see section 5.2.

Table 6-7 - Example of allowable test parameter deviations, suitable for the measurements shown in Figure 6-3. These are the maximum allowable deviations of the measured values from the mean during the test period, for it to be considered as steady-state. The allowable deviations are inspired by ISO 916 and EN 13771.

Parameter	**Allowable deviation**	**Unit**
Compressor inlet temperature	± 2	K
Compressor inlet pressure	± 2	%
Compressor speed	± 2	%
Sink inlet temperature	± 2	K
Sink mass flow rate	± 1.5	%
Source inlet temperature	± 2	K
Source mass flow rate	± 1.5	%
Evaporating pressure	± 2	%
Compressor voltage	± 1.5	%
Compressor electrical frequency	± 1	%

Figure 6-3 shows an example measurement period from a real process. From this, it is clear to see that the boundary conditions of the HP vary significantly beyond normal measurement uncertainty. The period is quite long, so the deviations are in some cases larger than that specified in Table 6-7. The measurements for determining the KPIs of the heat pump could be selected between e.g. 16:00 – 18:00, as this period contains deviations below the allowable maximums.

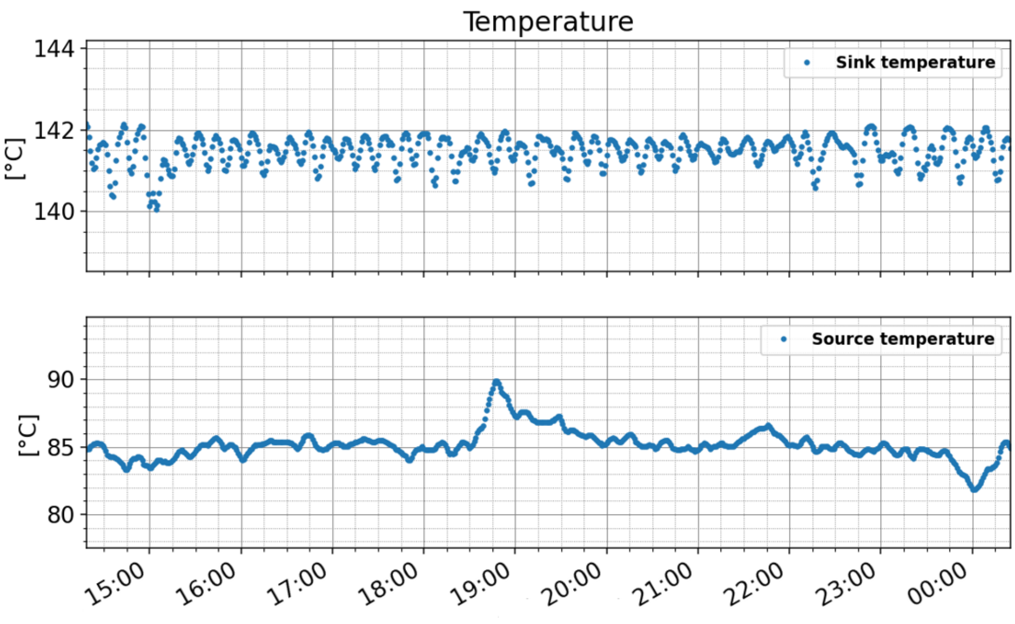

Figure 6-3 - Example of variations in boundary conditions with 9 hours of operating data for sink and source inlet temperatures for a HTHP in an industrial heat pump scenario where low-pressure steam is to be produced.

The key measurements of interest may differ depending on the design of the HP. The allowable deviations for a steam generating HP may for example differ from one producing hot water. Here the sink inlet pressure is more relevant than the inlet temperature, as the pressure defines the saturation temperature of the generated steam. For steam with no superheating, the outlet quality must also be measured.

Another example is HPs with water/steam as refrigerant, as these can in many cases be open systems with water injection on the discharge side of the compressor. In this case, the injected water should be included in the sink mass flow rate.

Along with the allowable parameter deviations for accepting steady-state, agreements should also be made upon the maximum measurement uncertainty due to sensor inaccuracy that can be accepted. The values given in Table 6-8 are recommended values, these values are considered to cover a 95% confidence interval. The uncertainty given in the table are deviations from the mean.

