Technology Collaboration Programme
by iea

Technology Collaboration Programme on Heat Pumping Technologies (HPT)

Annex 56

Digitalization and IoT for Heat Pumps

Task 3: Data analysis

Task Report

Operating Agent:
Veronika Wilk
AIT Austrian Institute of Technology

September 2023
Report no. HPT-AN56-4

Published by Heat Pump Centre
c/o RISE – Research Institutes of Sweden
Box 857, SE-501 15 Borås
Sweden
Phone +46 10 16 53 42

Website https://heatpumpingtechnologies.org

Legal Notice

Neither the Heat Pump Centre nor any person acting on its behalf:
(a) makes any warranty or representation, express or implied, with respect to the information contained in this report; or
(b) assumes liabilities with respect to the use of, or damages, resulting from, the use of this information.
Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement recommendation or favouring.
The views and opinions of authors expressed herein do not necessarily state or reflect those of the Heat Pump Centre, or any of its employees. The information herein is presented in the authors' own words.

Production Heat Pump Centre, Borås, Sweden

ISBN 978-91-89821-69-9
Report No. HPT-AN56-4

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 56. 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:
Heat Pump Centre
c/o RISE - Research Institutes of Sweden
Box 857, SE-501 15 BORÅS, Sweden
Phone: +46 10 516 53 42
Website: https://heatpumpingtechnologies.org

Operating Agent

Annex 56 on Digitalization and IoT for Heat Pumps is coordinated by the Operating Agent:

Veronika Wilk veronika.wilk@ait.ac.at
AIT Austrian Institute of Technology, Center for Energy

The Annex is operated from 01/2020 to 12/2022. Further information is available on the Annex website https://heatpumpingtechnologies.org/annex56/

Participating countries

The following countries participate in Annex 56:

- Austria
- Denmark
- France
- Germany
- Norway
- Sweden
- Switzerland

A detailed presentation of the national teams and their research work is available on the Annex website https://heatpumpingtechnologies.org/annex56/participants/

Participants and contributors to this report

This task report is the result of a collaborative effort with contributions from various authors that are listed in the table below. The report was coordinated by the Task leader Tim Rist, tim.rist@ise.fraunhofer.de

Please cite as:
IEA HPT Annex 56 Digitalization and IoT for Heat Pumps, Task 3 report: Data analysis, 2023.

DOI 10.23697/dymh-5x14

Danny Günther Tim Rist	Fraunhofer ISE	Germany
Reinhard Jentsch Regina Hemm Bernd Windholz Veronika Wilk Gerhard Zucker	AIT Austrian Institute of Technology	Austria
Goran Music Gernot Steindl Wolfgang Kastner	TU Wien	
Jonas Lundsted Poulsen	Danish Technological Institute (DTI)	Denmark
Kristian Stenerud Skeie	SINTEF Community	Norway

Foreword

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

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

IoT is also associated to different important risks and requirements to connectivity, data analysis, privacy and security for a variety of stakeholders. Therefore, this Annex has a broad scope looking at different aspects of digitalization and creates a knowledge base on connected heat pumps. The Annex aims to provide information for heat pump manufacturers, component manufacturers, system integrators and other actors involved in IoT. The Annex is structured in 5 tasks:

Task 1 – State of the Art:

This task summarizes the state of the art and gives an overview on the industrial Internet of Things, communication technologies and knowledge engineering in automation. It reviews the status of currently available IoT enabled heat pumps, heat pump components and related services in the participating countries and provides information on information security and data protection.

Task 2 – Interfaces:

This task identifies requirements for data acquisition from new built and already implemented heat pump systems and provides information on types of signals, protocols and platforms for different heat pump use cases in buildings and industrial applications.

Task 3 – Data analysis

This task gives an overview on data analysis based on examples of IoT products and services, Different targets for data analysis are derived, data analysis methods are categorized and assessed, starting with visualization and manual analysis reaching to machine-learning algorithms. The report provides insights in the pretreatment of data, the use of data models, meta data and BIM (building information modeling).

Task 4 – Business Models

This task evaluates market opportunities created by connected heat pumps and presents different types of IoT services and business models based on literature and market research including detailed SWOT analyses (strengths, weaknesses, opportunities, and threats).

Task 5 – Dissemination

This task aims at reporting results and disseminating information developed in the Annex. Interactions and synergies with other Annexes or Tasks in the IEA Technology Collaboration Programs are sought.

IoT for heat pumps

Table of Contents

1 Introduction

Task 3 gives an overview on data analysis in the context of connected heat pumps. The aim of data analysis is to make wise use of the collected data to provide targeted information e.g. for the optimized operation of heat pumps. Based on the examples of IoT products and services, that are presented in Task 1, different targets for data analysis are derived. Data analysis methods are categorized and assessed, starting with visualization and manual analysis reaching to machine-learning algorithms that learn from the user's behavior in the past to optimize heat supply or big data methods learning from a large number of heat pumps, how specific heat pumps are performing compared to others and how to improve. Furthermore, the report provides insights in the pretreatment of data, the use of data models, meta data and BIM (building information modeling).

2 Pre-treatment of data

The application of data analysis methods relies heavily on the quality of the available data. In the context of buildings and heat pumps such analyses are mainly concerned with time series data. In this case, proper data acquisition and storage is of paramount importance, because repetition of measurements usually is no option and thus any missing data is lost to the analyses. Data acquisition is in parts covered in the Task 2 report. Once the time series data has been stored persistently, data quality checks have to be performed to allow interventions at the acquisition chain if need be. Then, proper pre-processing of the time series data structures the data according to the respective analysis method.

Based on previous work of the partners, some general guidelines for the pre-processing of data can be derived. Whereas an extensive discussion of pre-treatment of data would be beyond the scope of this report, the following section delivers condensed take-aways of these projects.

Based on the original data sources, some notes about the quality of measurements can be made:

Temperature probes

- Both the surface clamp-on pipe kind and the type inserted within pipe tees (or into heat exchanger ports) can be in poor contact with the medium, leading to low accuracy and slow response time.
- Air temperature sensors can be under the influence of fans and internal heat gains of the unit or to direct sunlight if not shielded properly.

Power meters

- Cumulative meter readings (for heat, energy, or water) transformed into mean values using a difference operator often have an inferior resolution compared to instantaneous values.

» When the actual power (or flow) is measured at too sparse sampling time resolution, obtaining the mean values from accumulated meter readings may be advisable.

Furthermore, following preliminary assertions for initial pre-processing can be formulated as best practices:

» Variables are named correctly, and scaling (units) are as expected/documented.

» Data is parsed correctly into the data platform (timestamps, missing values) and checked for missing values or timestamps on regular intervals.

» Time zones are set correctly, especially when joining data of different origins.

» Synchronization issues are checked if multiple data acquisition systems are used.

» Correct averaging is ensured, especially for variables with high-frequency variation such as control signals. If some variables are averaged or filtered, the same method must be used for all variables.

A good starting point can be to begin an analysis by grouping data and applying filters:

» Time series should be plotted over different durations, e.g., a couple of days and the full period. Checks for outliers, frozen values, and other irregularities should be applied. It might be useful to use boxplots to plot diurnal cycles for each hour of the day etc.

