Final report

1. Project details

Project title	Danish participation in IEA HPT Annex – IoT Annex – Digitalization and IoT for Heat Pumps
File no.	64020-2071
Name of the funding scheme	EUDP
Project managing company / institution	Teknologisk Institut
CVR number (central business register)	5697 6116
Project partners	Energy Machines™ DTU Compute (Department of Applied Mathematics and Computer Science) DTU Construct (Department of Civil and Mechanical Engineering)
Submission date	01 December 2023

2. Summary

2.1 English version

This project comprised the Danish participation in the Annex 56 about “Digitalization and IoT for Heat Pumps” as part of the Technology Collaboration Programme for Heat Pumping Technologies of the International Energy Agency.

InAnnex 56, opportunities and challenges of ‘Internet of things’ (IoT) enabled heat pumps were elaborated. Connected devices will play a major role in the future addressing multiple aims, such as increased comfort for the user, reduction in energy consumption and decarbonization of heat supply. The aim of this annex was to increase knowledge at different levels in the heat pump industry, and to create a knowledge base, which can be used to explore and identify the possibilities and challenges associated with the use of IoT enabled technologies and digital solutions for heat pumps, as well as evaluate success factors and address the demands related to software and hardware infrastructure.

Annex 56 was organized in four tasks covering the following topics, to which the Danish working group has made a significant contribution:

- Task 1: State-of-the-art
- Task 2: Interfaces and platforms
- Task 3: Data analysis
- Task 4: Business models

A key part of the project were 23 Danish case descriptions, which were based on interviews of product and service suppliers of IoT and digitalization technologies for heat pumps, as well as research and development projects working on the subject. The case descriptions show that several stakeholders at different levels in the Danish heat pump industry are already focusing on enhancing and deploying digital and IoT-enabled solutions for heat pumps in Denmark.

The review clearly showed that digitalization will be a key aspect in the future development of heat pumps for the energy system, e.g. for enabling the provision of monitoring, predictive maintenance, and ancillary services for heat pumps. The knowledge base created by this Annex serves as inspiration for further developments within the field of IoT enabled heat pumps.

2.2 Dansk version

Dette projekt omhandlede den danske deltagelse i Annex 56 om "Digitalisering og IoT for varmepumper" som en del af teknologisamarbejdet for varmepumpeteknologier (TCP HPT) under det internationale energiagentur (IEA).

I dette projekt blev muligheder og udfordringer ved IoT-forbundne varmepumper undersøgt. Forbudne enheder forventes at have en stor rolle i fremtiden med henblik på at løse flere formål, såsom øget brugerkomfort, reduktion i energiforbrug og dekarbonisering af varmeforsyningen. Formålet med projektet var at øge viden på forskellige niveauer i varmepumpeindustrien, og at skabe en vidensbase, som kan bruges til at udforske og identificere muligheder og udfordringer forbundet med brugen af IoT-teknologi og digitale løsninger til varmepumper, samt evaluere succesfaktorer og adressere kravene relateret til software- og hardwareinfrastrukturer.

Annex 56 var overordnet organiseret i fire arbejdspakker, der dækkede følgende emner, som den danske arbejdsgruppe har ydet et væsentligt bidrag til:

- Task 1: State-of-the-art
- Task 2: Grænseflader og platforme
- Task 3: Data analyse
- Task 4: Forretningsmodeller

En central del af projektet var 23 danske casebeskrivelser, som blev lavet i samarbejde med produkt- og serviceleverandører af IoT- og digitaliseringsteknologier til varmepumper, samt F&U projekter, der arbejder med emnet. Beskrivelserne viste, at flere interessenter på forskellige niveauer i den danske varmepumpebranche allerede har fokus på at udbrede og implementere IoT- og digitaliseringsløsninger til varmepumper i Danmark.

Analyser i annex projektet viste tydeligt, at digitalisering vil være et centralt aspekt i den fremtidige udvikling af varmepumper til energisystemet, f.eks. for at muliggøre serviceydelser af overvågning, forbyggende vedligehold, og fleksibilitet. Vidensbasen der er skabt gennem dette projekt kan bruges som inspiration til yderligere udvikling inden for området omkring IoT- og digitaliseringsteknologi for varmepumper.

3. Project objectives

This project comprised the Danish participation in the Annex 56 about "Digitalization and IoT for Heat Pumps" as part of the Technology Collaboration Programme for heat pump technologies (TCP HPT) of the International Energy Agency (IEA). The international Annex 56 group consisted of wide range of organizations as shown in Table 1.

Table 1: Participating organizations in IoT Annex 56.

Organization	**Country**
AIT Austrian Institute of Technology GmbH, Center for Energy	Austria
TU Wien, Institute of Computer Engineering, Automation Systems Group	Austria
University of Applied Sciences Burgenland, Center for Building Technologies	Austria
Institute of Technology Assessment of the Austrian Academy of Sciences (ITA ÖAW)	Austria
Technical University of Denmark, DTU Construct, Department of Civil and Mechanical Engineering	Denmark
Technical University of Denmark, DTU Compute, Department of Applied Mathematics and Computer Science	Denmark
Energy Machines™	Denmark
Danish Technological Institute, Refrigeration and Heat Pump Technology	Denmark
Fraunhofer Institute for Solar Energy Systems ISE, Freiburg	Germany
RWTH Aachen University	Germany
Competence Center Thermal Energy Systems and Process Engineering, Lucerne University of Applied Sciences and Art (HSLU)	Switzerland
KTH, Royal Institute of Technology, Department of Energy Technology	Sweden
RISE, Research Institute of Sweden	Sweden
SINTEF Energy Research, Department of Thermal Energy	Norway
SINTEF Community, Department of Architecture, Materials and Structures	Norway
EDF – Research & Development, Department of Technologies and Research on Energy Efficiency	France

In this Annex, opportunities and challenges of IoT enabled heat pumps were elaborated. Connected devices will play a major role in the future addressing multiple aims, such as increased comfort for the user, reduction in energy consumption and decarbonization of heat supply. The aim of this annex was to increase knowledge at different levels (original equipment manufacturers (OEMs), heat pump manufacturers, consultants, installers, legislators, etc.).

Figure 1 illustrates the main scope of Annex 56. The Annex included both heat pumps for household and commercial applications and heat pumps for industrial applications.

Heat pumps for household and commercial applications are serial products that are sold in large quantities by heat pump manufacturers. IoT enabled heat pumps provide data that can be used for preventive analytics, such as what-if analysis for operation decisions, predictive maintenance, fine-tuning of the operation parameters and benchmarking. IoT enabled heat pumps can be used for smart demand response to reduce peak load and/or to optimize electricity consumption as a function of the electricity price. IoT enabled heat pump can also be integrated in the building energy management (BEM).

By contrast, industrial heat pumps are usually designed, manufactured, and installed on a project-specific basis by contractors and installers. 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 a higher-level energy management system, which can be used for overall optimization of the process.

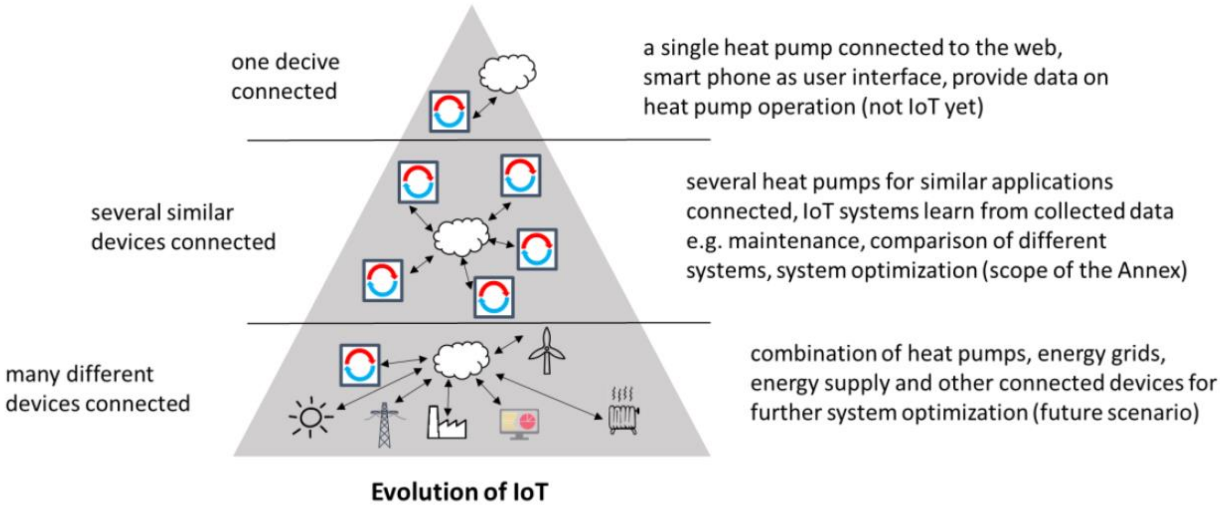

Figure 1: Different levels of interconnection related to IoT [1].

Within the Annex, three central topics were elaborated:

- Interfaces
- Data analysis
- Services

Interfaces:

IoT enabled devices are equipped with sensors that collect a multitude of data. For a heat pump, this data ranges from compressor data, temperatures and pressures in different sections of the heat pump, information on the status of the expansion valve, etc. Central questions and challenges are how data is transferred to the Internet of Things, where different data is processed, and where operation decisions are made. As illustrated in Figure 2, it can either be on the level of the intelligent components (compressors, heat exchangers, etc.) or on the level of the heat pump controller or on higher levels, such as the building energy management system or the power system controls (in case of services for the power system).

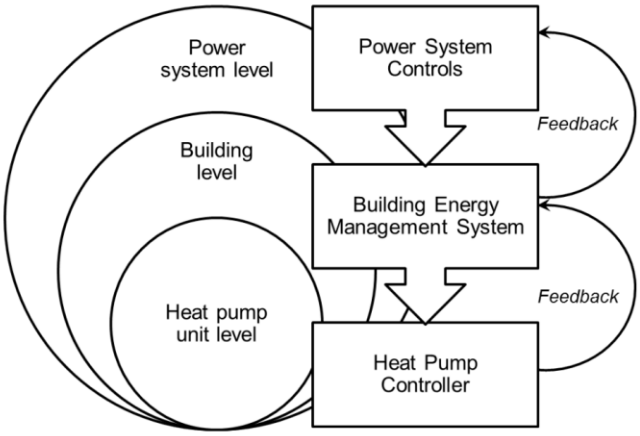

Figure 2: Control hierarchy and level of integration for heat pumps in smart grids [2].

Data analysis:

The aim of data analysis is to make wise use of the collected data to provide targeted information for the optimized operation of heat pumps. This might be machine-learning algorithms that learn from the user's behavior in the past to optimize heat supply or to learn from a large number of heat pumps, how specific heat pumps are performing compared to others and how to improve. Data analysis also includes soft sensors. These are models that calculate process variables that cannot be easily measured directly either based on models relying on other sensor data or on historic data. A common application of soft sensors is the process industry, where a large number of (hardware) sensors is used for process monitoring and control. In addition, data-driven soft sensors provide information on variables related to product quality that can only be determined at a low sampling rate or by offline analysis [3], [4].

For heat pumps, soft sensors can also provide information that cannot be measured directly. An example is the detection of frost formation on the evaporator of air-source heat pumps by acoustic measurements or the use of optical effects to calibrate sensors for thermal properties. For industrial applications of heat pumps, predictive maintenance is of importance. Soft sensors can be applied to extrapolate compressor failure from changes in vibration patterns.

Services:

In the literature, four IoT services are distinguished:

- Identity-related Services
- Information Aggregation Services
- Collaborative-Aware Services
- Ubiquitous Services

Identity-related Services connect real world objects with the internet by using clear identifiers. Information Aggregation Services collect and summarize raw sensory measurements that need to be processed and reported to the IoT application. Collaborative-Aware Services use the obtained data to make decisions and react accordingly. Ubiquitous Services aim to provide Collaborative-Aware Services anytime and anywhere. For example, smart grids are referred to as Information Aggregation Services, as they collect, analyze, control, monitor and manage energy consumption of a large number of smart meters. Smart homes are Collaborative-Aware Services, providing increased comfort to the residents by controlling different devices. An example for a Ubiquitous Services is a Smart City, connecting even more devices and domains, such as health, utilities, transportation, government, homes and buildings [5], [6].

IoT enabled heat pumps can provide different services connected to various business models. In a smart grid, IoT enabled heat pumps can be applied for smart demand response to reduce peak load and/or to optimize electricity consumption as a function of the electricity price. Preventive analytics are of interest for operators providing for example what-if analysis for operation decisions and information for predictive maintenance. IoT enabled heat pumps can be integrated in larger energy management systems, for example in buildings (BEM) or in industrial processes, where the provided data can be used for overall optimization of the process. The requirements for the different services were assessed in a structured way.

Overall, the aims of the international Annex 56 were as stated:

- Provide guidance and increase knowledge at different levels in the heat pump industry
- Establish a knowledge base for IoT enabled heat pumps
- Contribute to future standards
- Contributions to the strategic goals of the IEA Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The objective of the Danish participation in Annex 56 was to increase the knowledge level of digitalization and IoT for Heat Pumps in Denmark. The Danish participation in the Annex was also expected be an effective measure to disseminate the research and development (R&D) activities of the Danish knowledge partners on an international level, and to position the importance and relevance of digitalization onto the international agenda within the heat pump sector.

4. Project results

Annex 56 was overall organized in four tasks covering the following topics:

- Task 1: State-of-the-art
- Task 2: Interfaces and platforms
- Task 3: Data analysis
- Task 4: Business models

The key results and conclusions from each of these tasks are described in the following sections. Focus is both on presenting the results and conclusions from the task reports published by the international project group [7], [8], [9], [10], and on also on emphasizing the main Danish contributions to the task reports.

4.1 Task 1: State-of-the-art

The results from Task 1 are collected in the Task 1 report [7]. The summary presented in this section is based on [7].

4.1.1 Introduction

The Task 1 report provides an overview of the current state of the art of IoT technologies in heat pumps. The various types of IoT sensors and devices that are commonly used in heat pumps are discussed, and the benefits of IoT integration, and the challenges that still need to be addressed are discussed. Additionally, a review of recent R&D in this area is provided, as well as an outlook for IoT technologies regarding heat pumps.

4.1.2 State-of-the art

The 30-page section covers a review of:

- Introduction to the Industrial Internet of Things, with focus on trends in the evolution of machine-to-machine communication and movements in the industrial sector for industrial IoT (IIRA and RAMI 4.0)
- Industrial communication protocols such as industrial ethernet fieldbus, Modbus, KNX, BACnet, AMQP, MQTT, CoAP, oneM2M, OPC UA, and others.
- Knowledge engineering in automation (information modelling and facility management).

4.1.3 Security and data protection by design and by default

Ten pages elaborate on information security and data protection. It is here concluded that it is important to consider the specific characteristics of IoT heat pumps when implementing privacy by design and by default. Due to both the long lifecycle as well as the systems importance for building comfort and user privacy it is paramount to take a long-term perspective.

Technological and security standards may change, while the IoT heat pump system shall remain reliable and available and data protection shall be upheld throughout the lifetime of the systems. To that end, it is important to build on technologies which can be expected to remain available during the systems lifetime, both at the end users and the supplier's side, while also providing the possibility for frictionless security updates of the system. Data protection and security should not be evaluated once, but regularly during the lifetime of the project to ensure that the assessment remains up to date.

Data protection and security are not only technical procedures, but a property of the system as a whole. It needs to include organizational as well as technical measures. Therefore, external suppliers, third-party software as well as internal procedures used for data processing also have to be evaluated. Only when the whole system lifecycle is considered, privacy by design can show its true potential in both guiding and aiding the system development.

4.1.4 Research literature

The Internet of Things (IoT) has the potential to revolutionize the way we interact with heating and cooling systems in buildings. In particular, IoT technologies have the potential to improve the efficiency and performance of heat pump systems, which are widely used for space heating and cooling in residential and commercial buildings.

In recent years, there has been a growing interest in integrating IoT technologies into heat pump systems to enhance their performance and functionality. IoT-enabled heat pump systems can be remotely controlled, monitored, and optimized for energy efficiency. Additionally, they can be programmed to adjust to the preferences and needs of building occupants, providing a more personalized and comfortable indoor environment.