*Table 6-8 - Recommended values of maximum measurement uncertainty to be allowed during the SAT. Based on EN 13771 (2017) and EN 13141-7 (2021). (*Steam flow is measured via the feed water flow.)*

Measured quantity	**Uncertainty**	**Unit**
Absolute pressure	± 1 %	Pa
Refrigerant flow	± 1 %	Kg/s
Rotary speed	± 0.07 %	1/min
Temperatures - Temperature for differences (for individually calibrated sensors) - Temperature differences (for calibrated sensor pairs) - Other temperatures	 ± 0.05 K ± 1 % ± 0.3 K	 °C K °C
Electrical quantities - Power - Voltage - Current - Frequency	 ±1 % ±1 % ±1 % ±1 %	 W V A 1/s
Torque	± 1 %	Nm
Water flow	± 1 %	Kg/s
Air flow	± 3 %	m^3/s
Steam flow*	± 1 %	Kg/s

Recommended tests

The following list contains further suggestions as to which tests should be made to verify the performance of the HTHP, including the dynamic and off-design behaviour:

a) Continuous operation over a longer timeframe at the specified operating conditions (design points) in steady state mode. It can also be considered if the heat pump must be tested at full load only, or if lower capacities also should be tested. It needs to be stressed, that every given test point for SAT and performance tests requires resources, so any unnecessary tests will cost extra without giving any benefits. Part load testing is highly dependent on the application case, and only relevant/possible if the production site allows it. E.g. if another heat supply is able to work in parallel with the heat pump, or if there are times when the production requires lower capacities.

b) Startup and shutdown tests. This includes testing of ramping rates for when the system starts from a long standstill period, and for system startup from standby mode where it is pre-heated.

c) Standstill tests: Needs to be included to measure energy losses in system when not operating.

d) Total testing of at least 30 days is recommended as a “hand-over” test to check for the full availability and functionality of the new heat pump system.

e) Reporting and documentation: Establishment of requirements for comprehensive documentation and reporting of test results must be clarified, including handling of raw data, performance data, and any deviations from the standard testing protocols.

f) Quality assurance and control: Implementation of a quality assurance and quality control measures throughout the testing process to minimize errors and ensure the accuracy of the results.

g) Third-Party verification: In some cases, it is recommended to involve third-party verification or certification bodies to validate the test results and ensure impartiality and credibility.

The following list further specifies site test elements that are more "nice-to-have", i.e, things that are not direct requirements, but can be used to further verify the heat pump performance and optimize the system:

- Oil samples can be taken in predefined intervals for the site testing in order to monitor its quality and to discover potential compressor issues not immediately identified. Oil measurements can e.g. contain information about humidity levels in oil, viscosity, acid level, particles, etc.
- Non-intrusive working fluid flow measurement. This data can be used to validate any simulation models or digital twins that might be created for the project. It can also help with establishing more accurate measurements of the heating capacity.

6.2.2. Example of COP variations and uncertainties during site testing

Data from the heat pump demonstrator at Wienerberger (Dryficiency project[1]) can provide an example of how the heat pump efficiency (COP) as a function of the temperature lift can vary during site testing, and how uncertainties also can be considered. Figure 6-4 shows data points that represent at least 10 h of stationary operation (adequately defined) with constant temperatures and compressor speed. The error bars illustrated for each data point show how much variation were found in operation data that is presented as a single data point. So, despite fluctuating operation conditions, interesting results can be derived.[2]