» Statistical methods for anomaly detection (or simple physical thresholds) can be used to flag data for manual inspection, discard samples or mark points for interpolation.

» Variables that denote operating conditions (operating modes, defrost cycles, functioning of fans and circulation pumps, etc.) should be derived or identified.

» Data should be filtered based on given conditions or modes and calculate performance indicators.

» The length of operating cycles should be identified, and averages should be calculated to make comparisons.

In use cases where data ingestion is to be performed repeatedly to prepare data for downstream use, additional automation and robustness of the processes can be achieved through additional measures. Such as:

» A predictable data processing pipeline using formalized rules, like ETL (Extract, Transform, Load) principles.

» A scalable data pipeline to meet growth in data throughput, it is reliable and testable.

» Data to be stored in a database or streamed via a REST API / MQTT to be used by others must be enriched with meta-information and should be provided with documentation.

» If time-series are to be used in a simulation model chain, it may have to meet specific requirements on the quality e.g., no gaps or double counting and no missing data points etc.

Data enrichment techniques can be utilized, to obtain information that is not directly available. Especially, meteorological data can be accessed for reference or to augment data measured on site. Many meteorological agencies have (open) APIs that can be used to acquire observations from nearby stations or access high-resolution gridded data that can be interpolated to the site. Weather service providers return kilometer-scale weather forecasts of elements that are rarely measured on-site (like shortwave and longwave irradiance, windspeed and soil temperature, etc.). An example is *open-meteo.com* that stores several months of past forecasts from multiple providers and their API is open and free to use for non-commercial purposes [1].

Example from an analysis in the ZEB Laboratory project with two on/off heat pumps operating

- All the available variables from the heat pump controller unit, energy and electricity meters, circulation pumps and secondary temperature circuits were recorded every 1 minute.
- Only a single heating meter was installed on the sink side water loop, but operating modes were used to distinguish between periods where each of the units were running separately or combined.
- Only operation cycles longer than 20 minutes were considered in performance analysis. The first 5 minutes (start-up period) and the last 1 minute were excluded from analysis in COP calculations. Average temperatures, power, and COP (per cycle) were calculated and stored as a new complementary dataset.
- The electricity use under defrost and start-up mode was also analysed separately since the hydronic meter readings from these periods were not usable.
- It was found from analysing the temperature difference and the total flow meter that the circulation flow to each heat pump differed by nearly 50 % due to a faulty valve.
- Another finding was that the control strategy during the analysis period led to far too many short operating cycles, mostly occurring without heating demand in the building.

Further insights in the ZEB Laboratory project are available in the factsheet and the Task 2 report.

3 Use of data models, meta data, and BIM

While the previous section mainly addressed time series data gathered through measurements at the heat pump or building, the analysis of such data usually requires additional information in form of static or semantic meta data. For instance, details on the used sensors, like the unit of measure, must be available to allow analyses to process their readings properly. But also, meta data on the building (like size, year built, etc.) and the technical appliances needs to be made machine readable to allow generalization and automation of analyses. In buildings, such information is usually available in form of text documents. Building Information Modeling (BIM) is a comprehensive digitalization method for buildings and aims to consolidate the large number of different information sources throughout the life cycle of a building (see also section 2 of the Task 1 report on the State of the Art). The key is to use one single model which contains geometry and data information, that is needed to support different phases of the building life cycle like planning, construction, operation, and maintenance of the building. In future, all such information should be made machine readable through BIM. Yet, up to now most standards in the field of BIM, like the openBIM standard Industry Foundation Classes (IFC) [2], focus mainly on the geometry aspect of buildings and HVAC components. As such, there is no major standard that allows the digitalization of all required information. Instead, such meta data would usually be stored in a proprietary data model, suitable for the task at hand.

Since the need of standardized information also plays its role on the level of data exchange, modern communication standards like BACnet and OPC UA also incorporate data models that go beyond that the description of sensor attributes.

3.1 Representation of HVAC components in BIM

To cope with the fact, that HVAC components such as heat pumps are currently hardly represented through IFC in a standardized way, the Austrian research project metaTGA developed for 56 standard HVAC components (domain heating and ventilation) detailed property sets, to be able to model and represent these components in a BIM project [3]. The property sets are highly detailed in order to be used by different stakeholders (e.g. architects, different HVAC-planners, and facility managers), in various development stages (planning, construction, maintenance) and applications. More than 800 different properties are considered to cover the entire life cycle from design to operation of a building. The sets are available for download on the project website for further use [4]. In addition to that, process models of how to use the property sets in BIM projects and process models of how to create own data sets are also available.

The key aspect of BIM is that information is up to date and (re)usable for different stakeholders. A comprehensive BIM model can be used for the operation and maintenance of the building. Accurate energy information for e.g. heat pumps is an important prerequisite for further applications in the building energy management.

3.2 Leveraging Industrial IoT Data Models for Building Systems

The technological spectrum of Industrial Internet of Things (IIoT) is extremely wide and entails semantic web and IP-based protocols as well as semantic description and information exchange technologies in automation-adjacent domains. One of the main stated goals of the IIoT is to focus on integrating these different (also legacy) technologies into a transparent, seamless, coherent, and networked unit. The functional and operational (“runtime”) aspect of automation systems, i.e. entities or “Things” in general, is most consequential for the quality of end-systems, yet at the same time proportionally least researched topics in the context of IIoT and Industry 4.0. Due to its nature as a result of all preceding engineering disciplines, the operational aspect can be utilized as a common denominator for related domain specific representations.

As a case study on how such IIoT data models can be leveraged for building systems, a core information model supporting modeling of the operational aspect of HVAC circuits has been built. OPC UA has been chosen as the modelling technology, as it is most closely related to runtime systems representations, as well as aligned with a large number of different standards and technologies, offering advantages in the context of integration and transformations between different domain models, as well as reusability. The created models of specific HVAC circuits can, on the one hand, be used directly for the generation of OPC UA nodes and data structures, which are infused with real-time data at runtime. On the other hand, by using further transformations and OPC UA integrations, it is possible to generate projections (i.e. “shadows”) to a wide range of different representations and technologies, and vice versa.

For transformations and integration of different domain models to be enabled, different data sources must be interconnected and synthesized with contextual information. Semantic web technologies are especially suitable for this purpose. Different contextual information, such as the structural composition of the building and HVAC systems, can be modelled using dedicated domain ontologies, e.g. Building Topology Ontology (BOT), Brick Schema or Semantic Sensor Network Ontology (SSN). A method has been developed, which enables generation of domain specific ontologies from the created OPC UA HVAC circuit models, and Ontology-based Data Access (ODBA) to contextualized runtime information and data. Sensor data and HVAC system information are thereby connected with a knowledge graph. This linked-building data can be utilized in, e.g., (semi-) automatic runtime sensor data analysis. Figure 1 illustrates the method of Linked Building Data.