During the Annex 56 an assortment of literature resources has been collected into a public Zotero group available at this link:

https://www.zotero.org/groups/4871439/annex56/library

The Danish working group has provided above 100 of the references collected in this database. This collection of references aims to provide an overview of the current state of research on IoT technologies for heat pump systems. The resources include literature on various types of IoT devices and sensors used in heat pump systems, and explains the benefits and challenges of IoT integration. Additionally, the Zotero library includes papers on the latest research on IoT-enabled control strategies, optimization algorithms, and predictive maintenance techniques for heat pump systems.

4.1.5 IoT use cases: Products, services and research projects

This section provides a collection of specific IoT use cases involving the design, development, and implementation of IoT solutions for heat pump systems. These use cases were gathered in the national projects contributing to this Annex. They cover both market available IoT products and services related to heat pumps and ongoing, planned or recently finished research projects in the field.

For each use case, information is summarized in a dedicated factsheet that is available on the IoT Annex website. The case descriptions of typically 2-3 pages and include information about the following; overall description of the technology, current and/or potential applications and key learnings from the development phase and implementation phase.

Based on the collected information, common patterns are found among the use cases that result in the description of the following main IoT categories: heat pump operation optimization, predictive maintenance, flexibility provision, heat pump operation commissioning, heat as a service. A use case can fall into more than one IoT category.

Heat pump operation optimization: The optimization of heat pump operation is crucial for maximizing energy efficiency and reducing energy costs. IoT technologies can be used to continuously monitor and analyze heat pump performance, allowing for real-time optimization and adjustment of operation parameters. By optimizing heat pump operation, building owners and operators can reduce energy consumption and improve system performance, resulting in cost savings and environmental benefits.

Predictive maintenance: Predictive maintenance is an essential aspect of ensuring the longevity and reliability of heat pump systems. IoT-enabled sensors can continuously monitor system performance and provide real-time data on system health. By analyzing this data, predictive maintenance algorithms can identify potential issues before they become critical, allowing for timely and cost-effective maintenance interventions. By implementing predictive maintenance strategies, building owners and operators can reduce downtime, extend the lifespan of heat pump systems, and optimize maintenance costs.

Flexibility provision: Flexibility provision refers to the ability of heat pump systems to provide flexible energy services to the grid. By incorporating IoT technologies, heat pump systems can be configured to operate in a way that provides maximum flexibility to the grid. This can include adjusting the timing and level of heat production in response to grid demand, as well as providing ancillary services such as frequency regulation. By providing flexibility to the grid, heat pump systems can help to stabilize the electricity system, reduce energy costs, and facilitate the integration of renewable energy sources.

Heat pump operation commissioning: Commissioning is a critical aspect of ensuring the safe and effective operation of heat pump systems. IoT technologies can be used to streamline the commissioning process, allowing for faster and more accurate system setup. By using IoT-enabled commissioning tools, building owners and operators can ensure that heat pump systems are configured to operate optimally from the outset, minimizing energy consumption and optimizing system performance.

Heat as a service: Heat as a service is an emerging business model that aims to provide heat pump systems to customers as a service rather than as a product. This model can help to overcome some of the barriers to heat pump adoption, such as high upfront costs and technical complexity. By implementing IoT technologies, heat pump service providers can remotely monitor and optimize system performance, ensuring that customers receive high-quality, reliable, and cost-effective heating services. Heat as a service can help to accelerate the adoption of heat pump systems, enabling more buildings to benefit from the energy and cost savings they offer.

In total, 41 use cases were collected, where the Danish working group provided 11 cases from suppliers and 12 cases from R&D projects in Denmark, see Table 2. In appendix A, the country summary report for Denmark can be found. This report contains the full descriptions collected for the 23 Danish IoT cases on heat pumps. In addition to this, all factsheets for the cases, both from Denmark and the international project group, can be found on the Annex homepage:

https://heatpumpingtechnologies.org/annex56/factsheets/

Table 2: Overview of collected IoT cases in Task 1.

Name	Type	Country
Bitzer Heat Pump Eco System	Supplier	Austria
XBALL® Smart Expansion Ball Valve	Supplier	Austria
KRIWAN protective equipment	Supplier	Austria
Energie Burgenland HP Neusiedl am See	Supplier	Austria
myiDM +energy - iDM Energiesysteme	Supplier	Austria
KNV S Serie – KNV / NIBE	R&D project	Austria
DIGIBatch	R&D project	Austria
Flex+	R&D project	Austria
EDCSproof	R&D project	Austria
Soft sensor for heat pump icing	R&D project	Austria
BAC in Action: Connected heat pumps in the ZEB Laboratory building	R&D project	Norway
Data-driven lab for heat pump systems	R&D project	Sweden
Data-driven models for estimating heat pump power consumption	R&D project	Sweden
Avoidance of heat pump efficiency losses by digital operation analysis (DIBA-WP)	R&D project	Switzerland
Virtual energy storage network based on residential heating systems: tiko Energy Solutions AG	Supplier	Switzerland
Smart Guard: Meier Tobler AG	Supplier	Switzerland
Losange Project	R&D project	France
Digital twin of heat generator systems as an enabler for the development of low-emission building energy technology (DZWi)	R&D project	Germany
Energy Machines – Energy machines verification	Supplier	Denmark
Neogrid – PreHEAT for Heat Pumps by Neogrid Technologies ApS	Supplier	Denmark
LS Control - SmartConnect Center	Supplier	Denmark
Centrica Energy Marketing and Trading – Energy Planning and Optimization Platform	Supplier	Denmark
Climify – Indoor Climate Monitoring Platform	Supplier	Denmark
Nærvarmeværket – Community owned Heat Pump Company	Supplier	Denmark
AI-nergy – Artificial Intelligence Assisted Products	Supplier	Denmark
ENFOR A/S – Energy Forecasting and Optimization Platform	Supplier	Denmark
Center Denmark – The Digital Data Platform	Supplier	Denmark
EnergyFlexLab	Supplier	Denmark
METRO THERM - MyUpway™	Supplier	Denmark
Digital Twins for Large-scale Heat Pump and Refrigeration Systems	R&D project	Denmark
EnergyLab Nordhavn - Smart Components	R&D project	Denmark
Flexheat – Intelligent and Fast-regulating Control	R&D project	Denmark
Smart-Energy Operating-Systems (SE-OS) framework	R&D project	Denmark
Combined Optimization of Heat Pumps and Heat Emitting Systems (OPSYS 2.0)	R&D project	Denmark
Cool-Data	R&D project	Denmark
SVAF phase II	R&D project	Denmark
HPCOM	R&D project	Denmark
Flexible Energy Denmark	R&D project	Denmark
Res4Build - Renewables for clean energy buildings in a future power system	R&D project	Denmark
Development of Fast Regulating Heat Pumps using Dynamic Models	R&D project	Denmark
CEDAR (Cost Efficient heat pumps using DigitAl twins and Reinforcement learning)	R&D project	Denmark

From the 23 collected cases the Danish working group made a review and conclusion about digitalization and IoT for heat pumps in Denmark which is described in the following section.

4.1.5.1 Review of the status of Digitalization and IoT for Heat Pumps in Denmark

The collected information from both product and service suppliers and R&D projects in Denmark shows that several stakeholders at different levels in the heat pump industry are focusing on enhancing and deploying digital and IoT-enabled solutions for heat pumps in Denmark. There are overlaps with companies being present in more groups, but in general the suppliers and service providers in this review can be grouped as follows:

- Heat pump manufacturers: Energy Machines, Johnson Controls, DVI, and METRO THERM
- Aggregator: Neogrid Technologies
- Service Provider: Climify, Centrica, ENFOR, EnergyFlexLab, AI-Energy
- End-user: HOFOR, Nærvarmeværket
- OEM: LS Control
- Datahub: Center Denmark

In addition to this the authors are aware of various other companies in Denmark working on digitalization and IoT solutions, who did not directly give input to the review. The groups have different roles and interactions between each other, which is visualized in Figure 3. The figure shows a general setup for an IoT-based energy system around heat pump(s) and the involved groups, but it must be emphasized that there are also other possible setups depending on the specific use case.

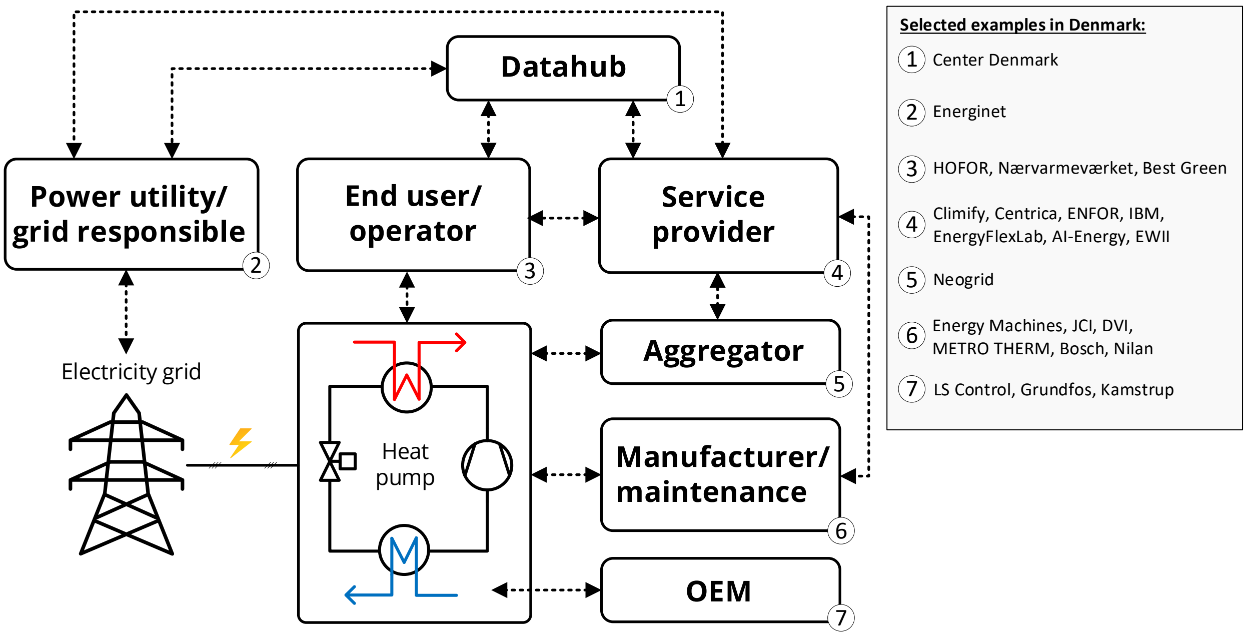

Figure 3. Visualization of supplier groups and examples of associated suppliers in an IoT-based energy system for heat pumps.

In recent years, the number of installed household heat pumps in Denmark has strongly increased. Among other reasons this is due to economic and political incentives supporting electrification and a ban on oil boilers. Moreover, around 66 % of Danish households are supplied by district heating in 2022 [11]. Also in the district heating networks both the number of heat pumps and the total capacity installed has increased significantly in recent years as seen in Figure 4. This is aligned with the target of using heat pumps to supply around one third of the heat in Danish district heating networks by 2030 [12].

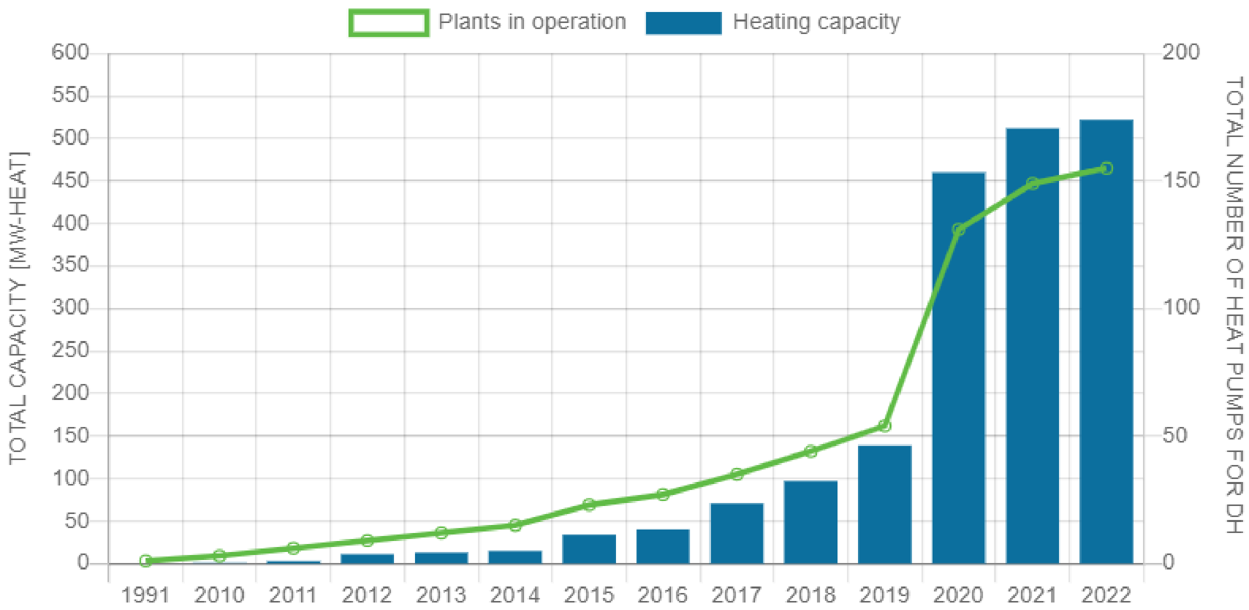

Figure 4. Overview of large-scale heat pumps for the Danish district heating network [13].

In Denmark there are strong incentives to install heat pumps to reduce the dependency of the heating sector on fossil fuels and leverage the increasing amount of renewable (fluctuating) power in the electricity grid, of which the average annual share in Denmark was 47 % in 2021 [14]. Regarding the electricity price different tariffs applies depending on what time of the day it is. The tariff comes on top of other costs such as the spot electricity price and taxes. For example during the evening between 17:00-21:00 in the winter period increasement in tariffs around 1.8 DKK/kWh (0.24 €/kWh) compared to the cheapest period applies [15]. Furthermore, most Danish electricity providers offer their customers to pay hourly adjusted prices, which are settled according to the tariffs and hourly marked spot prices. If the primary heating installation is operating on electricity the consumption above 4,000 kWh for a household can get a reduction in the tax cost for electricity [16]. These measures incentivize the use of smart controls and digital solutions, enabling a high potential to integrate the heating and power sectors by using heat pumps. This is further supported by the Danish Society of Engineers who in a report on how to reach a climate neutral Denmark recommends more interaction between energy consumption and supply in “smart buildings”, and encourages to use apps and/or smart meters to control indoor climate and energy consumptions [17].

In this context, a number of technology suppliers such as Neogrid, Centrica, AI-energy, ENFOR and METROTHERM, offer solutions towards the use of heat pumps for sector integration. Here, the most common type of solution is the remote or local adjustment of the heat pump operation based on measured and/or forecasted electricity prices. This enables a reduction of operational costs for users by the use of available low-cost renewable energy resources and the avoidance of periods with limited power supply.

The provision of ancillary services through heat pumps is also possible with some of the technologies currently available in the market. However, in the case of residential heat pumps an aggregator is needed to pool a number of heat pumps, which may raise data security concerns. In the case of district heating heat pumps, their flexible operation has e.g. been analyzed in an R&D project (Flexheat). This investigation highlights potential opportunities to develop digital solutions that enable the estimation in advance of the constrains related to the provision of ancillary services by means of heat pumps and IoT-enabled frameworks for the remote surveillance of heat pumps under dynamic conditions.

Predictive maintenance of heat pumps complemented by IoT-enabled technologies is already available in several technologies offered in Denmark. This includes the solutions offered by Energy Machines, LS-Control, Neogrid, Nærvarmeværket and METRO-THERM. Remote predictive maintenance enables the reduction of operation and maintenance costs by decreasing the number of times that a heat pump requires the physical assistance of a service technician and by taking preventive measures before it is not possible to avoid or mitigate the negative effects of faults in the heat pump components. R&D projects have also aimed at developing predictive maintenance solutions by means of digital tools. In this case, the technologies under development include digital twins, where the potential effects of fouling can be analyzed and predicted based on adaptive model-based frameworks, as well as advanced data-driven methods that are able to describe and predict the effect of faults by means of real-time measured data.

Accessible data is one of the key elements needed towards the development of digital solutions supporting the sector coupling between electricity and heat sectors. The present review indicated that the digital data platform from the company Center Denmark is used for such a purpose in several projects. The data platform gives consumers in Denmark a direct opportunity for sharing energy consumption and operational data with Center Denmark, and hereby facilitating the development of energy-efficient data solutions in a secure and reliable manner. Service providers or other stakeholders can then purchase anonymized data to develop their solutions. Currently, tens of thousands of Danish households are taking part in this scheme, where e.g. data on electricity, heat, water, and indoor climate are shared.