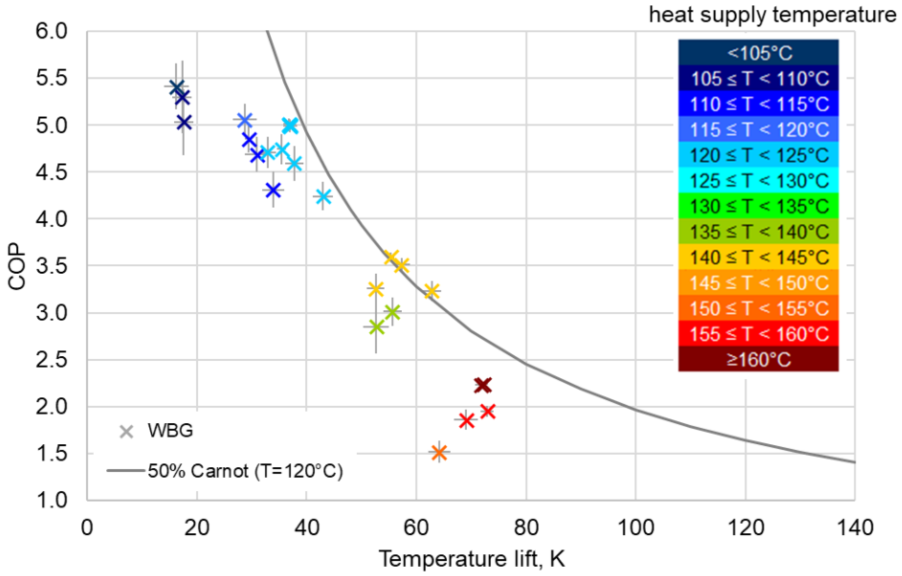

Figure 6-4 - Performance data of the heat pump demonstrator with ranges of variation at Wienerberger.[2]

The maximum allowed sensor inaccuracy can be calculated from the maximum uncertainty aimed for in the desired KPIs (e.g. COP in this case in this example) using error propagation calculations. One method is laid out in the "Guide to the expression of uncertainty in measurement"[3] in short GUM. For example, one way to derive the COP is to measure the delivered heating capacity (heat meter) and divide by the necessary electricity consumption (electricity meter) as follows:

$$\mathrm{COP} = \frac{\dot{\mathrm{Q}}}{\mathrm{P}}$$

[1] https://dryficiency.eu/

[2] V. Wilk, B. Windholz, A. Schneeberger: Report on the validation of the energy savings for each demo site D5.2, DryFiciency – Waste Heat Recovery in Industrial Drying Processes, https://dryficiency.eu/wp-content/uploads/2022/02/D5.2-Report-on-the-validation-of-the-energy-savings-for-each-demo-site_review.pdf

[3] JCGM, Guide to the expression of uncertainty in measurement – Part 6: Developing and using measurement models, First edition 2020, Link, last accessed: 02.08.2021.

The combined uncertainty depends on the total measurement chain. In case of the heat meter, two temperature probes, a flow meter, and a calculation are needed. The total uncertainty of the combined heat meter is, according to the standard EN-1434, the arithmetic sum of all the uncertainties of the parts. Furthermore, the uncertainty of the power meter can be found in the specifications. With $\text{COP} = f(\dot{Q}, P)$:

$$u_c(\text{COP}) = \sqrt{\left(\frac{1}{P_0} \cdot u(\dot{Q})\right)^2 + \left(-\frac{\dot{Q}_0}{P_0^2} \cdot u(P)\right)^2}$$

Where P_0 and $\dot{Q}_0$ are the respective measurements. The value $u(x)$ is the standard uncertainty. Depending on the description in the specification a distribution is chosen. In the worst case a rectangular distribution can be assumed. After calculating the combined uncertainty, an interval containing the true value of the COP with a specified level of confidence of 95 %, and assuming a normal distribution of the COP, a factor of $k_p = 1.96$ is derived and the COP can be described as:

$$\text{COP} = \text{COP}_m \pm k_p \cdot u_c(\text{COP}) = \text{COP}_m \pm 1.96 \cdot u_c(\text{COP})$$

with COP_m being the measured COP.

In the following figures, results from work performed on the effects of measurement uncertainty on the COP as well as on fluid properties are shown exemplarily for a HTHP. Figure 6-5 and Figure 6-6 show the COP and the refrigerant mass flow with their relatively narrow uncertainty intervals, allowing for good results. In contrast, the uncertainty of the isentropic efficiency (Figure 6-7) is high, weakening the trust in the results. To bring the uncertainty of KPIs to an adequate level aimed for, reducing the maximum allowed sensor inaccuracy of the relevant sensors (according to the shown calculations) is an obvious option.