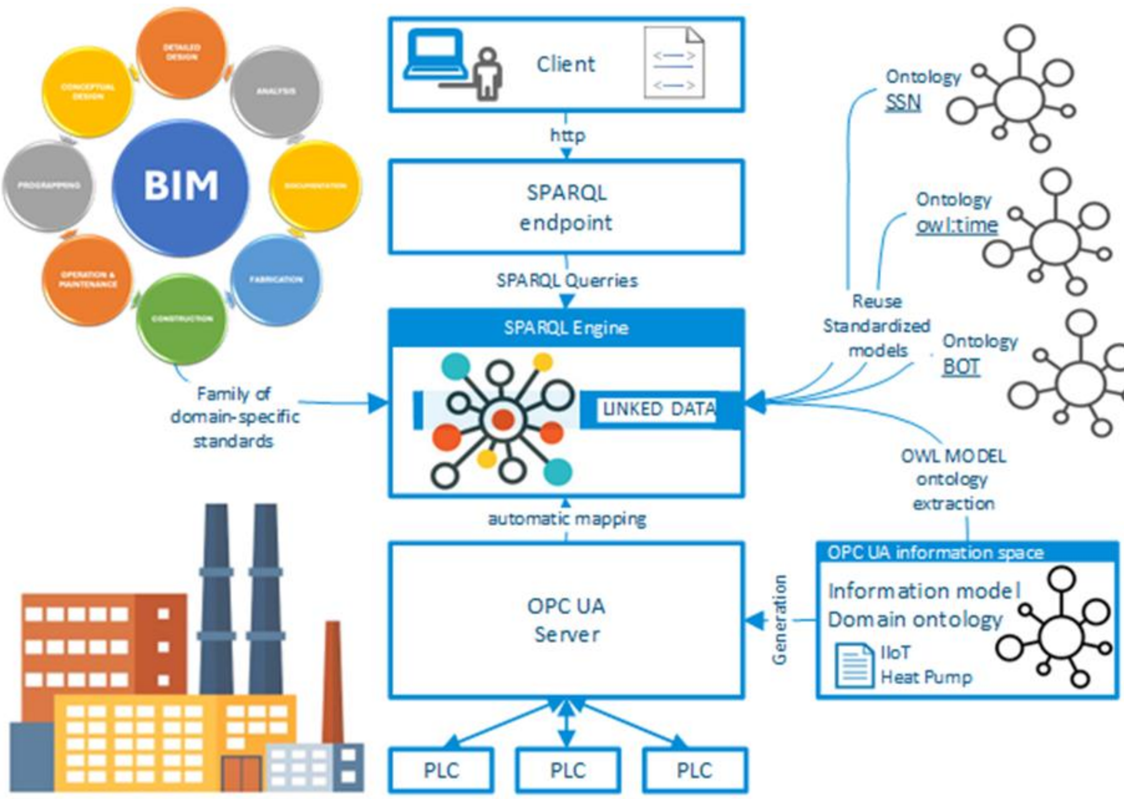

Figure 1: Linked (Building) Data - runtime data from the field into the knowledge base

4 Data analysis methods

4.1 Introduction on data analyses methods in the context of buildings

As described in the report of Task 1, a multitude of data driven applications are utilized in the context of IoT, especially in industries. Ever increasing amounts of data allow big data methodologies, in which statistical methods and machine learning are leveraged to give new insights and automate real time supervision of processes. The building sector however, historically showed slow adoption of such methodologies. One reason can be seen in the lack of proper data. The main source for measurement data from buildings is the measurement equipment installed for control purposes, mainly in the case of non-residential buildings, through a building automation system (BAS). Due to cost factors these usually only contain data points, which are essential for operation. Furthermore, improper commissioning and degradation over time leads to wrong readings and bad data quality. Both are related to lack of personnel to address or even notice failures. Many data driven applications rely on a central data storage. Here, the diversity of interest groups involved during the operation of buildings can hinder the transfer of data outside of the building. Finally, the heterogeneity of buildings makes it hard to standardize analyses of buildings at scale. Especially, detailed building simulations are typically mainly found in academic applications. In future, BIM may help to improve adaption of analysis routines to a building at hand.

With the use of IoT many of the mentioned issues can be bypassed. As such, the IoT equipment is independent of existing measurement equipment and addresses the transfer of data out of the building as a base prerequisite. By focusing the single devices, like a heat pump, the complexity of analysis task is reduced. The transfer of siloed solutions into a connected ecosystem then poses a next step, as can be sees in the smart building sector.

4.2 Analysis methods from use cases addressed in the Annex

Throughout the Annex project the partners gathered a collection of use cases related to IoT in heat pumps which are documented in the Task 1 report. In parts the use cases are taken from national research projects of the partners or are based on information provided by the heat pump manufacturer or the IoT service provider, while others are derived from publicly available information of products and services. Overall, 44 use cases are provided by the project partners of which 25 are on a research project level (low to medium TRL) and 19 are on product level (TRL 9). To describe those use cases, a comprehensive framework was developed covering a wide range of information, such as the type of use case, beneficiaries and stakeholders, technical information on data acquisition, transfer and processing, learnings, and technology readiness level. All the information is summarized in dedicated factsheets that is available on the IoT Annex website. An overview on the use cases is presented in the Task 1 report.

A total of 34 different items were assessed in the framework. To gain specific information for

- description of data analysis (DA) methods
- clustering/categorization of DA methods and
- qualitative assessment of DA methods,

11 of those items are directly linked to data analysis and further explained with some examples from different use cases in Table 1.

Table 1: Information from use case description linked to data analysis.

Item	Examples from different use cases
IoT aspect	- Heat pump operation data is transferred and aggregated in the cloud for predicted maintenance. - Heat pump directly exchanges data with IoT based control system/server.
Location of intelligence	- Cloud - Energy management system - Heat pump
Operation data required	- Performance data; temperatures; pressures; mass flows - Emission forecasts; operation states of other facilities; load profiles; weather forecasts; price forecasts - Compressor capacity information; temperatures; electricity prices
Semantic data required	- Building meta data (like size, year built, etc.); energy system meta data - Type of building (light or heavy building); user profile - Operational boundaries; operational characteristics; safety margins
Analysis or data processing methods	- Control engineering; visualization; decision support; optimization - Fault detection; alarms; comparison - Grey-box model; forecasting; control; model predictive control (MPC)
Implementation details	- Development of self-learning dynamic models that can give inputs to performance optimization. - An optimizer, using market/ heat pump / building model constraints, calculates optimal operation schedules for the heat pump considering comfort parameters for the user.
Modelling Requirements	- Validated dynamic model of heat pump system needed, can be created in Dymola and exchanged as FMU. - Requires dynamic models for the controller where the temperature control is performed by inputs from floor and room models, with feedback from the physical system. The building model is developed in Dymola (Modelica) and imbedded in a python script as a FMU.
Application Requirements	- Hardware modules (communication, power meter) need to be installed at costumer. - Deployment on controller of heat pump (ideally no additional hardware required). - Development of a control kit needed, includes development of room model, floor model, room temperature control.