Throughout the review, especially in the R&D projects, a number of different tools for numerical modelling of heat pumps were identified. This includes approaches such as white-box or physics-derived models, black-box or data-driven models, and grey-box models. The white-box paradigm is often applied when a model is required in the design of a system and/or its components, or to analyze the performance of a system and certain phenomena that can be described straightforwardly with physics. Contrarily, black-box and grey-box models are likely to be applied when simplified representations of reality are sufficient or when it is needed to analyze operational conditions that are difficult or impossible to predict by physically-derived representations, such as faults and performance degradation. Digital twin frameworks, which are under development in multiple R&D projects (Digital Twins for large-scale heat pumps and Refrigeration Systems and CEDAR), may integrate different types of modelling approaches, depending on the data availability, type of service, and communication constraints, among other factors.

In the review, it was identified that different stakeholders will need to interact (fast) through different interfaces, e.g over API interfaces, ModBus, MQTT, end-user-apps, and fog/edge-based computing facilities. This shows that the industry could overall benefit from making standardized interfaces to avoid having various suppliers using and developing each of their own. More standardized interfaces could e.g. include monitored data from the heat pump and the heat demand, but also electricity and heating prices, leading to further possibilities for incorporating comparison schemes between technologies in control and monitoring digital interfaces. Current general issues with this includes a lack for standards across countries, e.g. within the EU, particularly on how price signals shall be communicated to the heat pump. Challenges for those standards include considerations about where to best locate price-forecasts, what format it should have, what should be the cost for access, which areas should be included, and who exactly should control the heat pump without compromising its lifetime? Is it the grid system operator, aggregator, or heat pump manufacturer? The definition of such standards may contribute to answer those questions and may advance towards the improvement of operation of heat pumps and energy systems.

In Denmark there are various industry communities working with the energy system. An example of this is “Intelligent Energi” (https://ienergi.dk/) which is a community for stakeholders who work with advancing an integrated and flexible energy system that provides Danes with safe and green energy at competitive prices. Intelligent Energi supports this development by working on more uniform framework conditions for by being a platform for collaboration within and across electricity, gas, water, and heat sector, and hence also how to best include heat pumps in the energy system.

It can be concluded that the review provided a summary of the state-of-the-art digital and IoT-enabled technologies for heat pumps in Denmark. A description of the available technologies and those under development was made, which incorporated information shared by technology suppliers as well as research and development initiatives. The information collected indicated that several products and services that include IoT and digital solutions are already available in the Danish market, which enable the provision of monitoring, predictive maintenance, and ancillary services. Moreover, a number of ongoing research and development projects aim at the improvement of some of those services by means of modelling tools and data analysis and processing methods. Some of the future challenges for a broader implementation of digital and IoT-enabled technologies for heat pumps were identified. These include the definition of standards related to data security, price incentives, and digital interfaces.

4.1.6 Market report

In France the national heat pump association (AFPAC) made a study in 2019 with the topic "Heat pump of the future: smartness and connectivity". The focus in this study was that the smart heat pump can provide information, through appropriate interfaces, to building owners, occupants and operators on actual energy consumption, energy efficiency, energy bill, operating status. It can also signal malfunctions and preventive maintenance needs. In this way, a smart heat pump optimizes its operation for three use functions: heating, cooling and DHW production. To do that, some actions have to be ensured:

- Simplify the commissioning
- Anticipate the users' needs
- Optimize the performance
- Optimize the cost
- Optimize the maintenance

To address these five crucial actions, the study defines many aspects to be considered. These aspects are gathered and linked with the action that they can facilitate, see Figure 5.

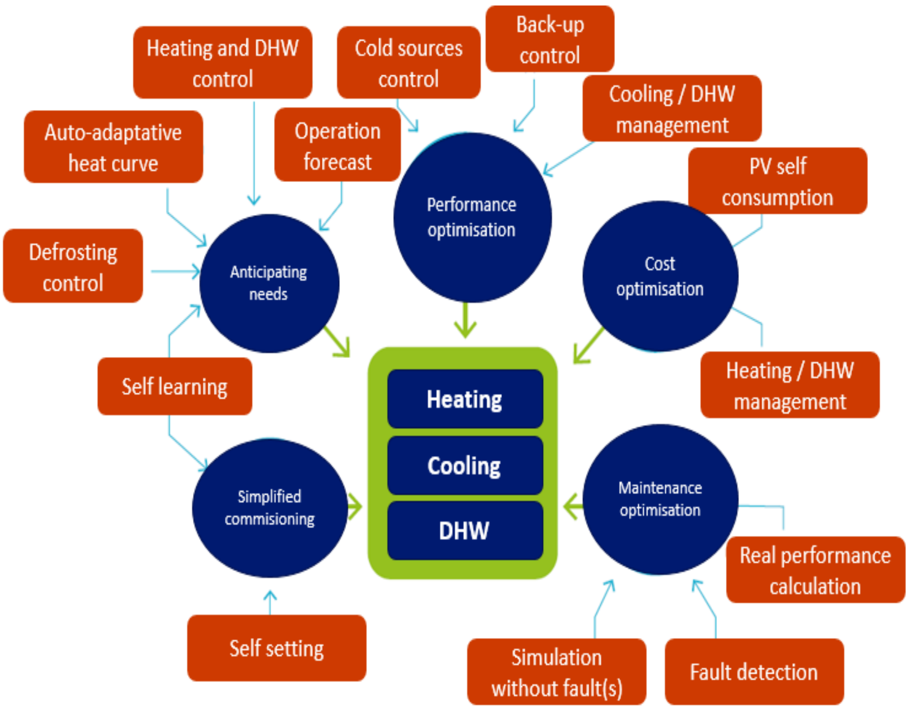

Figure 5: Use functions fulfilled by a heat pump.

The market report details the smart actions described for each use functions, including commissioning and maintenance, in the form of tables describing the action, the objective and means in terms of smartness, the needed data to be collected, the "physical" technologies that can be, or need to be associated and then the possible interactions with other smart actions. In the report it is further stated that an open policy on data sharing and exchange is desirable.

4.1.7 Manufacturer survey

A manufacturer survey was made in Austria and described on 10 pages in the Task 1 report. The purpose of the survey was to collect feedback from companies in the heat pump market segment in order to gather and evaluate the general sentiment on the importance of IoT. The survey had more than 50 questions, which were single and multiple choice, rating and ranking as well as free text questions. The average time for completing the survey was about 20 min. Besides being presented in the Task 1 report the results from the survey are also presented in [18].

The survey was divided in two different parts. The first part was equal for all participants. The second part was different for participants active either on the residential, commercial and office buildings market, or on the industrial heat pump market, with specific questions for each group.

The questionnaire was designed after conduction of interviews and focus groups with domain experts in residential and industrial heat pump technology, buildings automation, data security and electricity market from the IEA HPC Annex 56 expert group. Companies were contacted by the Austrian Heat Pump Association "Wärmepumpe Austria" (WPA) and asked for their participation in the survey. WPA covers the entire value chain of the heat pump industry in Austria and includes heat pump manufacturers in Austria, as well as all electricity supply companies, component suppliers and drilling companies as well as planners, installers, and engineering companies. Answers were collected from May to June 2022.

The survey was conducted to gather and evaluate the general sentiment on the relevance of interconnected heat pumps, state-of-the-art use cases, market availability and selected technology trends, and a total of 16 companies participated in the survey. 13 participants answered all questions in the survey, 3 participants only answered a part of them (76%, 84% and 91% completion).

Asked about the motivation for adopting IoT products, the top three selected answers were customer loyalty, service improvement and new business models, see Figure 6.

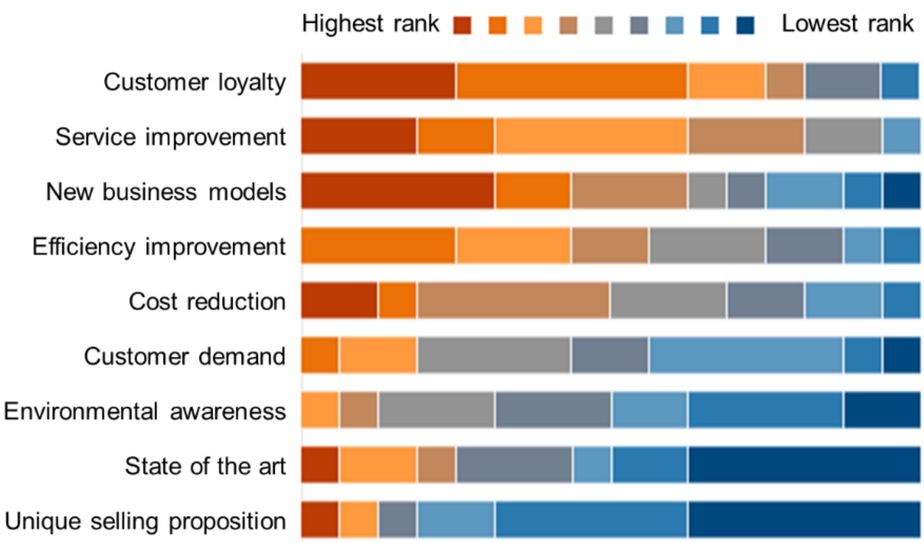

Figure 6: Motivation to introduce IoT products [18].

The survey showed that IoT enabled heat pumps are expected to become a part of a connected system in the future rather than an autonomous smart component. As shown in Figure 7 this was found for both residential and industrial heat pumps.

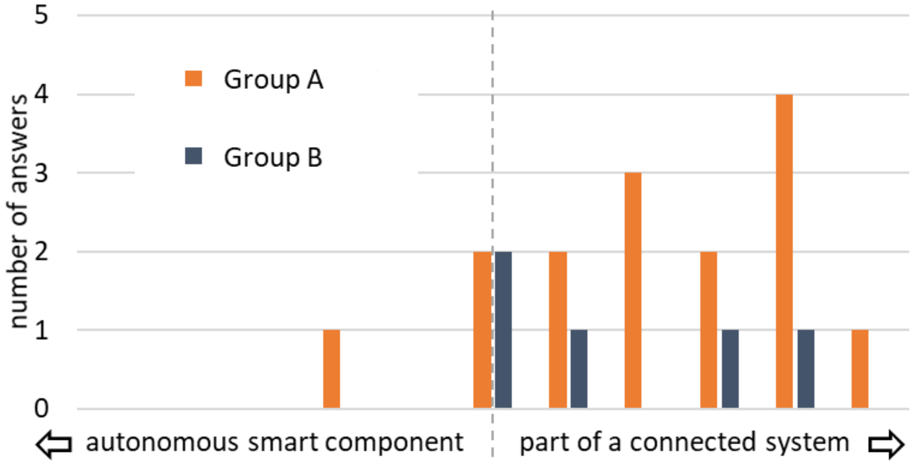

Figure 7: IoT enabled heat pumps in the energy system [18].

Almost all participants use LAN and WLAN communication interfaces to collect field and operational data. They are followed by local wired (USB, Serial, ...) and wireless (Lora, Bluetooth, ZigBee, ...) interfaces as well as GSM. Seven companies use specific interfaces needed for smart grid ready label

The collected feedback clearly indicates significant progress in technology implementation. All participating companies offer both IoT products (e.g. heat pumps with connectivity or intelligent components such as compressors or sensors), and related services (e.g. marketing of flexibility, remote service, monitoring, etc.). While two thirds of these products are already available either in the product portfolio of the companies, or in a large number in use, another third is currently under evaluation, under development or in a pilot phase. The survey showed that IoT technology is expected to bring significant changes in product development, business models and maintenance. For IoT enabled heat pumps this means that instead of being an autonomous smart component, they will be increasingly integrated and will be part of connected energy systems in the future.

4.1.8 Expert interviews

To gain further insights into the state of IoT technologies for heat pumps, a series of expert interviews were conducted in Sweden involving leading heat pump manufacturers, IoT companies, associations, and consultants. The interviews aimed to gather information on the current trends and challenges in the field of IoT-enabled heat pumps, as well as the opportunities and potential benefits of integrating IoT technologies into heat pump systems.

The interviews were conducted with a range of experts providing a diverse set of perspectives on the topic. The participants were asked a series of questions related to the following topics: the current state of IoT technologies for heat pumps, the challenges, and opportunities of IoT integration, the benefits of IoT-enabled heat pumps, and the future outlook for IoT technologies in the heat pump industry.

The expert interviews provides key insights and perspectives gathered, providing a valuable insight into the views of heat pump manufacturers on the potential of IoT technologies for enhancing the performance, efficiency, and functionality of heat pump systems.

4.2 Task 2: Interfaces and platforms

An application or a service that generates or adds value utilizing an IoT – or connected – heat pump or heat pump component can be described by a complete cycle of data acquisition, data processing, inference, and action based on that inference. In some cases the feedback (inference and action) can be weak, long term and indirect. For example, data analytics may affect the design of later heat pump generations or human behavior changes based on visualized data, and therefore does not act directly on the actual heat pump operation. In other cases, such as digital twins for heat pump operational management, the cycle may be clearly defined and fully automated. Without closing the cycle no value, e.g. revenue, energy savings, comfort gain, etc., can be added or generated by an IoT application.

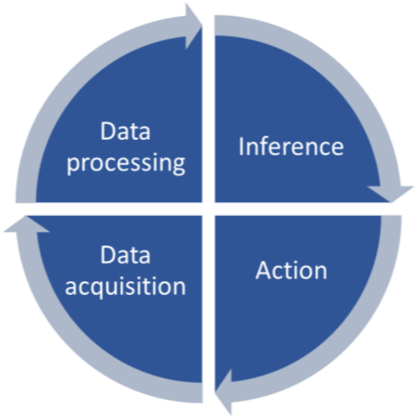

Figure 8: Decision making framework of an IoT application [8].

The topics of Task 2 originated from a desire to provide a structure (communication and processing capabilities) for the methods described in Task 3 which in turn were determined by the value cycle or IoT Service described in Task 4.

A selection based on specific use cases out of the plethora of possible IoT applications and concepts were presented in the Task 2 report, and are summarized in the following sections [8]. The use cases in focus here cover the topics listed below, and are described in the following sections. The examples presented are either commercially available or part of research projects. Based on these examples some common challenges and their possible solutions were elaborated.

- Digital twins of heat pumps
- Connected heat pumps in building automation
- Heat pumps in grid services
- Retrofitting

4.2.1 Digital twins of heat pumps

Four cases with digital twins were described. The four cases show that different services and different levels of integration lead to specific requirements on data, models, and simulations which in turn lead to different requirements on databases, simulation frameworks and processing power. The usage of a central message broker such as MQTT enables the distribution of data and workloads between field and cloud applications or services and are common to many use cases observed in the IoT Annex. Further commonalities are the usage of general purpose and high-level programming languages especially Python and models based on the *functional mock-up interface* called FMU. Reusability of workflows and ease of deployment is the main driver behind the usage of FMUs.

4.2.1.1 DIGIBatch: Digital Twin for heat pump performance prediction

This use case demonstrated in an Austrian national research project (DIGIBatch) is an example for the integration of a heat pump digital twin in a legacy industrial SCADA system.

During performance testing of heat pumps according to EN-14528 and EN-14511 the performance data is evaluated at certain temperature and part load conditions. A special case occurs if the compressor speed cannot be reduced, either by design or because of reaching the minimum compressor speed. In this case the performance is evaluated at a different temperature that emulates the target temperature under on/off operation conditions. This new temperature in turn is dependent on the heat pump performance and therefore can only be determined iteratively. A plant operator assistance system based on a digital twin of the heat pump suggests simulated plant operation data, mass flows and temperatures, and therefore can save operation time and resources by avoiding wrong decisions, and non-optimal iterations in the real world. The digital twin was implemented into an accredited lab infrastructure, therefore minimal invasiveness was a key element.

When the operators need to decide on the settings for the next operating point, they can trigger the prediction algorithm of the digital twin in the human-machine interaction (HMI). The determination of the temperature and mass flow settings is done iteratively by the digital twin. The results are fed back to the HMI which the operators can either accept or overrule. The functional and information structure of the DIGIBatch heat pump digital twin can be seen in Figure 9.