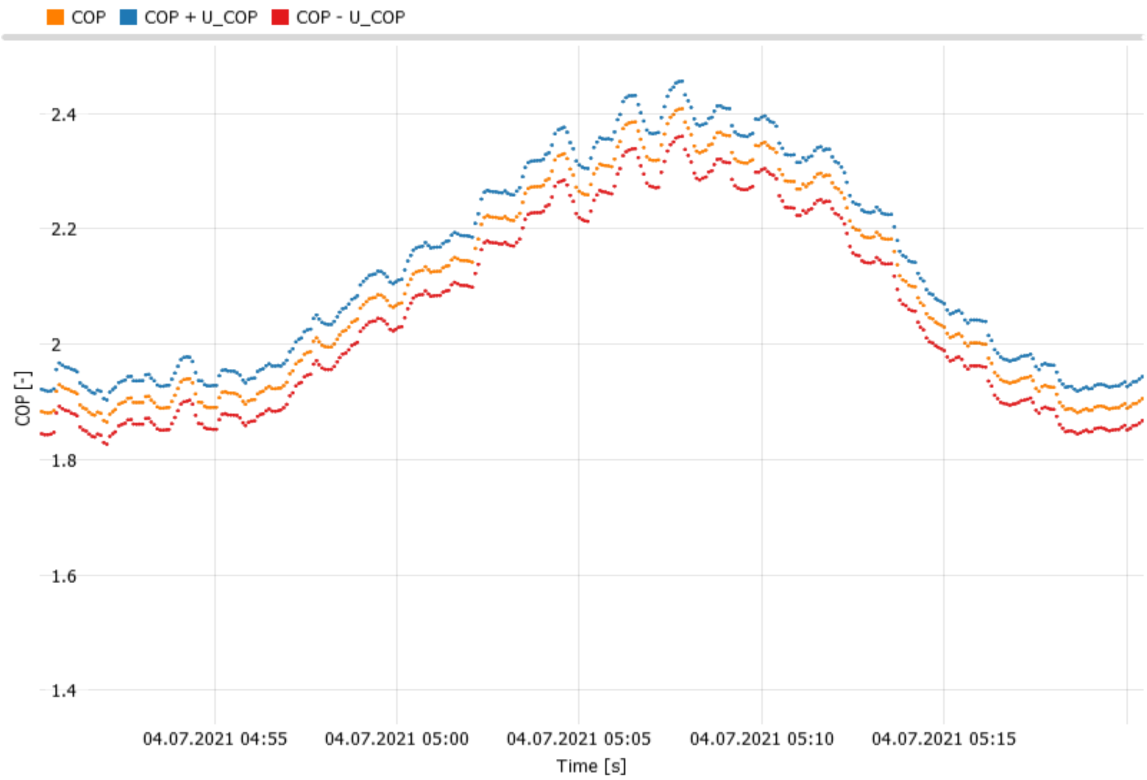

Figure 6-5 - Example of COP derived from measurements and its calculated uncertainty (Source: AIT Austrian Institute of Technology GmbH).