Item	Examples from different use cases
Incoming data (to the heat pump)	- Heat pump control parameters - Inlet/outlet temperatures; mass flows; pressure; outdoor temperature - Heat pump controller setpoints and price signals for control based on incentives
Outgoing data (from the heat pump)	- Current room temperatures; current temperatures of hot water storages - Power consumption - Internally available operation data of heat pump
Quality of service (QoS) of the connection	- Daily, hourly, real-time - Seconds; real-time - Minutes

Most items such as “Incoming data (to the heat pump)”, “Outgoing data (from the heat pump)” or “Location of intelligence” could be complemented with explicit information. Other categories, for example “Modelling Requirements”, contain information on different levels. Same with the most significant category “Analysis or data processing methods” what is precisely focused within Task 3. The examples of this items shown in Table 1 illustrate the different levels of the given information. For example, control engineering and fault detection belong to a group of targets whereas visualization and MPC rather belong to a group of methods. Accordingly, a hierarchy considering main IoT use case categories, data analysis targets and data analysis methods was introduced that is further detailed in the following.

5 Categorization of data analysis methods

As mentioned in chapter 4.2 the categorization of analysis methods is based on the information gathered by the project partners according to each use case. Because of lacking information, particularly for the use cases representing products (TRL 9) only 16 use cases are considered in this evaluation. Hence, from the 16 remaining use cases only 3 use cases belong to the product category (Tiko, Smart Guard, Hi Kumo pro), the others are research projects.

To systematically evaluate the data analysis methods of the use cases, they are further categorized along the aspects of the specific target to be reached by the analysis method and the way on how these targets are reached. This analysis target usually aligns with the overall IoT category of the use case. Subsequently each use case has been assigned an IoT category, analysis target(s), and analysis method(s). The summary of those attributes derived from the 16 evaluated use cases is displayed in Figure 2.

Most of the use cases are attributed to a single IoT category, but often address various DA-targets and DA-methods. For example, the IoT category “HP Operation Optimization” can be targeted with “Control engineering” and “Comparison with other HPs” using “Visualization and manual analysis” or “Machine Learning” as methods. During the categorization process it became clear, that an explicit distinction between IoT category and targets as well as targets and methods is not possible. Additionally in some cases the indication of the targets and the methods applied here does not necessarily correspond to the official definitions. Thus, further explanation of the differentiation is presented in the following sections.

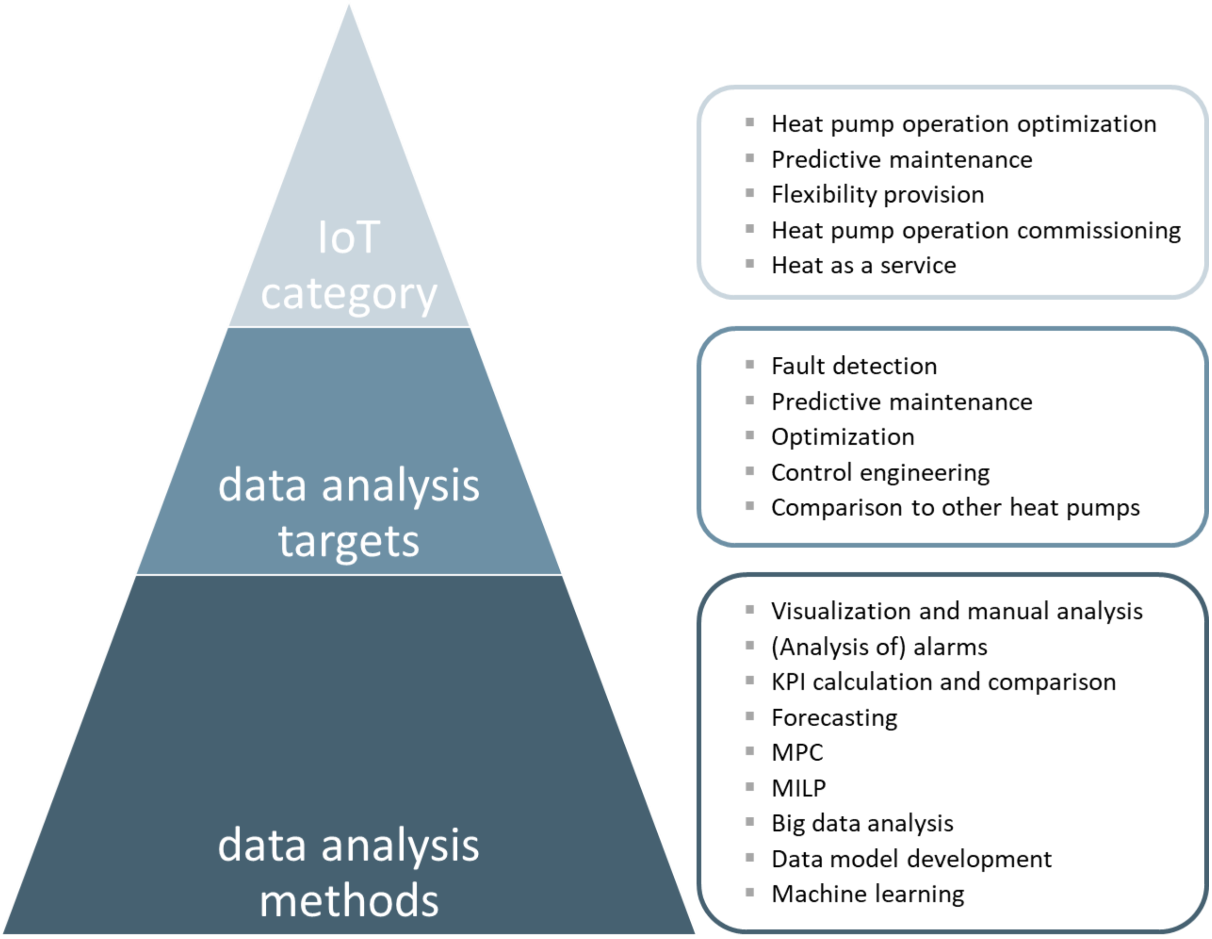

Figure 2: Hierarchy derived from the use cases: IoT category, data analysis targets and data analysis methods

There are 5 **IoT categories** considering different fields of application in terms of IoT-services. “Flexibility Provision” and “Heat as a service” address rather commercial applications. The remaining 3 categories address the field of appropriate heat pump operation in different phases of the heat pump life cycle. Starting with “Heat pump operation commissioning” towards “Heat pump operation optimization” and “Predictive maintenance”. Especially the category “Heat pump operation optimization” covers a wide field of applications, reaching from the improvement of heat pump operation to the explicit optimization of heat pump operation using appropriate mathematic algorithms.

The intermediate level consists of 5 **data analysis targets** which partly overlap with the categories and methods. For example, “Predictive maintenance” is defined as a category as well as target since it can both function as an overall category as well as the direct target of a specific analysis. The category “Heat pump operation optimization” mostly overlaps with the target “Optimization”, whereas the DA-target “Optimization” also links to “Predictive maintenance” and “Heat pump operation commissioning”. Furthermore, with MILP (Mixed integer linear programming) a certain mathematical optimization method is stated within the data analysis methods. The data analysis target "Control engineering" covers a wide range of applications and is characterized by any kind of deviation in the operation of the heat pump compared to the initially set standard control. Thus, "Control engineering" ranges from simple on/off-control of heat pumps to realize "Flexibility provision" to adapted heat pump control for "Heat pump operation optimization".