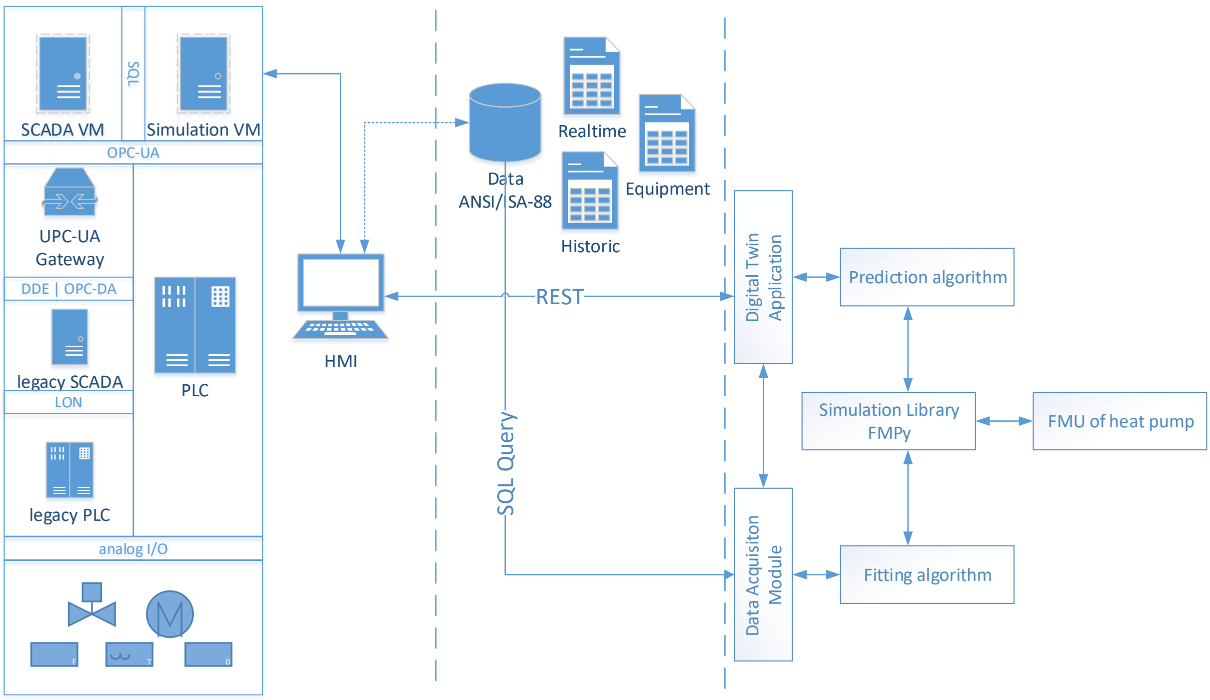

Figure 9: Functional and information structure of the DIGIBatch heat pump digital twin [8].

4.2.1.2 Distributed Digital Twin – Digital Twin project

This section is describes a suggested functional architecture and provides comments regarding a possible implementation for a distributed digital twin. This investigation has been made as part of the R&D project "Digital Twins for Large-scale Heat Pumps and Refrigeration Systems“ (http://digitaltwins4hprs.dk/), and is hence an input from the Danish IoT Annex 56 working group.

4.2.1.2.1 Background

Digital twins are here defined as a set of models of the physical asset or parts of it that are updated based on current measurement data and used possibly together with further inputs to provide different services. These services may serve internal optimization of the plant's operation or they may serve to communicate the plant's status to external entities, e.g. the plant operator or the maintenance service provider.

Based on the kind of service different information needs to be provided by the model at different response times. It is therefore reasonable to have different models for different services, instead of trying to have one extremely detailed model to provide all information for all services. This would result in computationally extremely heavy models that require large amounts of time to be developed and calibrated to the respective plant.

Such a modular digital twin further allows integrating the digital twin with the existing plant control infrastructure by integrating the models directly on the control level, where they should be used. Compared to implementing all digital twin modules externally (in the cloud, external computers, etc.), the amount of data that needs to be transferred between the plants local control system and external databases may be reduced. Further, the need for data storage and for meta data explaining internal variables from the low-level controllers is less.

An example would be the detection of malfunction of a cooling cabinet in a supermarket refrigeration system. At the cabinet controller all available measurement data and control parameters for that cabinet are available and could be used as input for a model to assess the state of the cabinet.

In principle, the same service could be supplied when implemented in the cloud. This would however require that all the local data, which is not currently available at the higher control levels, is transported via the plant control system to the cloud and possibly that controller set points are send back to the local controller. In terms of plant security, it is an advantage if the low-level controllers are not accessible from outside.

A distributed digital twin is thus an implementation of the digital module that is based on the current plant control structure and is divided to the different control levels according to the respective service that should be supplied and the required response times. A possible functional architecture and implementation of the proposed distributed digital twin will be described in the following. It has not been implemented yet, hence only the conceptual set-up is described.

4.2.1.2.2 Functional architecture of a distributed digital twin

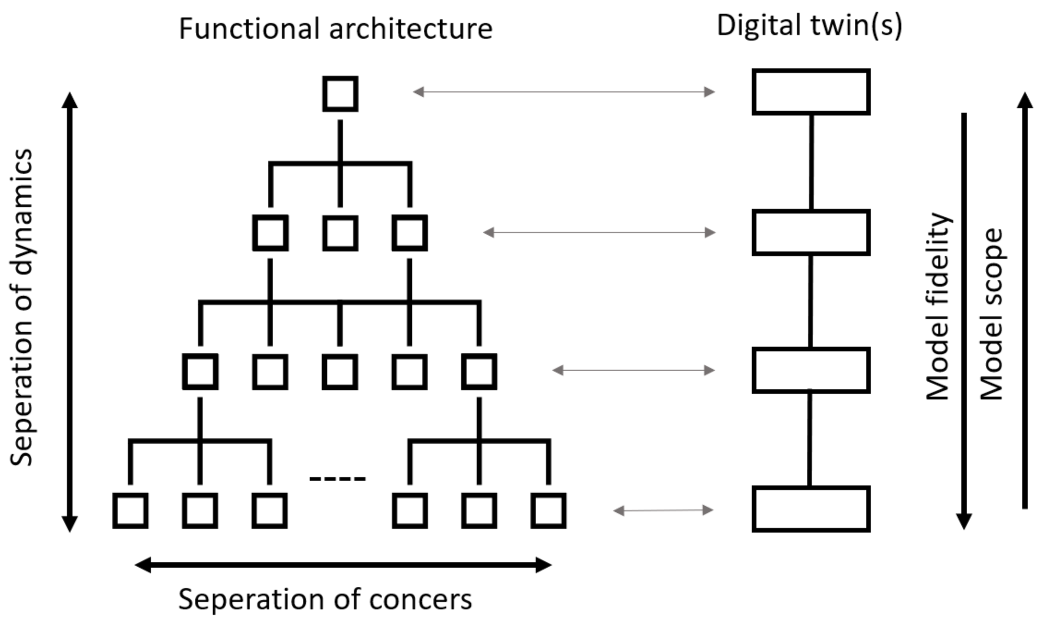

Figure 10: Functional architecture and digital twin [8].

The functionalities of a digital twin for large-scale vapor compression systems may be categorized by the type of services, according to the principle of "separation of concerns" and by the required response times of the different services, denoted here as "separation of dominating dynamics". The separation of concerns and of dominating dynamics is graphically presented in Figure 10.

The top layer in Figure 10 contains functionalities requiring the slowest update frequencies, while the layers below are requiring faster and faster update frequencies to fulfill their objectives. Note that the latter is also a reflection of the requirements to the scope and fidelity of the underlying models. At lower layers, detailed and accurate sub-system models to support the operational optimization as well as condition monitoring are needed. At higher layers, the scope of the model is larger, meaning that it covers a larger part of the system but in less detail, as here the interconnections of the underlying sub-systems are handled.

Within the "Digital Twins for large-scale heat pumps and refrigeration systems" project a number of relevant services supplied by a digital twin were identified. Figure 11 shows a categorization of these services according to the scope of the service (concern), the required response time (dominating dynamics) and the relevant system layer on which the respective service is required. It may be seen that different services require vastly different response times. Further, the location where a certain service is supplied is on the low-level controller levels for services requiring fast response, while it may be in the cloud or on a remote machine for the slow services. This clearly indicates that the digital twin should be set up out of different models and service modules that are designed for the respective services. The appropriate model used for a specific service, will thus depend on the information required to provide a certain service and the acceptable computational time to execute the respective model.

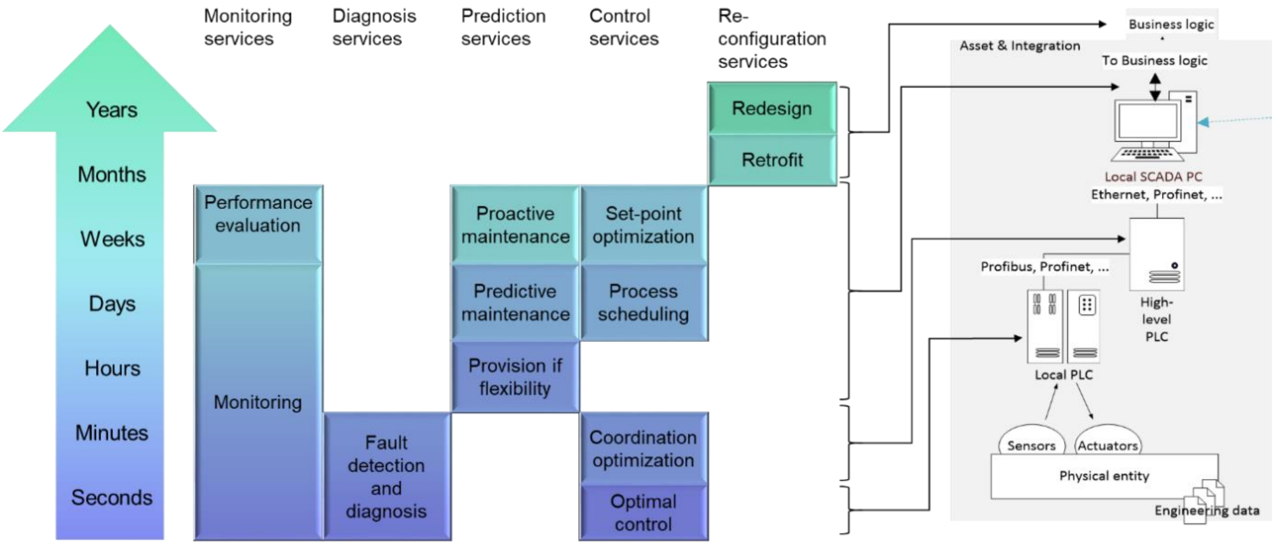

Figure 11: Categorization of services provided by digital twins according to scope, required response time and relevant system level on which the service is executed. The scope categories are based on [19].

4.2.1.2.3 Possible implementation of the distributed digital twin

In order to reduce the required data traffic a distributed digital twin implementation is proposed. Different locations of the different digital twin service modules could be relevant according to different use cases:

- Long-term services, such as use of simulation models as a virtual testbench to develop improved controller design could be run on the cloud. As these are not time-critical, and a reduced amount of data is required to supply these services.

- Real-time related services could be integrated within the service manager (SCADA system). Thereby, unnecessary, and possibly slow information exchange via the cloud is avoided. Further, this set-up is more secure as the control signals are not sent via the internet.
- Small specialized service modules could run on the PLC level (edge computing), E.g. to supervise the performance of single refrigeration cabinets (10-20 data points per cabinet). This could be especially relevant, since the required data does not have to be sent to the service manager and the cloud, which would easily add up to huge amounts of data. Keeping a lean data structure is a relevant aim for cloud-based services/digital services in general.

This approach may reduce the required data traffic considerably as only the data relevant to long-term service modules is send further to the higher level digital twin for further use. A further advantage of this approach is that it allows for a modular structure of the digital twin that could allow adding or removing components from the system with minimum reprogramming effort for the digital twin.

This approach does however require a detailed overview of the desired services provided by the digital twin, as the decision on which data to use locally and which data to send further to the system level is taken early in the development process and is expected to be more difficult to update later on. The respective digital twin modules need to be installed on the hardware, which typically has a live time of minimum 10 to 15 years. So, it is important to take the expected developments of the next couple of years into account when designing local controllers and the upward and downward communication paths. Further, the calculation capacity available at the lower levels need to be designed to fit to the services to be supplied at these levels and is fixed once installed. In the long term, the controllers are likely to be replaced hence opening for the possibility to add sub-models (distributed twins) in the edge controllers. In future control systems the possibility to do remote up-dates/uploads of smart algorithms on edge devices will render it more feasible to also update already commis-sioned systems.

The proposed distributed digital twin infrastructure is expected to be especially suitable for the implementation in plant control systems. Thus, this is only a long-term option as the hardware capable of providing the required additional computing power and possibility to install updates has to be rolled out. Considering that large-scale vapor compression units have expected lifetimes of at least 15 to 20 years, this approach is not feasible as a retrofit solution. For the retrofit of existing plants it is therefore expected that the services that can be provided by the digital twin are limited to services that are not sensitive to the time delay due to data transport and can be provided using the plant data available on the plant level control (SCADA).

4.2.1.3 Digital Twin – DZWi

This section gives an overview of the approach for a German government-funded project Digital Twin of Heat Generating Systems as a Pioneer for the Development of Low-Emission Building Energy Technology (DZWi, https://dzwi-waerme.de/).

The main focus of the project is to develop a digital representation of different energy conversion systems like heat pumps in detail, which will help to shorten R&D times. Based on "hardware-in-the-loop" (HiL) tests, fun-damental parameters for heat pumps and fuel cells will be determined. In addition to the metrological analysis, an important aspect is a precise description of the dynamic and static behavior, e. g. of the refrigeration cycle. Here, a generally applicable methodology is to be developed that also takes into account the use of future refrigerants with regard to the F-gas regulation. The core of all development work is a cloud environment, which should enable scalability of the results for the entire life cycle of the system.

The Fiware open-source platform was used within the project. Fiware provides standardized software solutions for the management of context data in order to significantly accelerate the development of intelligent systems. In order to be able to declare context data uniquely, it must be provided with a universal ID and a data type. In addition, further (optional) attributes can be added. Due to its generic data structure, Fiware offers various software packages (so-called "Generic Enablers") and different functions for implementation in the overall system. To keep the handling of the software packages user-friendly, the FiLiP (Fiware library for Python (Storek et al., 2021) is used. This ensures fast and easy development of individual applications in the IoT area (Internet of Things). For a scalable use of the Fiware software platform that is independent of the operating system, these are started within containers via Docker. Communication within the software platform takes place via the Open API specification "NGSI" (Next Generation Service Interface), which represents a uniform format for describing an API (Application Programming Interface) for context data. The advantage of this format is that the API can be operated very easily using HTTP commands (POST, GET, DELETE, ...). An actuator can thus be operated via a simple PUT command, for example. The present IoT-structure enables a user-friendly integration of customized micro services such as fault detection (see Figure 12).

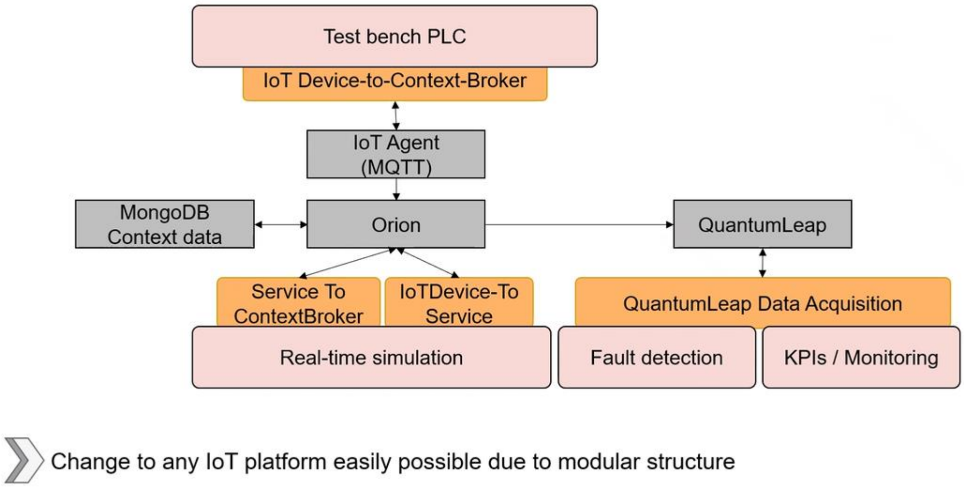

Figure 12: IoT modular concept for connecting real experiment with the digital replica and microservices [8].

A fault detection module is developed which detects deviations and sends and issues a message about the incident to a predefined target group at regular intervals (red circles) via a Telegram bot.