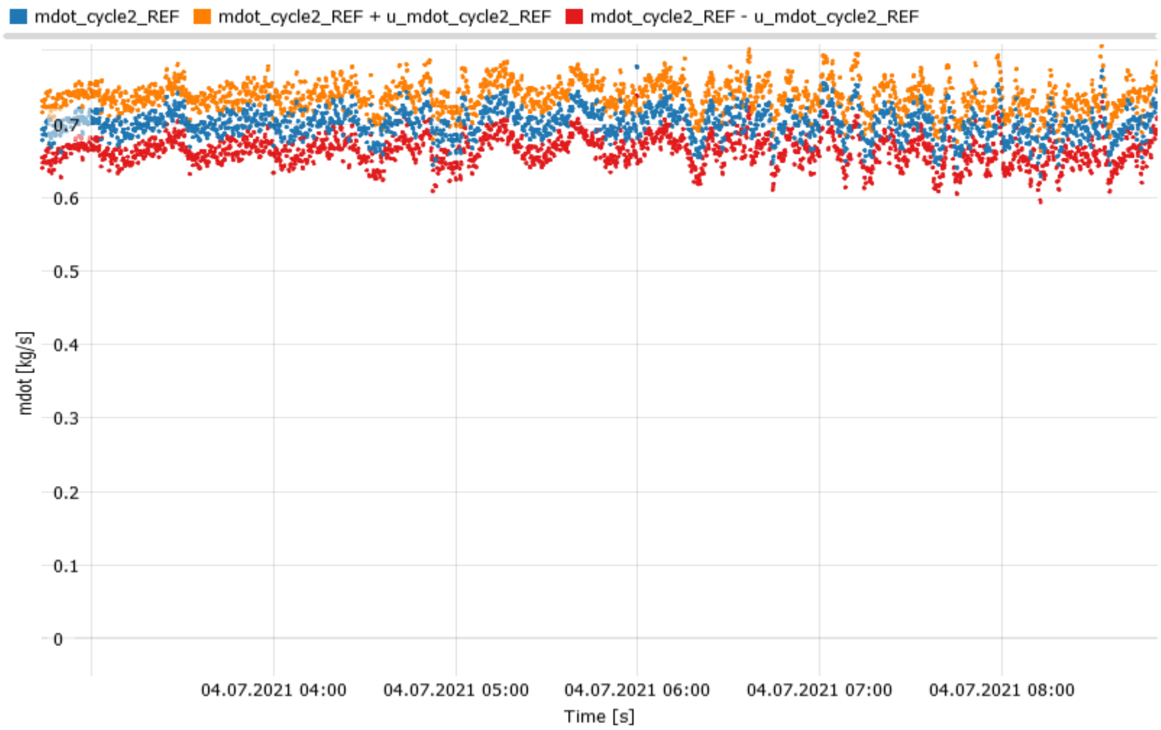

Figure 6-6 - Example of refrigerant mass flow derived from measurements and its calculated uncertainty (Source: AIT Austrian Institute of Technology GmbH).

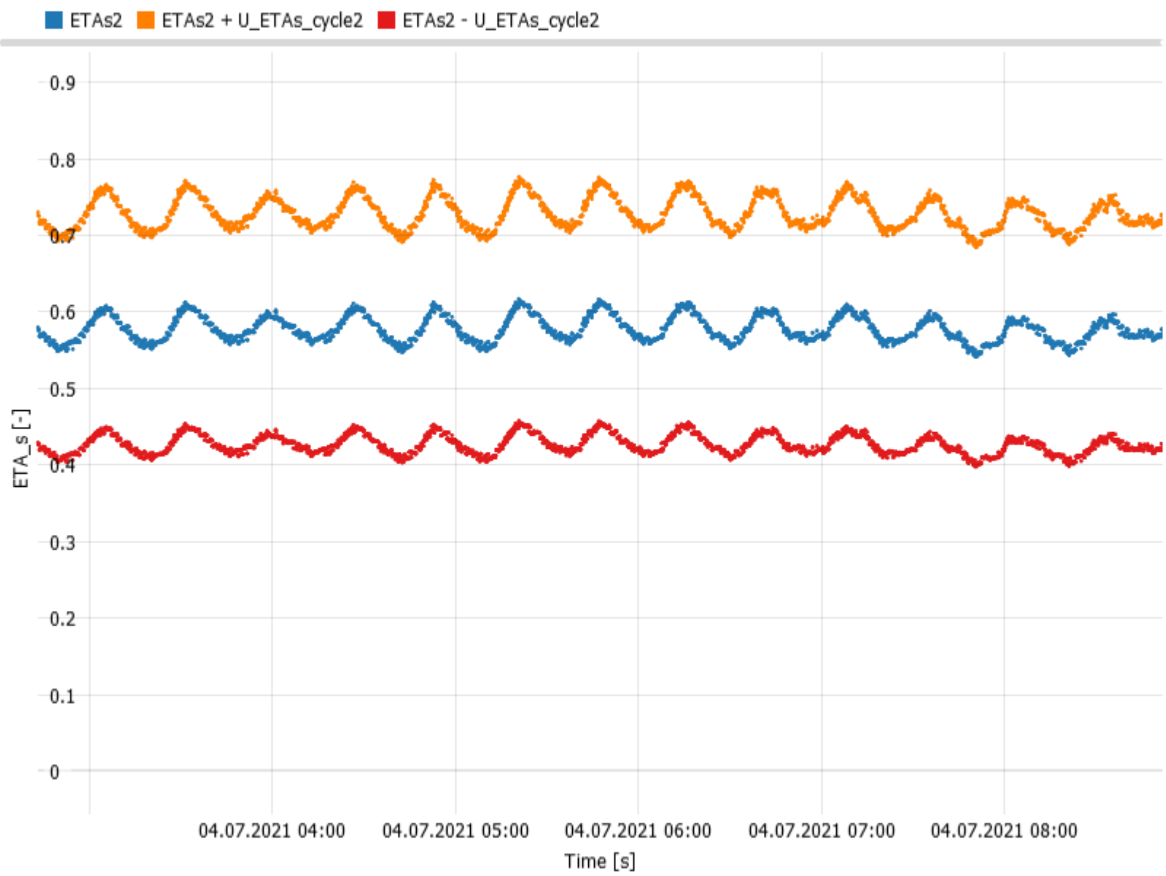

Figure 6-7 - Example of isentropic compressor efficiency derived from measurements and its calculated uncertainty (Source: AIT Austrian Institute of Technology GmbH).