The derived 9 **data analysis methods** should indicate the very basic methods in terms of data analysis and consider methods on different levels e.g., "(Analysis of) alarms" and "Machine learning". The methods "Visualization and manual analysis", "KPI calculation and comparison" and "(Analysis of) alarms" are options of usual pre-processing of measurement data. "Forecasting" refers to any kind of forecast such as whether forecast data or the presence of residents in a house. The methods "MPC" (model predictive control), "MILP" (mixed integer linear programming), "Machine learning" are standing terms and applied as such. For one use case "Big data analysis" is mentioned; here, a strict match to definitions according to amount of analyzed data as well as used analysis architecture is not further investigated. The "Data model development" is listed here as method of data analysis in the sense, that the development of a data model typically must be performed on parts of the application data. The resulting model could then contribute to all other data analysis methods.

Table 2 provides an overview on the evaluated use cases, their IoT category, the data analysis targets and methods. It also indicates the applied models. Further details on data analysis are compiled in section 8.

Table 2 Listing of data analysis methods from use cases with the respective analysis targets

Data analysis targets				
Fault detection (FD)	Predictive maintenance (PM)	Control engineering (CE)	Optimization (OPT)	Advanced system monitoring (ASM)

Use case	IoT category	Data analysis methods: Visualization and manual analysis	(Analysis of) alarms	KPI calculation and comparison	Forecasting	MPC	MILP	Big data analysis	Data model develop-ment	Machine learning	Applied models
Flex+	Flexibility provision						OPT				RC-Buildung-Model; COP model
tiko power	Flexibility provision							CE			grey-box model
Hi Kumo Pro	HP operation optimization	FD									
EnergyLab Nordhavn	HP operation optimization	OPT			OPT	CE OPT				CE OPT	dynamic simulation model black-box model
Flexible Energy Denmark	HP operation optimization				OPT CE	OPT CE					grey-box model
Center Denmark (Eur. Digi-Hub for Smart E-Systems)	HP operation optimization	PM		PM	OPT CE	OPT CE		OPT	OPT CE	CE	grey-box model, semi-parametric models,
DZWi	HP operation optimization, HP operation commissioning, Predictive maintenance	FD PM	FD PM	FD PM OPT	OPT CE	OPT CE			FD PM OPT	FD PM OPT	grey-box model
EDCSproof	HP operation optimization					OPT CE	OPT				grey-box model
EnergyMachines "EMV"	HP operation optimization	PM CE OPT		PM CE ASM							
DIBA-WP	HP operation optimization			OPT							Buildung/floor heating-Modell; HP model
OPSYS 2.0	HP operation optimization			CE	OPT	CE OPT	OPT				Building model (Dymola) Battery model and controller (Python) PV model (Python)
Smart guard	Predictive maintenance	FD PM OPT		OPT							
ZEB Lab	HP operation optimization, Predictive maintenance	FD PM		FD PM	OPT CE						RC-Buildung-Model for OPT/CE, COP model for OPT/FD/PM
Digital Twins for large scale heat pumps (1-3)	HP operation optimization, HP operation commissioning, Predictive maintenance	FD PM OPT ASM FD PM OPT ASM		FD PM OPT ASM FD PM OPT ASM	OPT ASM OPT ASM	CE OPT CE OPT		FD PM ASM FD PM ASM	FD PM CE OPT ASM	FD PM FD PM CE OPT	dynamic and quasi-dynamic simulation models grey-box model

6 Conclusions

A hierarchy was determined to differentiate IoT category, data analysis targets and data analysis methods. Some findings can be derived when further comparing the targets of the data analysis methods with the IoT categories of the use cases. The two use cases with the category “flexibility provision” use data analysis methods with slightly different targets; one uses “MILP” to realize “optimization”, while the other uses “big data analysis” for direct “control engineering”. As such, the applied methods are suited for different levels of detail which also holds for the utilized models.

All six use cases, which use data analysis methods that target “Predictive Maintenance” rely on “Visualization and manual analysis” as well as “KPI calculation and comparison” (with one exception). Four of these also target “Fault detection”. This makes sense since fault detection and predictive maintenance are closely related. Likewise, data analysis methods targeting for “Advanced system monitoring” also seem to be related. On the other hand, only two use cases also state “Predictive maintenance” as the IoT category, while the others address “Heat pump operation optimization”.

All use cases in the category “Heat pump operation optimization” but one utilize data analysis methods which also state some sort of “Optimization” as target. These data analysis methods are typically also used for “Control engineering. Usage of data analysis methods “Forecasting” and “MPC” stand out as a typical combination towards this goal, often through grey-box models.

Modeling and data analysis are core activities for IoT enabled heat pump products and services, as they allow for making wise use of the collected data to provide targeted information for the required purposes. Most of the information on data analysis was derived from research projects because this information is openly available. However, this should not lead to the conclusion that data analysis is only used in research projects. There are many more IoT enabled heat pump products and services available, where this information is not disclosed. Further details on already implemented business models and services are presented in the Task 4 report.

7 References

[1] "Features | Open-Meteo.com." https://open-meteo.com/en/features#terms (accessed Apr. 13, 2023).

[2] "Industry Foundation Classes (IFC)," *buildingSMART International*. https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/ (accessed Apr. 13, 2023).

[3] S. Hauer, J. Murschetz, A. Bres, A. Sporr, M. Schöny, and M. Monsberger, "metaTGA: a chance for BIM in the field of MEP," *Bauphysik*, vol. 42, no. 6, pp. 345–351, 2020, doi: 10.1002/bapi.202000028.

[4] "Ergebnisse – metaTGA." http://www.metatga.org/ergebnisse/ (accessed Apr. 13, 2023).

8 Further information on use cases used for analysis

8.1 Flex+

General information: Heat pumps provide information such as storage and building temperatures. The pooling is done by the component manufacturer and an optimization is run where the heat pump is modelled based on heating curves and a building model. The pool is moreover receiving market data from suppliers via the Flex+ platform. An optimization algorithm creates an optimal schedule for heat pumps and calculating which products to bid at the balancing markets. This information is transferred via the Flex+ platform to the suppliers, which are trading these amounts at the markets. Activation signals for balancing markets are also transmitted to the heat pumps; via the Flex+ platform and the pools of component manufacturers. (Additional information: in Flex+ there are also a boiler, a battery, and an EV pool, but these should not be mentioned here in further detail)

Country of application	AT
IoT category	Flexibility provision
Type of use case	HP pooling
Topics	operation, market participation, spot markets, balancing markets
Location of intelligence	server solution
Incoming data	Csv file with 15min rounds per second (rps) values, modular signal; SmartGrid Ready Label
Outgoing data	Current room temperatures; current temperatures of hot water storages