4.2.1.4 Live Digital Twins - EnergyMachines™

EnergyMachines (https://da.energymachines.com/) have described how to deploy Digital Twins by using the platforms numerous (https://www.numerous.com/) and Energymachines.cloud, which are further described in this section.

Numerous is a platform for setting up cloud-based simulations, optimization, digital twins, automatic reporting tools and many more applications. Simulations and analytics tools can be developed using the numerous python SDK and shared with other users. Via the web application users have access to configure and run the tools and explore the results. On the platform the tools run on cloud resources provisioned by the platform. In this way multiple users can run the tools in parallel and share their results without installing anything locally. Numerous is available as software-as-a-service.

Energymachines.cloud is a SCADA/HMI platform, which enables sensor logging on the heat pump system, visualization for operators, setting alarms, and reporting results back. It also is the key gateway into accessing all historical data logged on connected systems. Combining the powers of numerous and energymachines.cloud allows running simulations with live sensor readings as inputs and deploying multiple instances each configured for a specific system. This way Energymachines have live digital twins for their heat pump systems and use the results to augment the real measurements with data from the simulations.

Modelling heat pumps

To run a digital twin of a heat-pump, there first needs to be a model. EnergyMachines have several models of their heat-pumps. The best candidates are based on so-called Long-short term memory (or LSTM) neural networks. Figure 13 shows an example of such an LSTM model trained using data from energymachines.cloud on one of the installations from Energymachines.

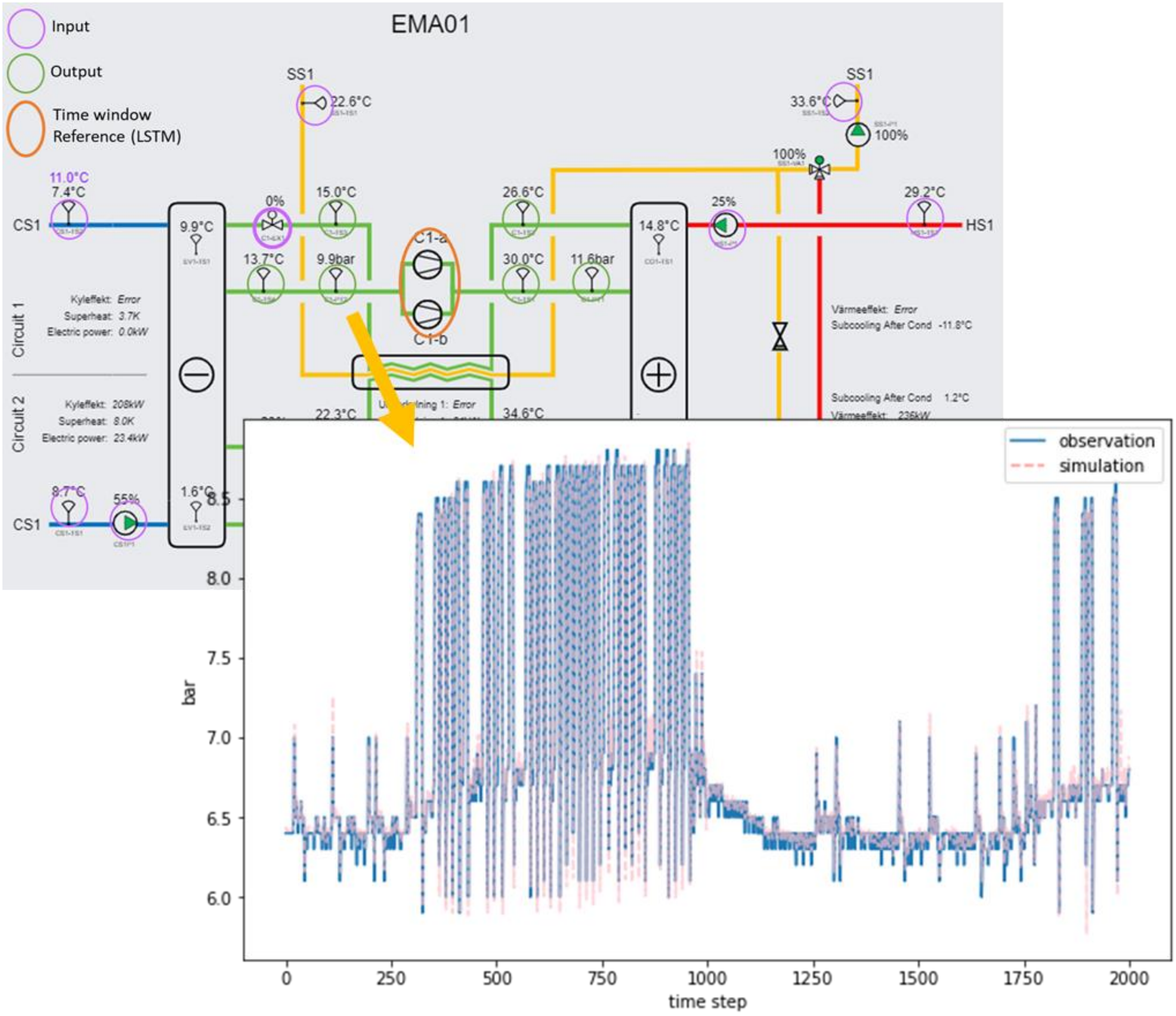

Figure 13: An example of a trained LSTM model which shows that transient operation is captured by the model [8].

Infrastructure for running digital twins

Numerous was created out of a need internally at Energymachines to easily make available simulations and analytical tools to application engineers and to deploy these tools in a structured way as digital twins, continuously adding the power of advanced analytics to systems in the field.

The current architecture for running heat-pump digital twins from Energymachines can be seen in Figure 14. The users range from the developer who wants to execute their digital twin application, to the user who wants to take advantage of the digital twin, for example for the purposes of predictive maintenance. In the figure it is shown how the model developer configures the applications (harvester and digital twin) using the numerous.cloud platform and how energymachines.cloud polls sensors from a heat-pump connected to the cloud via a local client and publishes its data on its backend using MQTT

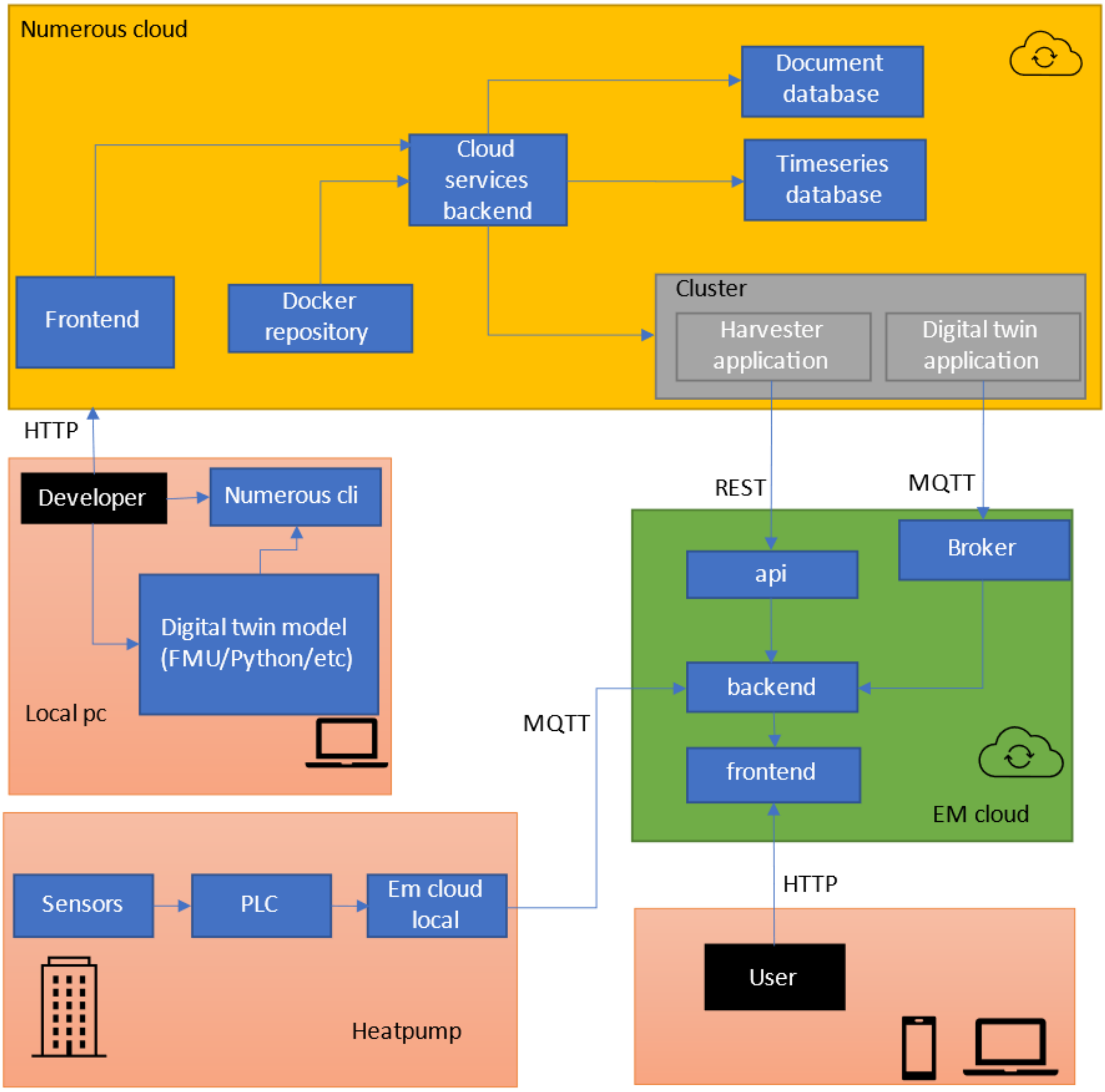

Figure 14: The digital twin infrastructure at Energymachines [8].

Packaging the model for numerous

The model developer creates a model using any application which can be interfaced from python and integrates it with the numerous platform using the python SDK (software development kit). The developer then deploys the digital twin from the numerous web application. Python was chosen as the most popular programming language with the largest ecosystem of packages available for data science and analytics, as well as its ability to run on most operating systems. The developer uploads the application to numerous using the numerous command line interface.

Running the model as a digital twin

A main feature of numerous is the ability to run any model in real-time as a digital twin. There is in-fact no distinction between a simulation using static data and one running as a digital twin. The definition of a digital twin is here a simulation which runs continuously with input data coming from a real system. Typically, simulations can run in multiples of times faster than real time and so resources consumed for a digital twin is much less CPU intensive as the application only does its calculations a fraction of the time. When running as a digital twin, Energymachines typically take advantage of the hibernation functions, to save resources, which will be described later.

Configuring the application on numerous

Accessing the numerous web application, users set up two application scenarios: A harvester, which extracts data from energymachines.cloud, a standard tool included with the platform, and the second is the digital twin which uses the outputs from the harvester as inputs to the digital twin simulation. After configuring relevant parameters, the digital twin can be set up to run either continuously, or periodically (every hour, every day, etc.), to conserve resources. A screenshot from the numerous platform is shown in Figure 15.

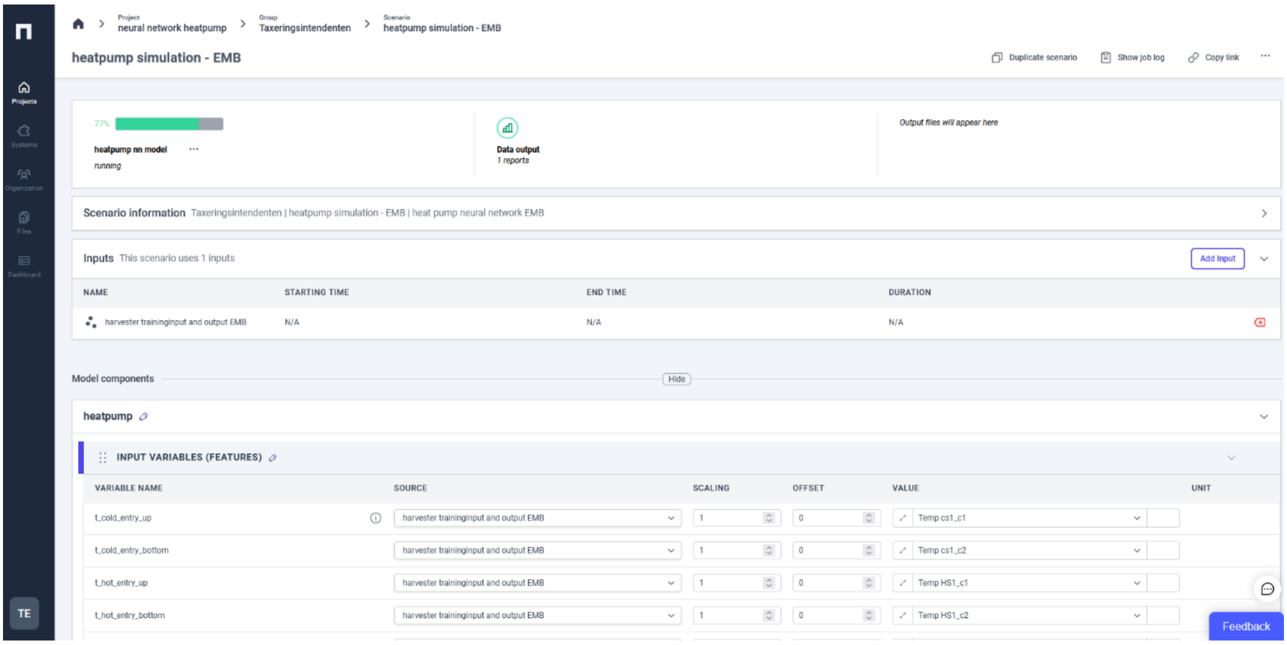

Figure 15: Screenshot from numerous where a heat pump model is executed. In this example, the simulation is not executed as a digital twin, but there is no marked difference between a digital twin application and simulation application, as so far as the UI is concerned. The difference is the progress bar will show the message "running as digital twin" instead of a percentage completion [8].

Running applications in the cloud

The two application scenarios are then launched from the frontend: first the harvester application is started, so that data is available when launching the actual digital twin application. Then, naturally the digital twin application is launched. In either case, the 'numerous' frontend calls the backend, which configures the applications to run on cloud resources. The cluster pulls the images containing the developer's application code from an image repository and deploys them on provisioned resources.

Handling data flow between numerous, the applications, and externally

Both applications communicate with the platform via the numerous SDK, using the GRPC protocol. Outputs are sent back and are saved in numerous timeseries database service.

As mentioned, when setting up the application in the frontend, outputs can be shared between applications, so that the output from the harvester, can be used as inputs in the digital twin. In practice, the application running on the cluster requests the data from the numerous platform using the numerous SDK. The digital twin application furthermore writes its output to the energymachines.cloud using the MQTT protocol.

State-full applications

If the harvester application is set to execute periodically, it can hibernate, which triggers the listener (digital twin) application to hibernate as well. The numerous platform then schedules the application to re-launch based the configured schedule. When hibernating, the model states are saved before closing the application. The model states are then reloaded once the model is re-launched. This is important, as models are typically not stateless.

Monitoring the results

Results from the digital twin applications can be integrated with the energymachines.cloud pages, but are also available on the numerous platform. Energymachines.cloud is directed towards plant operators, and is therefore more intuitive towards operation, whereas numerous is a general analytics platform, and is directed towards simulation developers who want to monitor progress, configure applications, document and share results.

4.2.2 Connected heat pumps in building automation

For this, two use case were elaborated in the Task 2 report. Here focus is on the connected heat pump acting as a part of a building automation system:

- ENERGETIKUM - living lab: The use case demonstrated by FH Burgenland shows the integration of a Data-driven Predictive Control (DPC) strategy into the office building ENERGETIKUM. The Building Management System of the ENERGETIKUM allows the integration of an intelligent Energy Management System and connectivity with various systems via API-interfaces (e.g. weather forecast). The developed DPC strategy is an approach, which minimizes the operational costs of the heat pump while ensuring at the same time the thermal comfort in each thermal zone

- ZEB laboratory at SINTEF: The use case demonstrated by SINTEF is an example of an integration of heat pumps and other building automation devices with a time-series platform to perform consistent analytics and to help develop services that optimize the operation of the heat pumps as well as the use of on-site generated electricity and heat storage. The development of data processing pipelines, models and analytics was streamlined by utilizing the time-series platform that integrated data from various sources, including message transfer from BACnet devices, external web services (nearby weather stations and forecasting services) and post-processed measurements and model results.