6.2.2.1. Example case of resulting COP uncertainty using Table 6-8 values

Given the uncertainties stated in Table 6-8, the uncertainty of the calculated COP can be established. This will be shown for the following case:

A hot water circuit with a flow rate of 10 L/s is heated up from 60 °C to 140 °C. The heating output is measured via a flow meter and two temperature probes, one probe at the sink inlet and one at the sink outlet.

The uncertainties used in this calculation are:

- $\mathrm{u}(\dot{\mathrm{V}}) = \pm\, 10\frac{\mathrm{L}}{\mathrm{s}} \cdot 1\,\% = \pm\, 0.1\,\frac{\mathrm{L}}{\mathrm{s}} = \pm\, 0.0001\,\frac{\mathrm{m}^3}{\mathrm{s}}$
- $\mathrm{u}(\mathrm{T_i}) = \pm\, 0.3\,\mathrm{K}$
- $\mathrm{u}(\mathrm{T_o}) = \pm\, 0.3\,\mathrm{K}$
- $\mathrm{u}(\mathrm{P}) = \pm\, 1\,\%$

The heating output is given as:

$$\dot{Q} = \dot{V} \cdot c_p \cdot \rho \cdot (T_o - T_i)$$

Where $\dot{V}$ is the flow rate, c_p is the specific heat capacity, ρ is the density, T_o is the outlet temperature and T_i is the inlet temperature.

The uncertainty of the heating output is given via the propagation of uncertainty as:

$$u(\dot{Q}) = \sqrt{\left(\rho \cdot c_p \cdot (T_o - T_i)\right)^2 u(\dot{V})^2 + (\dot{V} \cdot c_p \cdot \rho)^2 u(T_i)^2 + (-\dot{V} \cdot c_p \cdot \rho)^2 u(T_o)^2}$$

Where $u(x)$ is the uncertainty of the individual measurements. Inserting the respective values yields:

$$u(\dot{Q}) = \sqrt{\begin{gathered}\left(1{,}000\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 4{,}200\frac{\mathrm{J}}{\mathrm{kgK}} \cdot (140\,°\mathrm{C} - 60\,°\mathrm{C})\right)^2 \left(0.0001\frac{\mathrm{m}^3}{\mathrm{s}}\right)^2 \\ + \left(0.01\frac{\mathrm{m}^3}{\mathrm{s}} \cdot 4{,}200\frac{\mathrm{J}}{\mathrm{kgK}} \cdot 1{,}000\frac{\mathrm{kg}}{\mathrm{m}^3}\right)^2 (0.3\,\mathrm{K})^2 \\ + (-0.01\frac{\mathrm{m}^3}{\mathrm{s}} \cdot 4{,}200\frac{\mathrm{J}}{\mathrm{kgK}} \cdot 1{,}000\frac{\mathrm{kg}}{\mathrm{m}^3})^2 (0.3\,\mathrm{K})^2\end{gathered}} = \pm\, 38.03\,\mathrm{kW}$$

And for the given values the total heating output is:

$$\dot{Q} = 3360\,kW$$

The final uncertainty of the calculated COP is given as:

$$u(COP) = \sqrt{\left(\frac{1}{P} \cdot u(\dot{Q})\right)^2 + \left(-\frac{\dot{Q}}{P^2} \cdot u(P)\right)^2}$$

Since the sensors are assumed to have their uncertainty given for a 95 % confidence interval, there is no need to multiply the uncertainty with a coverage factor. Assuming a COP of 3, the power, P, is 1120 kW. This yields:

$$u(COP) = \sqrt{\left(\frac{1}{1120\,\mathrm{kW}} \cdot 38.03\,\mathrm{kW}\right)^2 + \left(-\frac{3360\,\mathrm{kW}}{1120\,\mathrm{kW}} \cdot 11.2\,\mathrm{kW}\right)^2} = \pm 0.045$$

Thus, the COP is:

$$\mathrm{COP} = 3.0 \pm 0.045$$

6.3. Using simulations for heat pump rating

Performing a FAT for large industrial heat pumps can be very expensive, which in many cases means that the FAT is skipped in favour of only performing a SAT. It may however be difficult to provide the exact boundary conditions in the SAT as specified in the contract between the end user and the heat pump contractor. This can bring up the question of whether the heat pump performs as contractually promised. To eliminate this challenge, the SAT can be paired with a simulation-based rating of the heat pump. The simulation model can for example be built by an independent third party and can be verified by results in the SAT, or in case of serially produced heat pumps with known performance, the model can be built beforehand by the contractor, and the model shared ahead of the SAT with the end-user. In the latter case, the contract should be constructed such that the performance indicated by SAT results must match within a specified uncertainty or exceed the model performance for the same conditions. Simulation can further be used for services such as monitoring, fault detection and optimization.