Connection platform	wired (via internet/router of the customer)
Protocols	TCP, ModbusTCP
QoS of the connection	daily; hourly (when ID), real-time
Technology Readiness Level	4-7
Availability	research project
Additional Information	www.flexplus.at
DA-Method	Optimization (MILP); RC-Building-Model
Implementation Details	An optimizer, using market/HP/Building-model constraints, calculates optimal operation schedules for the HP considering comfort parameters for the user.
Modeling requirements	linearized model optimization: Mixed Integer Linear Programming (MILP); HP-model: performance map modelling of the HP (thermal power, electrical power according source and outdoor temperature); Building model: RC model is calibrated with historical data (rolling horizon) and used as constraint in the optimizer, with the aim to convert thermal power input from the HP (optimization variable) +solar irradiation + outdoor temperature into a room temperature (aim of the optimizer is to meet comfort criteria); single simulation of each object, additionally hot water storage or domestic hot water storage if available as simple capacity models; Market constraints: Optimizer aims to consume at the times, where prices are low (variable price curve as input) and to place balancing products at times with the highest rentability, as well as reserve power for rebuy, in case that the activation differs from the expected activation and comfort criteria cannot be met anymore. Required input data: Day-Ahead price forecast data, Intraday price forecast data, balancing price forecast data at two different merit-order-list positions and a correlating call probability to each one
Application Requirements	For similar objects: realize data connection from HP to Server (manual adding IP address in a list of connected HPs); manual collection of semantic data about building, heat transfer system from data sheets, questionnaires, and from the HP

	(performance map); measurements and regression model of performance map (heating curve) of the HP; manual copy of HP/building-model; manual parameterizing of the building model and the HP-model according semantic data; operational data feed HP-model automatically after manual implementation of the data flow For different objects: assumption: MFH instead of SFH; same steps as for same/similar objects plus; adapting building model (effort depends on the type of model for the assumed SFH)
Operation data required	heating curves, temperature forecast, heat source temperatures, weather forecast, forecast hot water demand; accepted schedules, activation signals, min/max temperatures for building and storage (from now: this data does not arrive "in the component itself" but is rather necessary for calculations within the pool/processes related to that) calculated balancing bids, price forecasts, calculated schedules
Semantic data required	Building meta data (i.e. building dimensions, window wall ratio, number of heating circuits, mass flow rate of heating circuits, thermal capacity and u-values for building masses; information from "energy certificate") With empirically gained manufacturer heating curves, rps(P) and rps(Q), a linearized curve Q(P) (calculated newly in every timestep, depending on current heat source temperature and outdoor temperature) is used for optimization

8.2 tiko power

General information: Data analysis based grid balancing service. Switching HPs and PV on and off depending on grid situation and price incentives.

Country of application	CH
IoT category	Flexibility provision
Type of use case	HP pooling
Topics	grid, operation
Location of intelligence	cloud
Incoming data	forced switching of HP on/off via installed hardware
Outgoing data	power consumption

Connection platform	Power Line Communication (PLC), GSM (3G/4G), wired, Aggregated heat pump data is sent via Gateway to cloud. In the cloud algorithms calculate optimal switching on/off of the individual devices. The heating devices are blocked/released with a signal from the cloud trough the gateway to the heat pump.
Protocols	TCP-IP, Modbus RTU, Modbus TCP
QoS of the connection	seconds, real-time
Technology Readiness Level	9
Availability	available
Additional Information	https://tiko.energy/
DA-Method	big data analysis, control engineering
Implementation Details	Data analysis is used to determine the energy consumption-characteristics of the heating devices depending on local weather conditions and other parameters. Based on this the algorithm (in control of service provider Swisscom Energy Solutions) takes the control actions (on/off) in real time for the individual devices in the network due to the request of the grid operator (Swissgrid). Due to the pooling Swisscom Energy Solutions are allowed to participate in the secondary grid market. Leading to a peak shaving of the energy grid load. Grid connection of HP and PV are remotely controlled in real time from the service provider within defined boundaries to ensure comfort of the inhabitants and prevent lifetime reduction of the HP (limited number of switch actions).
Modeling requirements	Data driven model
Application Requirements	Hardware modules (communication, power meter) need to be installed at costumer
Operation data required	power consumption, weather forecast, user behavior (optional inputs e.g. absence), grid prices, grid operator demands
Semantic data required	type of building (light or heavy building), user profile

8.3 Hi Kumo Pro

General information: Analyses based on alarms, direct and instantaneous access to operational data (operating modes, discharge temperature, evaporation temperature, compressor frequency) and history backup for 3 months, alerts in case of malfunction with fault code, it is accessible for exclusive reseller and maintenance companies

Country of application	worldwide
IoT category	HP operation optimization
Type of use case	Remote access for on-site maintenance
Topics	efficiency, operation, availability
Location of intelligence	heat pump
Connection platform	wired Wired box to be connected to the HP and Hi Box to be connected to the internet box
QoS of the Connection	real-time
Availability	available
DA-Method	fault detection, alarms, comparison
Operation data required	performance data, temperatures, pressures, mass flows, storage data, indoor temperatures

8.4 EnergyLab Nordhavn

General information: Spare compressor capacity from supermarket refrigeration system is utilized for heat production to local space heating and local domestic hot water heating and for the district heating grid. A smart controller using price signals is used to decide whether heat is produced for local consumption or for the district heating grid.

Country of application	DK
IoT category	HP operation optimization
Type of use case	Utilization of heat pump capacities in supermarkets
Topics	operation, efficiency
Location of intelligence	heat pump

Incoming data	HP controller setpoints
Outgoing data	HP operation data, parameters/settings
QoS of the connection	real-time
Technology Readiness Level	7-9
Availability	research project
DA-Method	control engineering through integration of live price signal data in hp control
Implementation Details	a heat recovery control method was proposed and tested based on temperature measurements and incoming real time price signals.
Modeling requirements	no specific modelling requirements
Application Requirements	the application requires temperature measurements in the hot water storage tank where heat for local space heating and domestic hot water is stored.
Operation data required	compressor capacity information, temperatures, grid prices

8.5 Flexible Energy Denmark

General information: Heat pumps are controlled either by minimizing the cost of operation, efficiency, or by minimizing the CO_2 emission. The system can be linked to high level controllers for providing grid services. The system is called the smart-energy OS.

Country of application	DK
IoT category	HP operation optimization
Type of use case	Cloud based control of heat pumps
Topics	operation, efficiency
Location of intelligence	cloud, fog, edge
Incoming data	HP controller setpoints and price signals for control based on incentives
Outgoing data	power consumption, temperatures, parameter settings

QoS of the connection	near real-time
Technology Readiness Level	7
Additional Information	Hierarchical setup concerning "Location of Intelligence", Data lake is used to store the data, and cloud based control, self-learning models of the buildings or district heating systems
DA-Method	grey-box model, forecasting, control, MPC
Implementation Details	Typically, the model is built using the grey-box principles, which provides a data-driven digital twin model. Such models are optimized for assimilation of information from sensors and energy meters in near real time.
Modeling requirements	COP model, grey-box identification of buildings, heat pump, and disturbances like solar radiation and ambient air temperature, data-driven model of HP integrated in the thermal dynamic model of the building
Application Requirements	Typically, temperature measurements are needed
Operation data required	CO_2 forecasts, weather forecast, occupancy forecast, water temperature, air temperature, price forecasts
Semantic data required	building meta data (like size, year built, etc.), energy system meta data

8.6 Center Denmark

General information: Heat pumps are controlled either by minimizing the cost of operation, efficiency, or by minimizing the CO2 emission. The system can be linked to high level controllers for providing grid services. The system is called the smart-energy OS.