  Considering that many buildings use BACnet for communication, the plan is to improve the robustness of the "BACnet2Influx" application, which retrieves data from building automation networks and formats it for storage in a manner suitable for downstream operational use of the time-series data. Additionally, the "BACforsk" application will be further developed to enable algorithms to exert control over certain aspects of building operations, with the added capability of remote access and computational control.

4.2.3 Heat pumps in grid services

Two examples were provided about interfaces for heat pumps in grid service:

- SLAV (Storskalig Laststyrning Av Värmepumpar i elnätet): This is a R&D project where the communication from the Transmission System Operator (TSO) or Distribution System Operator (DSO) to individual heat pumps has been investigated. The project found that today no available protocol fully fulfils the communication needs from the aggregator to individual heat pumps, but EEBUS and OpenADR are promising. EEBUS is a European initiative and could thus have an advantage in the EU, while OpenADR is sprung from the California electricity crisis in 2002. Lately some cooperation between these protocols is seen and hopefully the gaps in the protocols for heat pump demand response will be filled, as a world standardization would benefit the heat pump industry. Both EEBUS and OpenADR are open access and license free, in opposite to the in power subsystem already used IEC 61850. IEC 61850 is extended with wide-area-network (WAN) communication and security and should not be ruled out as the solution. If one or more TSOs point on IEC 61850 the heat pump industry must adapt.

- tiko: This solution developed by the Swiss company tiko Energy Solutions AG presents a heat pump pooling and power grid service use case where a large number of heat pumps and other electric consumer (e.g. domestic hot water heaters) are orchestrated from a centralized backend (a server). The tiko system can be divided into 4 parts (see Figure 16).

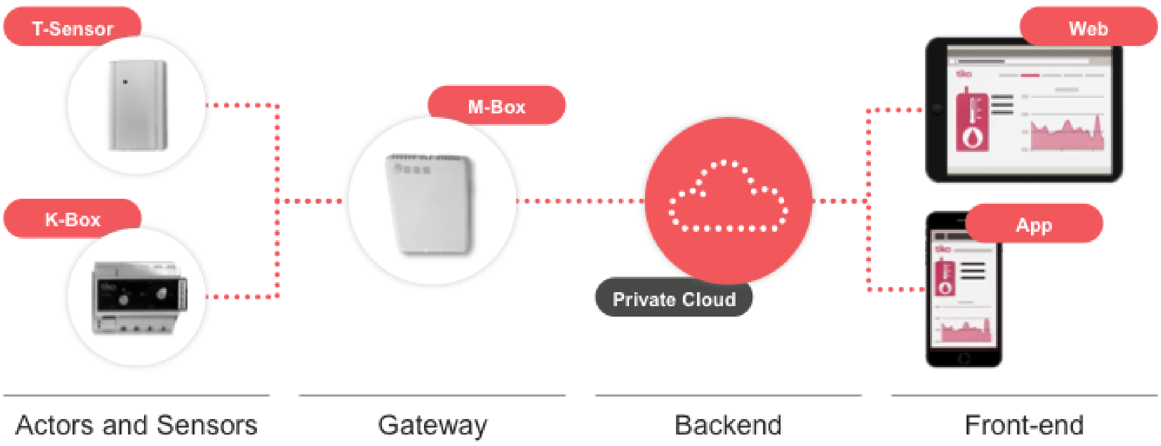

Figure 16: tiko system overview [20].

As actors and sensors, two devices are connected directly to the heating system. The "K-box" measures the power consumption and at the same time serves as a control switch using a relay. The T-sensor is used to ensure comfort, so that the room or water temperature does not drop out of the desired temperature limit due to a switch action. Both devices communicate via power line communication (PLC) with the "M-box" (gateway). The "M-box" collects all data and communicates via 3G/4G network with the private cloud (backend) of tiko. One important heat pump specific aspect in this system is the maximum number of on/off switching actions to prevent compressor damage.

4.2.4 Retrofitting

Two examples with focus on retrofitting were also provided. With the longevity of heat pump devices, the fact that computation platforms, interfaces and protocols must satisfy use cases of connected heat pumps possibly over a decade later makes retrofitting an apparent issue:

- One example focusses on monitoring in district heating system, especially on the lack of transparency regarding the operation of the decentralized substations in the buildings themselves. This case is described in the project AI4CITIES. The solutions from this project help district heating operators and customers identify and prioritize problems in their network more efficiently and quickly. The focus was on monitoring district heating transfer stations, which the project first measured using an IoT-based data logger. The data generated in this way has then been analyzed in a software tool using a patented AI solution for fault detection and diagnosis.

Through such measures the status of district heating transfer stations can be made more transparent, which allows operators and customers to make data-driven decisions and reduce CO_2 emissions. Likewise, similar solutions can be deployed to monitor heat pumps and connected heating systems, where existing measurement equipment is not sufficient, or data is not accessible. The paths in the IoT based solution is seen in Figure 17.

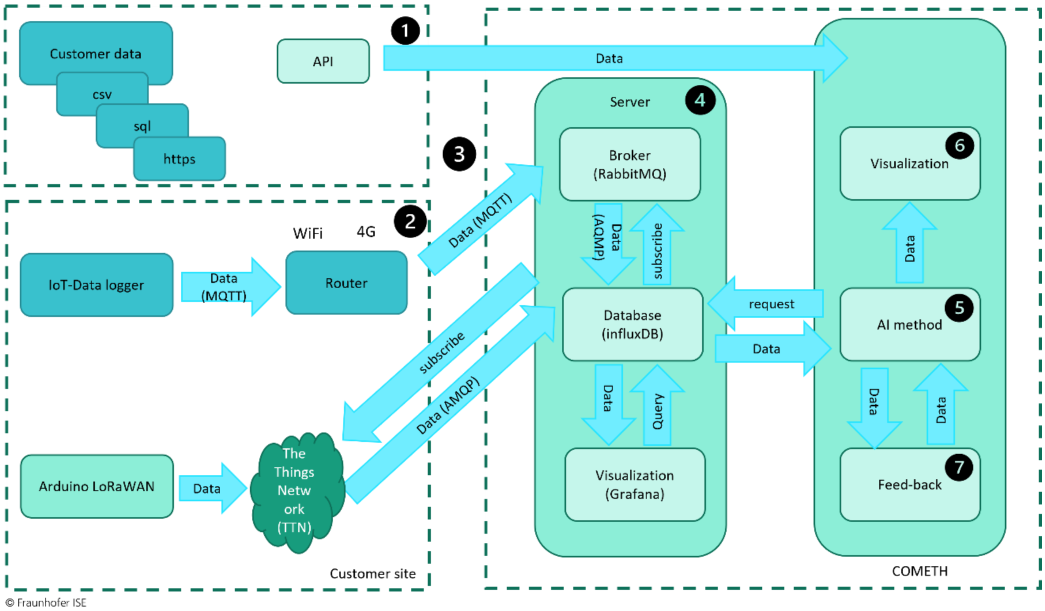

Figure 17: Data paths in the IoT based solution, made by Fraunhofer ISE [8].

- Another case is the solution SmartGuard developed by the Swiss company Meier Tobler AG provides an IoT extension for their heat pumps offering remote diagnostics, comfort features and facilitation of maintenance and repair works. The heat pumps are equipped with a local installation that connects to the heat pump to the server. The heat pump is controlled and monitored by the heat pump manager. The heat pump manager can redefine various control parameters. In addition, the HP-manager collects over 200 data points of the heat pump in a resolution of up to 1 second. The heat pump manager is directly connected to the MT-Gateway. The MT-Gateway has its own antenna on the building facade and thus communicates via 4G/LTE (LTE CAT1M) with Meier Tobler's remote diagnostics. On the server the data is stored and analyzed manually and automatically. Data is held available for inspection by experts of the company's customer support team and made available to the end customer.

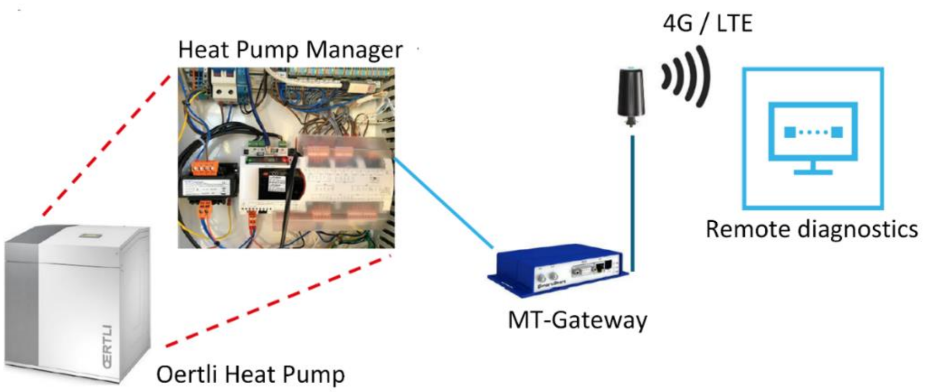

Figure 18: SmartGuard system setup [21].

4.3 Task 3: Data analysis

The results from Task 3 report are collected in the Task 3 report [9]. The report gives an overview on data analysis in the context of connected heat pumps. The aim of the 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 report, 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).

16 use cases from the IoT Annex have been analyzed in Task 3 to retrieve specific information about:

- Description of data analysis (DA) methods
- Clustering/categorization of DA methods and
- Qualitative assessment of DA methods,

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 19.

Most of the use cases are attributed to a single IoT category, but often they address various DA-targets and DA-methods. For example, the IoT category "Heat Pump Operation Optimization" can be targeted with "Control engineering" and "Comparison with other heat pumps" 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.

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 three categories address 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 goal "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 five **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 goal 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 mixed integer linear programming (MILP) () 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".

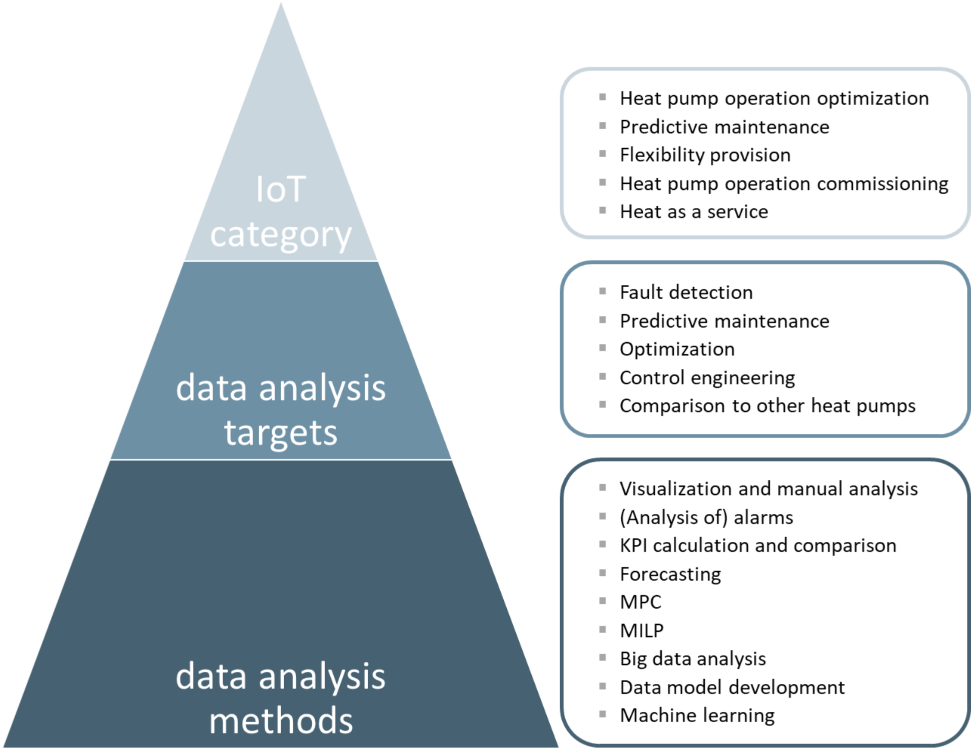

Figure 19: Hierarchy derived from the use cases: IoT category, data analysis targets and data analysis methods [9].

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", "Key performance indicator (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 "Model predictive control (MPC)", "MILP", "Machine learning" are standing terms and applied according to the definitions hereafter. 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 3 provides an overview of the evaluated use cases, their IoT category, the data analysis targets and methods. It also indicates the applied 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

Table 3 – Listing of data analysis methods from Task 3 use cases with the respective analysis targets [9].

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	OPT ASM	CE OPT		FD PM ASM		FD PM	dynamic and quasi-dynamic simulation models
		FD PM OPT ASM		FD PM OPT ASM	OPT ASM	CE OPT		FD PM ASM	FD PM CE OPT ASM	FD PM CE OPT	grey-box model

.

Further information about the Danish Task 3 inputs is shown in the following sections.

4.3.1 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
TRL	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 Require-ments	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

4.3.2 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
TRL	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

4.3.3 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
TRL	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

4.3.4 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
TRL	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.

4.3.5 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 intelli-gence	Controller in the building management system
Incoming data	HP controller setpoints
Outgoing data	Pressures, temperatures, flows
QoS of the connec-tion	Real-time
TRL	7-8
Availability	Research project
DA-Method	Control engineering.
Implementation De-tails	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 require-ments	Requires dynamic models for the controller where the temperature control is per-formed 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 Require-ments	Development of a control kit needed, includes development of room model, floor model, room temperature control.
Operation data requi-red	Performance data, temperatures, pressures, mass flows, weather forecast, PV production, storage data, indoor temperatures, grid prices
Semantic data requi-red	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.

4.3.6 Digital Twins (1)

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

Country of applica-tion	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
TRL	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.

4.3.7 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
TRL	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.

4.3.8 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
TRL	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.

4.4 Task 4: Business models

The results from Task 4 are collected in the Task 4 report [10], and the results summarized below are based on [10]. The Danish working group provided input to the analysis and discussion in the Task 4 report and has also provided seven case descriptions, which were analysed from a business model point of view. Furthermore, the Danish working group created the templates, which were used for gathering the information for the fact sheets regarding the case descriptions in the international group.

Task 4 evaluated market opportunities created by connected heat pumps and identified success factors and further development demands for software and hardware. To this end, different types of IoT services were described. An overview of business models for connected heat pumps is given in the Task 4 report based on literature and market research. For three business models a detailed SWOT analysis was out carried to elaborate strengths, weaknesses, opportunities, and threats. The full SWOT analysis can be found in the Task 4 report.

The various stakeholders involved in the lifecycle of a heat pump and the business models were identified. In the following, these main stakeholders are described, and their main contributions are visualized during construction, installation, and operation of the heat pump in Figure 20.

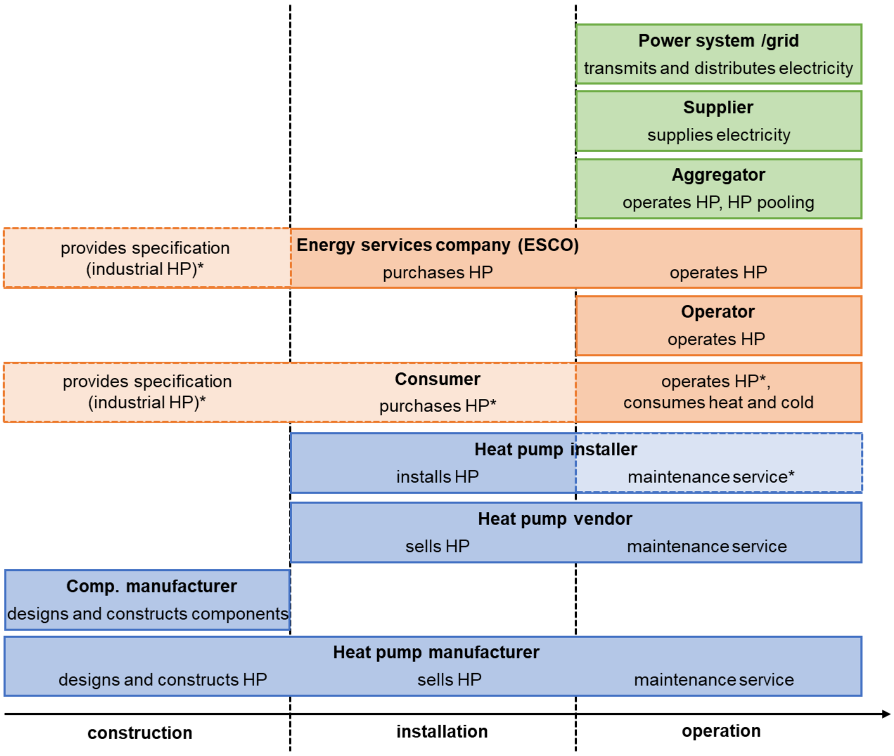

Figure 20: Overview on stakeholders in the life cycle of IoT enabled heat pumps (* indicates optional tasks) [10].