The process for using a simulation model can include:

- Build the simulation model.
- Retrieve test data for validation of model (most likely in other operating condition than specified in tender). Data is obtained from SAT test or from other operating heat pumps of the same type.
- Compare model results to data from tender specifications
- Obtain a rating based on the efficiency (e.g. Carnot or Lorenz) being above a certain level. Figures such at the maximum heating capacity may also be interesting.

Dynamic models can be used for characterization of the heat pump system in this scenario. Depending on the required accuracy and time available, different modelling approaches can be used, such as for example white and black box approaches. A dynamic model of a heat pump is used to predict the main output variables of the system (e.g. thermal capacity, electric power, supply temperature, etc.) once the input/boundary conditions are known. The heat pump can be considered as a whole or as an assembly of different components, however the modelling procedure is normally divided into the same different steps: model development, tuning and validation, as shown in Figure 6-8.

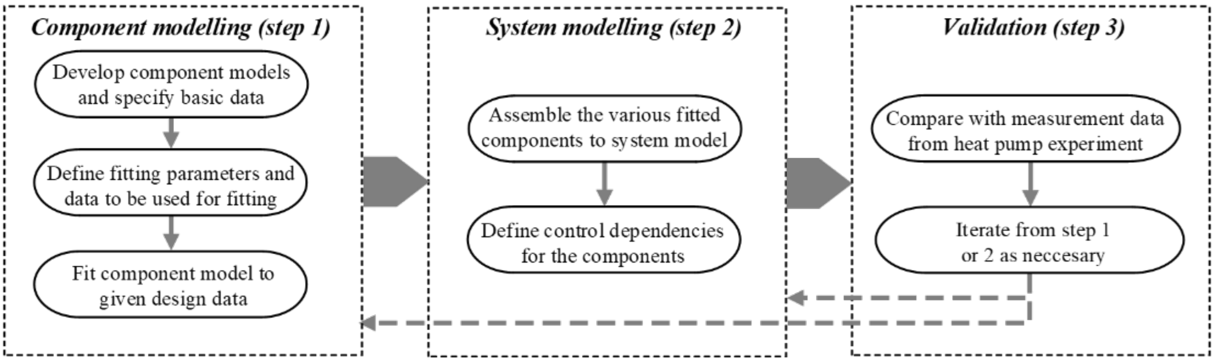

Figure 6-8 - Heat pump modelling procedure [Source: DTI].

The different modelling approaches (at component and/or system level) also depends on the data and knowledge available. We refer to white box modelling when the model is only based on physical equations, while black box modelling is a data-driven model without any knowledge on the physics behind. Gray box modelling approach is a combination of the previous two methods and combines the advantages of both (physically based model with easiness of behaviour interpretation and tuning with data for a higher accuracy).

A more detailed explanation of the different modelling approaches for heat pumps is provided below:

- **Physically based/Distributed parameters model**: The distributed-parameter modelling method considers independent variables in both time and space. This is particularly relevant to the heat exchangers in a heat pump. The advantage is that the evolving refrigerant states can be predicted as the refrigerant proceeds along the evaporator (or condenser). This is a rigorous modelling approach and high computational power. This method requires an in-depth knowledge of the components performance and is built by combining the detailed models of the different components of the heat pump.
- **Reduced order model**: the detailed system of equations of physically based models is reduced by introducing some simplifications (e.g. 1D, constant mean void fraction, etc.). Lumping of parameters varies in terms of specific device modelled for different models. It still requires a quite detailed knowledge of the system and can represent the dynamics but with a lower level of details. Preferred for developing control systems.
- **Performance fitting**: the performance of the heat pump is derived from experimental data used to build regression models. This kind of models can be 'quasi-steady-state' (i.e. the dynamics of the system is included but the heat pump is considered steady state because the time-step is too big to incorporate the heat pump transient behaviour) or even dynamic if the inertia of the heat pumps

components is additionally included.