Country of application	DK
IoT category	HP operation optimization
Type of use case	Cloud based control of e.g. heat pumps
Topics	European Digitalization Hub for Smart Energy Systems, operation, efficiency (energy, cost, emission)
Location of intelligence	cloud, edge, cloud, fog

Incoming data	HP controller setpoints and price signals for control based on incentives
Outgoing data	power consumption, temperatures, parameter settings
QoS of the connection	near real-time
Technology Readiness Level	5-8
Additional Information	Hierarchical setup concerning "Location of Intelligence", Data lake is used to store the data, and cloud based control, self-learning models of the buildings or district heating systems
DA-Method	grey-box model, forecasting, optimization, control, MPC
Implementation Details	Typically, the model is built using the grey-box principles, which provides a data-driven digital twin model. Such models are optimized for assimilation of information from sensors and energy meters in near real time.
Modeling requirements	COP model, grey-box identification of buildings, heat pump, and disturbances like solar radiation and ambient air temperature, data-driven model of HP integrated in the thermal dynamic model of the building
Application Requirements	Typically, we need temperature measurements - and for comfort control we also need e.g. CO2 measurements, humidity, etc.
Operation data required	CO2 forecasts, renewable generation forecasts, weather forecast, occupancy forecast, water temperature, air temperature, price forecasts
Semantic data required	building meta data (like size, year built, etc.), energy system meta data

8.7 DZWi

General information: A heat pump data model allows uniform communication between plant, user and grid and is therefore the enabler for all digital twin applications.

Country of application	Ger
IoT category	HP operation optimization, Predictive maintenance, HP operation commissioning
Type of use case	data model development

Topics	operation, efficiency
Location of intelligence	cloud, heat pump, gateway, building management system
Incoming data	on/off signal, control parameters
Connection Platform	FIWARE
Protocols	FIWARE, Beckhoff
QoS of the connection	real-time
Technology Readiness Level	5-6
Availability	research project, available
DA-Method	control engineering
Operation data required	depending on the use case
Semantic data required	building meta data, hp parameters, hp settings

8.8 EDCSproof

Country of application	AT
IoT category	HP operation optimization
Type of use case	Integrating the HP with the rest of the energy system, Adaption of operation schedules and provide energy flexibility, operation state, market prices, prediction of load profiles of plant is available to model predictive controller in real time
Topics	operation, efficiency
Incoming data	on/off signal, setpoints
Outgoing data	power consumption, mass flows, temperatures, actual values
Connection Platform	PLC, wired
Protocols	S7-TCP
QoS of the connection	real-time
Technology Readiness Level	7
Availability	research project

DA-Method	control engineering, visualization, decision support, optimization
Modeling requirements	dynamical model, COP model, performance model, physical model
Operation data required	emission forecasts, operation states of other facilities, load profiles, weather forecasts, price forecasts
Semantic data required	operational boundaries, operational characteristics, safety margins

8.9 EnergyMachines "EMV"

General information: The Energy Machines Verification tool (EMV) is a combined hardware/software solution based on physical measurements, a service REST API (REpresentational State Transfer Application Programming Interface) and thermodynamic models of the heat-pumps, in order to provide online/live transparent performance monitoring of these, as well as to provide early warning systems for predictive maintenance (to-be-implemented). The tool is based on measurements of temperature and pressure, and enthalpy data for the refrigerant(s). It provides an alternative measurement to energy meters, but also extends beyond the limitations of these, as even more information can be extracted from the thermodynamic cycles.

Country of application	SE, PL
IoT category	HP operation optimization
Type of use case	Optimize HP operation
Topics	operation
Location of intelligence	cloud
Outgoing data	Temperatures, pressures, power from compressor, state of compressor (on/off)
Connection Platform	CAN, PLC, wired, cloud
Protocols	TCP, Modbus
QoS of the connection	Aggregated over 60 seconds
Technology Readiness Level	9
Availability	available

Additional Information	www.energymachines.com
DA-Method	Energy balances calculate COP, compressor efficiency, and heating/cooling production, etc.
Implementation Details	The calculations are uniquely timestamped, and results are made available on demand. To reduce noise from raw measurements, know-how of the system is applied (typical time constants). Data is sent to RESTful API, and a receipt is returned. Data is then processed in the backend located on a Kubernetes-enabled cloud. Upon requesting the receipt, the results are returned. Results include coefficient of performance, refrigerant flows, heat flows (cooling/heating) and accumulated/averaged values.
Modeling requirements	Measurements of temperature and pressure, as well as power from compressor, and knowledge of refrigerant and the cycle. Thermodynamic tables with all relevant state variables as functions of measurable temperature and pressure. Given the heat pump cycle, energy balances calculate COP, compressor efficiency, and heating/cooling production, etc.
Application Requirements	Live monitoring of HP performance provides total transparency between supplier and customer. A typical use-case would be if customer has been promised a heat-pump that can deliver a COP (Coefficient of performance) of 5, they can live monitor the COP and see if they are getting what they are promised. This can potentially lead to better performing heat-pumps, as suppliers can be held accountable. Combining EMV with data-driven machine learning models, which run as digital twins, may even reveal early signs of deterioration, and we expect predictive maintenance to be an added feature.
Semantic data required	Sensor measurements of pressures and temperatures around the refrigerant circuit. Data on heat pump layout.

8.10 DIBA-WP

General information: Automated monitoring and analysis of HP operating data to avoid HP efficiency losses.

Country of application	CH
IoT category	HP operation optimization

Type of use case	Operation analysis
Topics	Efficiency
Location of intelligence	Heat pump, Cloud (tbd)
Incoming data	HP-Control parameters, user notifacations
Outgoing data	operation data
Connection Platform	PLC, Embedded controllers, Cloud platform (tbd)
Protocols	TCP-IP, Modbus, others to be determined
QoS of the connection	Deferrable
Technology Readiness Level	2-3
Availability	research project
DA-Method	to be determined, statistical process control
Modeling requirements	ongoing, static model of HP, abstract model of heat transfer inside building
Application Requirements	deployment on controller of HP (ideally no additional hardware required) or cloud backend (tbd)
Operation data required	HP internally available operation data of the heating system (including HP data, ambient temperature and available system temperatures)
Semantic data required	Settings of HP-controllers, meta data of building

8.11 OPSYS 2.0

General information: The flows in the heating system (for single family house) is constantly optimized; and also controlled in such a way that heat is stored in the building/water tank when there is a surplus of (PV) electricity; or the system is stopped with a low amount of renewable electricity. The control of the heating system will be a self-learning; dynamic and modulating type. The control kit can optimize both the forward temperature from the heat pump and the flow rate through the heat emitting system. The temperature control is performed by inputs from floor and room models, with feedback from the physical system. The house model is developed in Dymola (Modelica) and imbedded in a python script as a FMU (Functional Mock-up Unit).