- *Heat pump manufacturer*: designs and constructs heat pumps, sells them to vendors or end-users, also offers maintenance service, usually does not act as installer
- *Heat pump vendor*: sells heat pumps to end-users, also offers maintenance service, usually does not act as installer
- *Installer*: installs and commissions heat pumps, can also offer maintenance service

- *Consumer*: both residential and industrial end-users, consume heat (and cold) at a place where a heat pump is operated, can also be responsible for the operation of the heat pump, can provide specifications for the design of the heat pump (mostly for industrial heat pumps)
- *Operator*: responsible for the operation of the heat pump, provides heat (and cold) to consumers
- *Aggregator*: pools a large number of small assets into a large one to market flexibility to electricity markets or as grid services and thereby influences operation of the heat pump
- *Supplier*: supplies customers with electricity by trading at electricity markets and sometimes producing electricity e.g. from fossil fuels or renewable energy sources
- *Power system / grid*: transmits and distributes electricity, connects utilities and end-users, requires balancing of supply and demand
- *Energy service company (ESCO)*: offers service-based propositions for energy such as heat contracting, efficiency contracting, Heat as a service, Energy as a service, etc., can come from various sectors including energy suppliers, heat pump manufacturers and specialist startups.

11 factsheets of projects and/or companies providing innovative business models in the context of connected heat pumps were identified in Task 4. They are relating to the four IoT categories outlined in Task 1 and 3 as follows:

- Operation optimization: three use cases from Austria, three use cases from Denmark
- Predictive maintenance: one use case from Austria, two use cases from Denmark
- Flexibility provision: one use case each from Austria, Denmark, and Switzerland
- Heat as a service: one use case from Denmark

The main value proposition for the consumers identified in Task 4 are lower costs, more efficient heating systems and higher reliability.

For the heat pump value chain (component manufacturers, heat pump manufacturer, vendors, installers) digitalization leads to new products and services that make heat pumps more attractive and more future proof. Compared to traditional business models, they have more responsibility for the efficiency of the IoT enabled heat pump systems. The energy system (aggregators, suppliers, grid, etc.) has a strong need for flexibility provision to compensate for fluctuating renewable generation. Heat pumps allow for sector coupling by combining the heat and the power sector and can offer flexibility at various scales which is a valuable asset for the future.

Energy service companies (ESCO) are a rather new actor in buildings but are already established for industrial contracting. They help to spread heat pumps as their service reduces the involvement of the consumers.

The results from each of the business models analyses for the IoT categories is presented in the following sections.

4.4.1 Operation optimization

IoT services for operation optimization of heat pumps aim to save energy, emissions, and costs without compromising comfort requirements of the users. A basic version of optimization is monitoring and remote control via an app, that provides an overview of actual and historic data and allows set point adjustment by the user. Advanced systems allow adaption according to user habits and optimal interaction with other components e.g., to maximize self- consumption of PV production or solar thermal energy or the optimal management of a thermal or electric storage. Therefore, data analysis is typically carried out in the cloud of the service provider.

An example of operation optimization for heat pumps in buildings is the PreHEAT heat pump controller by Neogrid that is available in Denmark. Neogrid is a cleantech supplier working with intelligent energy visualization, monitoring and control. The purpose of PreHEAT is to save energy and reduce the cost of heat, by optimizing the heat pump operation in relation to demanded energy from the building and local electricity prices and tariffs. This enables customers to adapt to market flexibility and at the same time to save energy without compromising indoor comfort requirements. Sensor data like indoor temperature, consumed electricity and delivered heat are collected and sent to the Neogrid PreHEAT Cloud. Neogrid provides several services: model predictive control (MPC) of the heat pump via the cloud, the use of variable prices and aggregator-based services for different electricity markets.

Operation optimization based on price signals for heat pumps in buildings is part of myiDM+energy, a service offered by the Austrian heat pump manufacturer iDM. The purpose is to consume electricity preferably when electricity prices are low. The service requires an iDM heat pump, a smart meter, internet connection and a variable electricity tariff. To optimize electricity consumption, room temperature set points are tuned and hot water production is shifted as a function of the day-ahead hourly prices. The heat pump system can use the heating buffer, the domestic hot water storage as well as thermal building masses as energy storages to shift electricity consumption in time. If a PV system is available, self-consumption can be increased as well.

KNV, an Austrian heat pump manufacturer that merged with NIBE AB offers connected heat pumps for buildings since 2012. They allow for operation and monitoring via an app with automated logging of heat pump parameters and smart functions such as smart price adaption and weather control. Smart price adaption adjusts the heat pump operation to times with low energy prices based on electricity price information for the next 24h. Weather control considers the local weather forecast and adapts operation of the heat pump accordingly in advance.

A similar service is provided by METRO THERM, another daughter company of NIBE. In the case description collected by the Danish working group it is described how users of the myUpway service can monitor and control their heat pumps online, use Smart Price Adaption, and get suitable support from service providers.

An example of operation optimization in Danish district heating systems is the Centrica Energy Trading tool. It enables optimal utilization of several asset types including heat pumps for district heating supply. This enables the optimization of energy consumption and cost savings as well as the minimization of expensive imbalances. The platform provides an estimation of the power consumption, heat production, and COP of the heat pump based on forecasted weather variables such as outdoor temperature, humidity, wind direction and speed. The services provided by the platform include coordinating heating and electricity markets, optimizing heat pumps for the provision of frequency regulation services and guaranteeing electricity prices for large-scale heat pumps and other electricity consuming systems. To date, several Danish district heating supply companies have adopted the energy planning and pptimization platform developed by Centrica.

4.4.2 Predictive maintenance

Predictive maintenance aims to plan maintenance as precisely as possible in advance and to avoid unexpected equipment failures. Thereby, downtime of equipment is reduced and unplanned shutdowns that typically cause costs, delays and discomfort are reduced. Also, resources for maintenance work such as spare parts and work force can be planned more precisely. Predictive maintenance requires condition monitoring of the equipment and data analysis to detect anomalies and failures. It can either focus on critical components of a heat pump e.g., the compressor or it can analyze the complete heat pump system. Two descriptions from the Danish working group were provided for the Task 4 analysis:

- Energy Machines™ offers monitoring and control for heat pumps in buildings as a part of their service offering for design, implementation, and operation of integrated energy systems for buildings to transform buildings into climate solutions. Energy Machines Verification Tool (EMV) is a combined hardware/software solution based on physical measurements, a service representational state transfer application programming interface (REST API) and thermodynamic models of the heat pumps. It provides live online and transparent performance monitoring of the heat pumps. The EMV is the basis for an early warning system for predictive maintenance that is currently being developed and that may even reveal early signs of deterioration of the system. For more information see the factsheet annexed to this report.

- Digitalization is an important requirement to facilitate maintenance for the heat as a service proposition of Nærvarmeværket. It is a community owned Danish company which provides solutions for simplified heat as a service based on heat pumps for areas without district heating. The end-users can buy into a cooperative community, which ensures an overall solution with installation, service, and maintenance of the heat pump. A one-time fee for the installation cost is paid, together with a smaller annual payment, which ensures the cost of maintenance and a free replacement of the heat pump if it breaks down or needs to be changed. Service costs are reduced by remote monitoring. As the heat pumps are typically installed in remote areas, e.g., on an island, where there is no access to a larger district heating network, the travel cost for a service technician can be saved if the technician knows the fault on beforehand and has the spare part available the first time the heat pump is being serviced.

4.4.3 Flexibility provision

Heat pumps are well suited to offer flexibility to the electricity grid which is in greater demand with increasing shares of intermittent renewable energy production. In the power system, there are different types of flexibility that are distinguished by their time scale in Figure 21. The type of flexibility that can be provided with heat pumps depends on the characteristics of the heat pump system as well as on national regulation.

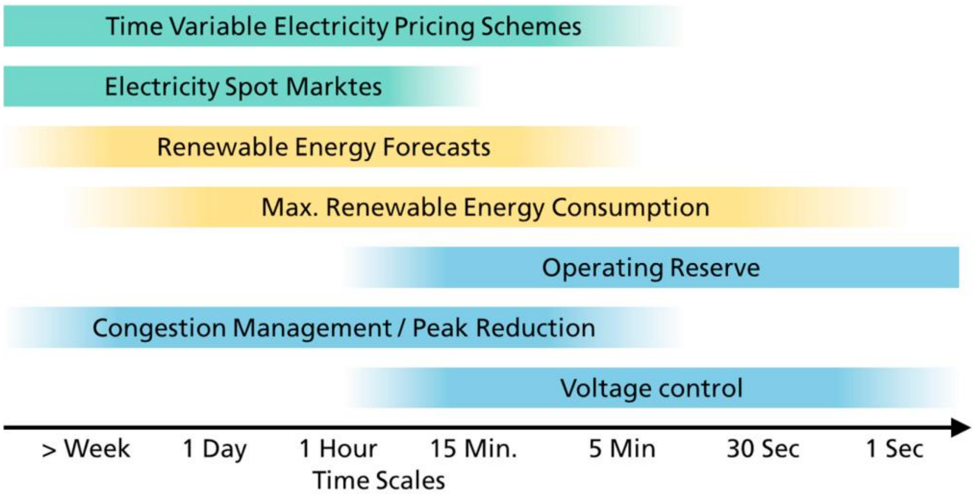

Figure 21: Time-wise characteristics of selected fields and mechanisms in the power system, where flexibility of the demand side might be used to create benefits [2].

The Swiss company tiko started with the development of its ancillary service business in 2012 and entered the market with its solution in 2014. They offer the grid operator both primary control quality (frequency stability) and secondary control quality (balancing between planned power and actual power in the grid) by combined electricity-based heating systems throughout Switzerland into a virtual power plant. In 2017, the virtual power plant of tiko had a capacity of up to 50 MW including over 10,000 electricity-based heating systems, more than half of these installations are heat pumps. The remaining installations are made up of direct electric heaters, night storage heaters and hot water boilers. tiko has been expanding its market internationally and has established customer bases in several countries in the EU. Devices are connected to tiko via a gateway solution and electricity consumption of the devices is managed by the tiko pool within adjustable comfort criteria. End-users benefit from monitoring and alarming functions, from energy savings thanks to eco-mode and additional revenue is created by the virtual power plant. The tiko system is described in more detail in the factsheet provided in the appendix of this report.

The Austrian project Flex+ investigates the flexibility provision by heat pumps in the context of the provision of automatic and manual frequency restoration reserve (aFRR, mFRR) by operating a pool of heat pumps. It was found that the total simulated revenues for all stakeholders per year per heat pump amounted to 8 € to 23 € (Day-ahead-market participation) and 65 € to 117 € (aFRR provision). Households can profit from reduced grid tariffs for negative balancing reserve, because balancing power is partly exempted from grid tariffs in Austria. However, it was challenging to predict user behavior (hot water, heating demand, thermal load) and define the right modelling depth for technical components for optimization. Changes in market regime and in flexibility products require adaptions of the optimization algorithms. The business case becomes more interesting, the simpler the processes are and the lower the implementation costs are. The demonstrations have shown that the concept is technically feasible and the regulatory framework in Austria is suitable for market integration of heat pumps, for DSO-TSO interaction more research is needed. Further details on the platform and the optimization are provided in the factsheet in the appendix of this report.

In the Danish Flex Heat Project, grid services are provided with a flexible energy system consisting of an 800 kJ/s ammonia-based ground-water heat pump with reciprocating compressors, 200 kJ/s electric boiler and a thermal storage tank of 100 m^3. This system delivers heat to four customers in an island district heating grid, which was supplied by oil-fired boilers previously. This system is optimized by a linear optimization model supported by a dynamic model of the heat system to schedule optimal production with a real-time communication setup to control the heat pump accordingly. The linear optimization model includes heat demand forecasts with inputs from weather data, complex stratified storage tank modelling, and start-up costs for the heat pump, and an electricity price forecast is supplied to optimize for the minimum costs of the system. Furthermore, the heat pump has been modified to provide fast regulation services to the grid. It was proven that ammonia-based heat pumps can regulate fast enough to deliver the FCR-N service (frequency stabilization service). The optimization module can additionally plan for the heat pump to deliver this service, and, still under construction, a setup is implemented to read the grid frequency and stabilize this accordingly by changing the set-points of the heat pump. The preliminary results indicate that operating costs can be reduced by 7 % by introducing intelligent operation with the linear optimization model, and an additional 6 % costs reduction can be achieved by delivering grid services.

4.4.4 Heat as a service

Heat contracting business model are already available in the commercial and industrial sector, where energy service companies provide heating, hot water, or process heat for industrial customers. Most typically, heat pumps with larger capacities are subject to contracting, as it is a considerable effort on the side of the contractor to set up the heat pump and operate it. Interoperability between the IoT components in heat pumps and a supply chain accustomed to installing IoT components in residential buildings will be needed to ensure a good customer experience in the long run to support heat-as-a-service concept. Various examples are described in the Task 4 report:

- The Norwegian company Aneo Industry offers heat pumps supplying up to 5 bar steam for industrial customers with an Energy as a Service contract. Aneo Industry evaluates how to integrate the heat pump in the process, carries out concept design, verification, and detailed engineering of the heat pump. Aneo Industry will finance the heat pump system and the integration according to agreed boundary conditions and is responsible for the operation through an Energy as a Service agreement. They will train the personnel of the customer how to operate the system and continuously monitor and follow up (second line of operation), carry out service and maintenance, as well as optimization of the performance. The energy contract includes a guaranteed annual operation to the customer.

- The Danish company Nærvarmeværket provides solutions for simplified heat as a service based on heat pumps for areas without district heating. The end-users can buy into a co-operative community which ensures a complete solution with installation, service, and maintenance of the heat pump. A one-time fee for the installation cost is paid, together with a smaller annual payment, which ensures the cost of maintenance and a free change of the heat pump if it breaks down or needs to be changed. In this way, the community structure ensures cheap and reliable green heat for the end-user. Nærvarmeværket cooperates with several heat pump suppliers, e.g. Vaillant, Pico Energy, DVI, and HS Tarm. They also offer a combined system with an air/water heat pump and PVT panels providing electricity with optimized operation to increase self-consumption. Further information is included in the factsheet in the appendix of this report.

- The German heat pump manufacturer Viessmann offers asset leasing based on their own products [22]. Thermondo a company specialized installing heating systems with a strong background in digitalization to facilitate design and construction of heating systems offers heat pumps by LG in a leasing model [23] In Austria, the utility company Energie Burgenland has launched a leasing program for heat pumps based on several manufacturers [24].

4.5 Dissemination and knowledge-sharing of the results

The dissemination overall consists of the following activities:

1) The Danish country review report and 23 case descriptions have been published on DTU Orbit.

2) The Danish country review report and 23 case descriptions have been published on DTI's homepage.

3) Sharing of results and activities on the international IoT Annex homepage, where the Danish IoT cases also are presented.

4) LinkedIn posts about the Annex results have been made on DTI Energy and Climates LinkedIn channel.

5) Newsletter about the Annex results has been published by DTI.

6) A topical article from EnergyMachines has been published in the HPT Magazine with the title "Control and Monitoring of Heat Pump Systems".

7) The following four papers:
   i) C. A. Thilker, M. P. Sørensen: Bringing Order to Disorder, A Method for Stabilising a Chaotic System Around an Arbitrary Unstable Periodic Orbit, Physica D: Nonlinear Phenomena, Volume 455, 2023
   ii) R. G. Junker, G. Tsaousoglou, H. Madsen: Incentivising and Activating Multi-Purpose Flexibility for the Future Power System (submitted), 2023
   iii) C. Thilker, H. Madsen, et. al.: A Review on Sensor-Based Real-Time Controllers for Buildings in Smart Grids (submitted), 2023

   iv) H. G. Bergsteinsson, M. L. Sørensen, J. K. Møller, H. Madsen, Localizing: Weather Forecasts for Enhanced Heat Load Forecast - Accuracy in Urban District Heating Systems (submitted), 2023

8) Inputs from the Danish working group were given to another article in the HPT Magazine about the IoT Annex 56 itself.