- **Machine learning**: different machine learning tools exist that can be trained with available data to deduce correlations between the inputs and outputs of the heat pump. The knowledge of the system is not requested, whereas a wide set of data for training and validating the model is needed. The accuracy will depend on the representativeness of the data used for the model identification.

In Table 6-9 a non-exhaustive summary of the main features of the different categories of models from the literature review is presented.

Table 6-9 - Comparison of state-of-the-art dynamic models of heat pumps.

Type	**Sub-categories**	**Accuracy expected**	**Positive aspects**	**Negative aspects**	**Input requested**	**Output calculated**	**Ref.**
Black box	Performance curve	0.5 % - 15 %	Features that can be easily included: -Cycling losses can be integrated by means of penalisation factors -Characteristic behaviour of the heat exchanger can be included to better represent the HP cycling behaviour - operational constraints such as minimum compressor speed, if the control aspects should be investigated	-Due to using performance curves or maps, the majority of these models are used for steady state conditions -Some models require the flow rate as an input and some of them give it as an output. Hence, some models partly incorporate the internal control.	Performance maps. For operation: Sink inlet temp Source inlet temp (Sink setpoint temp)*** (Sink mass flow)*** (Source mass flow)** (On/off signal)** (Comp. speed)** (Heating output)* (Ambient temp)*	Electrical power Sink outlet temp. (COP)*** (Source outlet temp.)** (Sink mass flow)* (Heating output)*	[1]–[7]
	Machine learning (ANN, MLR, SVM, RF, KNN)	CV(RMSE): coefficient of variation of root mean square error range = 1.75 % - 28.62 %. On average, CV(RMSE) = 8.04 %	-Potential for quick modelling process by only having to set up machine learning technique and select inputs & outputs -Fast models with ANN mainly being the fastest: one study showed: ANN= reference SVM = 2.58 x ANN RF = 4.13 x ANN KNN = 4.58 x ANN	-Some of the required inputs are not always measured -Exact structure of the model is not always fully described -Most of existing models adopt time steps of one hour. They neglect the on-board HP control and use the flow rate is a model input	Data for training and validation For operation: Source inlet temp Source outlet temp Sink inlet temp Sink outlet temp (Sink mass flow)*** (Source mass flow)*** (Heating output)*** (Ambient temp)** (Ground temp)** (Comp. cycles)* (Comp. inlet temp)* (Comp. outlet temp)* (Relative humidity)* (TES volumeflow)* (Pump suction pressure)* (Pump discharge pressure)*	COP (Electrical power)*** (EER)*	[8]–[13]
White box	Detailed Physical/distributed parameter model	COP – 2% Qth_cond – 1%	-Models are highly detailed with minimum simplifying assumptions. -Models can be/are experimentally validated. -Based on the first principles, more reliable for a wide range of operating conditions. -High encapsulation of dynamical perturbations	-High accuracy at the expense of high computational costs -Reliability highly subject to model/Heat Pump type	Compressor performance HX Geometry Fluid properties External boundary conditions	COP Electrical power	[14] - [17]
	Reduced order/Lumped Parameter models	COP: 2-3% Qth_cond: 1%	-Relatively low computational costs with relatively high fidelity -Lumping parameters (especially in HXs) reduces system order to linear	-Relatively lower accuracy, especially during transients -Inability to represent complete systems dynamics -Reliability highly subject to model/Heat Pump type	Compressor performance HX Geometry Fluid properties External boundary conditions	COP Electrical power	[18] - [21]

Grey box	White box models tuned with available data	2.7 - 10 %	It can be as detailed as white box models, but the lack of any details can be overcome thanks to data-tuning	Model identification require data available	Compressor performance HX Geometry Fluid properties External boundary conditions Data for training	COP Electrical power Heating output (Source outlet temp.)*	[22] - [25]

Note: Variables placed in brackets occur less frequent in available models and the asterisk is used to indicate their occurrence: *** = frequent; ** = moderate; * = rare

In order to choose the modelling approach that fits best with the considered application, it is necessary to find out the optimum trade-off between the needed accuracy and the computational time/effort. If the aim of simulation is the heat pump rating, the accuracy is for sure one of the most relevant KPI, together with the ability to reproduce the transient behaviour in operation. To the best of our knowledge, while there are different models/library available to simulate heat pumps, there are not validated tools that could be used straightforward for such general application of industrial heat pumps rating, without customization.

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