Country of application	DK
IoT category	Flexibility provision
Type of use case	Adaption of operation schedules and provide energy flexibility to the electricity grid
Topics	operation, efficiency
Location of intelligence	controller in the building management system
Incoming data	HP controller setpoints
Outgoing data	pressures, temperatures, flows
QoS of the connection	real-time
Technology Readiness Level	7-8
Availability	research project
DA-Method	control engineering.
Implementation Details	The control of the underfloor heating system will be a self-learning, dynamic and modulating type. This means that no complex manual fine-tuning is needed, and the flow is kept on the right level independently of the number of open circuits. The modulating approach secures the desired average valve setting by pulsing the power to the telestats (and later control thermostats on radiators) in order to obtain a desired opening degree of the valves.
Modeling requirements	Requires dynamic models for the controller where the temperature control is performed by inputs from floor and room models, with feedback from the physical system. The house model is developed in Dymola (Modelica) and imbedded in a python script as a FMU (Functional Mock-up Unit).
Application Requirements	Development of a control kit needed, includes development of room model, floor model, room temperature control.
Operation data required	performance data, temperatures, pressures, mass flows, weather forecast, PV production, storage data, indoor temperatures, grid prices
Semantic data required	The house model includes all constructions of the house, the underfloor heating system of the four rooms, internal gains

	(people and appliances), external gains (solar radiation through windows), and the ambient temperature.

8.12 Smart guard

General information: HP operation data are processed and visualized in the cloud. Maintenance dashboard allows HP-technician to have insight into HP operation status; important parameters. Operation failure can be predicted from the technician; when the customer is not aware.

Country of application	CH
IoT category	Predictive maintenance
Type of use case	Predictive maintenance
Topics	operation, efficiency
Location of intelligence	cloud
Incoming data	HP-Control parameters
Outgoing data	internally available operation data of HP
Connection Platform	GSM (3G/4G)
Protocols	information not available
QoS of the connection	deferrable
Technology Readiness Level	9
Availability	available
Additional Information	https://www.meiertobler.ch/de/loesung-und-produkte/smart-guard
DA-Method	visualization and manual analysis
Implementation Details	information not available
Application Requirements	remote access module of HP available
Operation data required	information not available
Semantic data required	information not available

8.13 ZEB Lab

General information: HP outlet temperature control via building management system with flexible HP operation strategy due to integration of other thermal sources (local district heating, thermal storage based on PCM).

Country of application	NOR
IoT category	HP operation optimization; Predictive maintenance
Type of use case	Integrating the HP with the rest of the energy system (HP combined with PCM thermal storage); Predictive maintenance
Topics	operation, efficiency
Location of intelligence	building management system
Incoming data	inlet/outlet temperatures, mass flows, pressure; outdoor temperature
Outgoing data	pump status; defrost status; temperature evaporator; compressor mode; operation mode;
Connection Platform	Wired, HP operational data transferred to a InfluxDB on the server for visualization and predictive maintenance
Protocols	Modbus RTU; BACNet
QoS of the connection	minutes
Availability	research project
DA-Method	Visualization; calculation of performance data; manual analysis; fault detection
Modeling requirements	hp-performance map, control of PCM storage
Application Requirements	Development of heat pump model for predictive maintenance; coupling measurements with model
Operation data required	water temperatures in the local grid, SOC of PCM, occupancy/schedule, indoor temperature, weather
Semantic data required	no semantics applied

8.14 Digital Twins (1)

General information: Analysis of functionality and performance; performance benchmarking; validity checks (installation errors); soft sensors.

Country of application	DK
IoT category	HP operation commissioning, HP operation commissioning
Type of use case	Advanced system monitoring
Topics	reliability, efficiency
Location of intelligence	energy manager
Outgoing data	pressures, temperatures, semantic data, mass flows, COP
QoS of the connection	deferrable
Technology Readiness Level	5-6
Availability	research project
Additional Information	http://digitaltwins4hprs.dk/
DA-Method	benchmarking, visualization, calculation of functionality and performance data, alarms, comparison with other heat pumps.
Implementation Details	Development of self-learning dynamic models that can give inputs to validity checks.
Modeling requirements	Validated dynamic model of heat pump system need. Can be made in Dymola and exchanged as FMU's.
Application Requirements	realize data connection from the heat pump to a server for data analysis; manual collection of semantic data about heat pump system, e.g. data sheets and questionnaires; development of dynamic model, including parameterizing; Set up of connection between Digital Twin and SCADA system
Operation data required	performance data, temperatures, pressures, mass flows
Semantic data required	Sensor measurements of power, pressure, and temperatures around the refrigerant circuit. data on heat pump layout.

8.15 Digital Twins (2)

General information: Current operation data is compared with historic data and other field measurements which can trigger early-stage warnings and predictive maintenance activities

Country of application	DK
IoT category	Predictive maintenance
Type of use case	Predictive maintenance
Topics	operation, efficiency
Location of intelligence	energy manager
Outgoing data	pressures, temperatures, mass flows
QoS of the connection	deferrable
Technology Readiness Level	5-6
Availability	research project
Additional Information	http://digitaltwins4hprs.dk/
DA-Method	visualization, calculation of performance data, alarms, comparison with other heat pumps
Implementation Details	The project develops a framework for fault detection and diagnosis that integrates a dynamic simulation model and different machine learning algorithms for classification
Modeling requirements	soft sensors, COP-model, machine-learning (failure detection)
Application Requirements	realize data connection from the heat pump to a server for data analysis; manual collection of semantic data about heat pump system, e.g. data sheets and questionnaires; development of dynamic model, including parameterizing; Set up of connection between Digital Twin and SCADA system
Operation data required	performance data, temperatures, pressures, mass flows
Semantic data required	Sensor measurements of power, pressure, and temperatures around the refrigerant circuit. Data on heat pump layout.

8.16 Digital Twins (3)

General information: Continuous set-point tuning and scheduling of production and downtimes by optimizing heat production by considering variable power prices and changes in cooling and heating loads for both daily and seasonal variations.

Country of application	DK
IoT category	HP operation optimization
Type of use case	Optimize HP operation
Topics	operation, efficiency
Location of intelligence	energy manager
Incoming data	HP controller setpoints
Outgoing data	pressures, temperatures, semantic data, mass flows, COP
QoS of the connection	real-time
Technology Readiness Level	5-6
Availability	research project
Additional Information	http://digitaltwins4hprs.dk/
DA-Method	fault detection, alarms, comparison, control engineering
Implementation Details	Development of self-learning dynamic models that can give inputs to performance optimization.
Modeling requirements	Validated dynamic model of heat pump system need. Can be made in Dymola and exchanged as FMU's.
Application Requirements	realize data connection from the heat pump to a server for data analysis; manual collection of semantic data about heat pump system, e.g. data sheets and questionnaires; development of dynamic model, including parameterizing; Set up of connection between Digital Twin and SCADA system
Operation data required	performance data, temperatures, pressures, mass flows
Semantic data required	Sensor measurements of power, pressure, and temperatures around the refrigerant circuit. Data on heat pump layout.

www.heatpumpingtechnologies.org

Heat Pump Centre
c/o RISE - Research Institutes of Sweden
PO Box 857
SE-501 15 BORÅS
Sweden
Tel: +46 10 516 53 42
E-mail: hpc@heatpumpcentre.org

Report no. HPT-AN56-4

www.heatpumpingtechnologies.org