9) A series of presentations by the Danish working group was given and coordinated to the IoT Annex international group through a number of deep dive sessions. This includes presentations about the subjects:
   i) Demo. case study: Optimization of heat pump for district heating operating with seawater and ammonia
   ii) Simulation and experimental study: Dynamic model and classification algorithms for fault detection and diagnosis (FDD) in a chiller
   iii) Simulation and field study: Prediction of heat exchanger fouling for predictive maintenance
   iv) Simulation and field study: Model-based online optimization of large-scale heat pump operation affected by fouling
   v) Digital Twin Project and Data Driven Modelling
   vi) Grey-box Modelling and Project Examples
   vii) Digitalization of Heat Pumps at HOFOR

10) The IoT Annex project, including inputs about results from the Danish working group have been presented by the operating agent on the following conferences:
   i) 8th International Symposium on Advances in Refrigeration and Heat Pump Technology, Copenhagen, 2023 (here a large number of stakeholders from the Danish heat pump industry were present)
   ii) IEA's heat pump conference, Chicago, 2023
   iii) European Heat Pump Summit, 2022

11) Presentations by DTI at the public open "Final Results Presentation Webinar for IEA HPT Annex 56 - IoT for Heat Pumps", October 18, 2023

12) Furthermore, a one-day seminar is planned for spring 2024 at DTI in Høje Taastrup. This seminar is planned to present results from projects, including the IoT Annex project, which focuses on digitalization of heat pumps.

5. Utilisation of project results

Through the Danish participation in the IoT Annex 56 an overview covering a wide range of applications, interfaces, data analysis, services, opportunities, challenges, and state-of-the-art descriptions for IoT and digitalization of heat pumps was successfully created. Furthermore, both IoT aspects regarding heat pumps for household and commercial applications and heat pumps for industrial application was described.

The project was used for disseminating results from a broad range of Danish R&D projects and Danish technology partners to an international level, and hence supporting the advancements in digitalization. Similar, an overview of the newest trends on an international level was obtained through the cooperation in the international IoT Annex project group and shared on a national level. Throughout the project regular project meetings were held, and furthermore both online and physical workshop meetings with the international project group were held to support knowledge sharing.

The results from the Danish participation in the Annex has created a knowledge base with an international perspective for IoT enabled heat pumps, and is available for increasing the knowledge at different levels within the heat pump industry such as for OEMs, heat pump manufacturers, consultants, installers, students, etc. This knowledge can serve as inspiration for further developments within the field of IoT enabled heat pumps.

Energy Machines are using digital twins and simulations in order to validate and optimize the performance of heat pumps, hence the experiences made in this project can directly be utilized for further developments within this area.

6. Project conclusion and perspective

In recent years, the number of installed household heat pumps in Denmark has strongly increased. Among other reasons this is due to economic and political incentives supporting electrification and a ban on oil boilers. Moreover, around 66 % of Danish households are supplied by district heating in 2022 [11]. Also in the district heating networks both the number of heat pumps and the total capacity installed has increased significantly in recent years. This is aligned with the target of using heat pumps to supply around one third of the heat in Danish district heating networks by 2030 [12]. Furthermore, it is also expected that heat pumps will have an increasing role for decarbonizing the process heat supply in the Danish industry in the coming years.

There is a strong incentive to increase the use of smart controls and digital solutions for heat pumps, and hence enable the high potential to integrate the heating and power sectors, and increase the efficiencies. This is supported by the Danish Society of Engineers who in a report on how to reach a climate neutral Denmark recommends more interaction between energy consumption and supply in “smart buildings”, and encourages to use apps and/or smart meters to control indoor climate and energy consumptions

Participation in the Annex 56 made it possible to gain detailed insights and get a state-of-the-art overview of digitalized heat pumps systems and processes. By leveraging connected devices it is in the Annex 56 described how a future energy system with a higher degree on IoT enabled on digitalized heat pumps enhances user comfort, reduces energy consumption, and supports the decarbonization of heat supply.

The focus of the project was to create a knowledge base, and to explore and identify the possibilities and challenges associated with the use of IoT enabled and digital technologies for heat pumps, as well as evaluate success factors and address the demands related to software and hardware infrastructure. This has been described within four tasks, to which the Danish working group has made a significant contribution:

- Task 1: State-of-the-art
- Task 2: Interfaces
- Task 3: Data analysis
- Task 4: Business models

A key part of the project was twenty-three Danish case descriptions, which were made after interviewing product and service suppliers of IoT and digitalization technologies for heat pumps, as well as research and development projects working on the subject. The case descriptions show that several stakeholders at different levels in the Danish heat pump industry are already focusing on enhancing and deploying digital and IoT-enabled solutions for heat pumps in Denmark. The review made in the Annex clearly shows that digitalization will be a key aspect in the future development of heat pumps for the energy system, e.g. for enabling the provision of monitoring, predictive maintenance, and ancillary services for heat pumps.

Cybersecurity issues has also been addressed in the Annex. All heat pump demand response initiatives will need internet connection of some kind, meaning the heat pumps will have a certain cybersecurity risk. When heat pump manufacturers enter the flexibility market, and makes adoptions to a higher degree of control complexity, adoptions of effective cybersecurity measures are hence needed.

7. Appendices and links

In appendix A, the country summary report for Denmark can be found this. This report summarizes and reviews the main information collected by the Danish project group related to the tasks, and contains the full descriptions collected about the 23 Danish IoT cases on heat pumps. The country summary report is also available on DTI's homepage and DTU Orbit:

- https://www.dti.dk/iot-for-heat-pumps/43060
- https://orbit.dtu.dk/en/publications/iea-heat-pumping-technologies-iot-annex-56-digitalization-and-iot

The full report for each of the four tasks from the international annex 56 group can be found in the following links under each task section:

- Task 1 – State-of-the-art: https://heatpumpingtechnologies.org/annex56/
- Task 2 – Interfaces and platforms: https://heatpumpingtechnologies.org/annex56/
- Task 3 – Data analysis: https://heatpumpingtechnologies.org/annex56/
- Task 4 – Business models https://heatpumpingtechnologies.org/annex56/
- In addition to this the 4 reports can be found on DTI's homepage about Annex 56 in the sections about results: https://www.dti.dk/iot-for-heat-pumps/results-and-cases/43060,2

The topical article in the HPT magazine can be found in Appendix B and in the following link. Title: "Opening the black-box: A case study of a borehole thermal storage" by Tobias D. Elmøe, Energy Machines™:

- https://issuu.com/hptmagazine/docs/hpt_magazine_no3_2022 (page 28)

Link to literature review made in Task 1:

- https://www.zotero.org/groups/4871439/annex56/library

Further info in general about the IoT Annex 56 can be found on the following homepage:

- https://heatpumpingtechnologies.org/annex56/

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Appendix A

IEA Heat Pumping Technologies -
IoT Annex 56

Digitalization and IoT for Heat Pumps
Country Summary for Denmark

IEA Heat Pumping Technologies - IoT Annex 56

Digitalization and IoT for Heat Pumps
Country Summary for Denmark

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Contents

1. Introduction

This report summarizes and reviews the main information collected by the Danish project group related primarily to Tasks 1 and 4 of the International Energy Agency (IEA) Heat Pumping technologies (HPT) Annex 56 about Digitalization and Internet of Things (IoT) for heat pumps. The Annex 56 project is an international knowledge sharing project with focus on digitalization and IoT for heat pumps. Focus is especially on what opportunities and challenges digitalization and IoT brings, as connected devices are expected to play a major role in the future energy system addressing multiple aims, such as increasing comfort for the user, reducing energy consumption, and supporting decarbonization of heat supply.

In general, the Annex 56 project aims to identify the possibilities and challenges related to the use of IoT-enabled and digital technologies for heat pumps at various levels such as OEM's, heat pump system suppliers, operators, and installers. Task 1 and 4 within Annex 56 are defined as:

- Task 1 - State of the Art: This task aims at reviewing the status of currently available IoT-enabled heat pumps, heat pump components and related services in the participating countries. A common glossary for the most important digitalization topics will be elaborated.
- Task 4 – Services: Evaluate market opportunities created by IoT-connected heat pump devices and identify success factors and further demands to software and hardware infrastructure.

The participating countries in the IoT Annex 56 project are Austria (operating agent), France, Germany, Norway, Sweden, Switzerland, and Denmark. The project group in Denmark consists of the following partners, all of whom have a key focus on the digitalization of heat pumps:

- Technical University of Denmark, Department of Applied Mathematics and Computer Science (Henrik Madsen, hmad@dtu.dk)
- Technical University of Denmark, Department of Civil and Mechanical Engineering, DTU Construct (Wiebke Meesenburg, wmeese@dtu.dk)
- Energy Machines ApS (Lasse Thomsen, lasse.thomsen@energymachines.com)
- Danish Technological Institute (Jonas Poulsen, jlp@teknologisk.dk)

More information on the international Annex 56 project can be found on the following link:
https://heatpumpingtechnologies.org/annex56/

2. Overview of collected cases

A review of the current state-of-art of IoT-enabled and digital technologies for heat pumps was developed for Denmark. Here, suppliers of such technologies as well as research and development (R&D) project groups working on the subject were contacted between 2021-2022. The information obtained from suppliers and R&D groups was summarized in the form of case descriptions of typically 2-3 pages, which included the following:

- Overall description of the technology
- Current and/or potential applications
- Key learnings from the development phase and implementation phase, if any

In total, 11 suppliers provided information for the case descriptions. Furthermore, the company DVI Energi (https://www.dvienergi.com/) completed a questionnaire about digitalization and heat pumps prepared by the international IoT Annex 56 group. The information was provided by the suppliers without third-party validation and may be different in installations depending on application-specific parameters.

Regarding R&D projects, 12 case descriptions were collected with the purpose of mapping projects on digitalization and IoT for heat pumps in Denmark in recent years. The participants of such projects cover a broad range of different organizations such as universities, research and technology organizations, system operators, suppliers, and consultants.

A brief summary of the 23 case descriptions collected in this project is given in Sections 2.1 and 2.2. The complete version of the descriptions is presented in the Appendix.

2.1. Product and service suppliers

2.1.1. Energy Machines™

Energy Machines™ is a leading company in the design, implementation, and operation of integrated energy systems for buildings. EnergyMachines is working to transform them into climate solutions. Energy Machines™ offers a combined hardware/software solution based on physical measurements, a service representational state transfer application programming Interface (REST API) and thermodynamic models of the heat pumps, named Energy Machines Verification Tool (EMV). This tool, shown in Figure 1, enables the provision of online/live transparent performance monitoring of heat pumps as well as the provision of early warning systems for predictive maintenance.

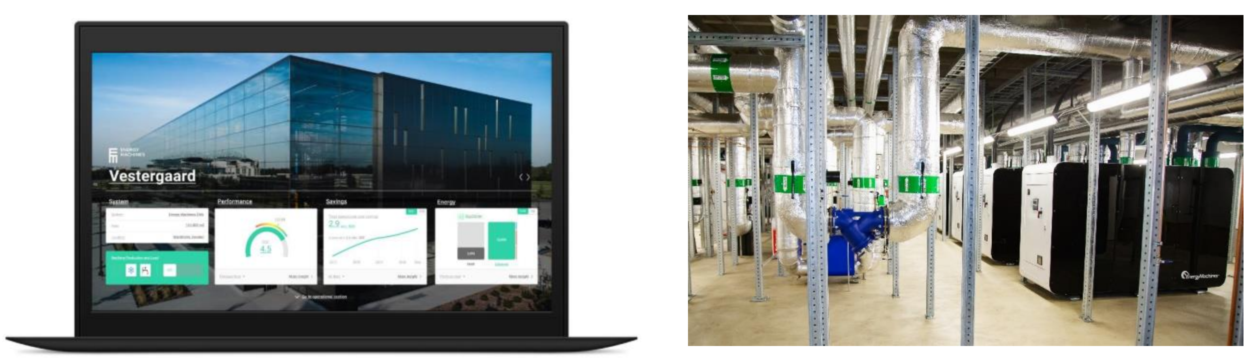

Figure 1. EMV dashboard with quick overview of current performance (left) and an Energy Machines heat pump installation with sensors placed inside the boxes (right).

2.1.2. Neogrid

Neogrid is a cleantech supplier working with intelligent energy visualization, monitoring and control. Neogrid has developed the PreHEAT heat pump controller. The purpose of PreHEAT is to save energy and reduce the cost of heat by optimizing the operation of a heat pump in relation to the building energy use as well as local electricity prices and tariffs.

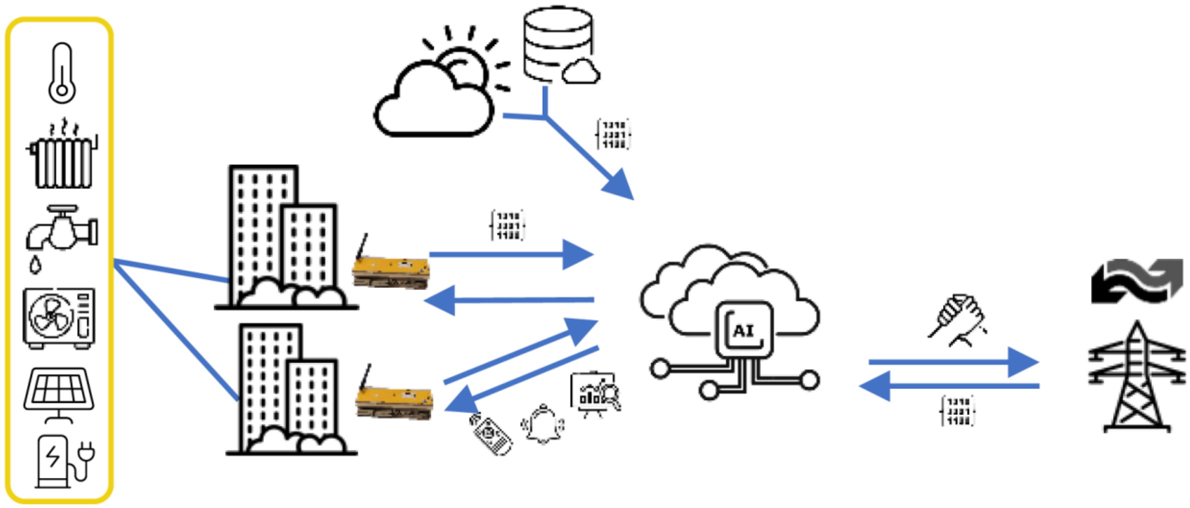

Figure 2. Neogrid PreHEAT Cloud.

This enables customers to adapt to market flexibility and at the same time to save energy without compromising indoor comfort requirements. Sensor data such as indoor temperature, electricity consumption and delivered heat are collected and send to the Neogrid PreHEAT Cloud. This measured data and operational data retrieved from the heat pump enables Neogrid to deliver three categories of services:

- Category 1: Services that are available as soon as data is collected from the heat pump and sensors included in the Neogrid system. If external control is activated, additional services like model predictive control (MPC) may reduce the operation cost for the heat pump. This category "only" requires a bilateral agreement with the heat pump owner and a cloud system operator.
- Category 2: Services that include variable prices, tariffs, and services to the distribution system operator (DSO). Variable prices and tariffs are deployed over most of Denmark, but DSO flexibility demand to cope with bottlenecks is still limited in Denmark.
- Category 3: Specialized services to the electricity markets. This includes the regulation of power and frequency reserves. Those services require separate settlement of the electricity to the heat pump and an aggregator.

2.1.3. LS Control

LS Control is a technology partner for manufacturers of heating, ventilation, and air-conditioning (HVAC) systems, control platforms, power components, and IoT service providers. LS Control have developed the LS SmartConnect Center, which is a tool for the provision of monitoring and other services for heat pumps, which enables fleet management of common residential heat pumps. LS SmartConnect Center provides a swift overview of the performance of all heat pumps and other HVAC products licensed by a manufacturer. This overview can be broken down into different segments and commercialized to specific end-users such as manufacturers, resellers or janitors, who may benefit from a fleet management system that incorporates a certain group of products, as shown in Figure 3.

Figure 3. Swift overview of products and data with LS SmartConnect Center [1].

In addition, the LS SmartConnect Center comes with an end-user app for consumers to manage their own products. For example, this includes the possibility for remote turn on/off of the system as well as supply temperature adjustment. The operational status of any product in the overview can be accessed for further investigation and for software updates. A security-software integrated in the controllers and gateways provides a safe connection between the user's PC, phone, or tablet and the LS SmartConnect product by the use of industry standard cryptography.

2.1.4. Centrica Energy Marketing and Trading

Centrica is an energy trading and asset management company that developed an energy planning and optimization platform. This platform consists of a web-based API with a data warehouse system for energy route-to-market services, shown in Figure 4.

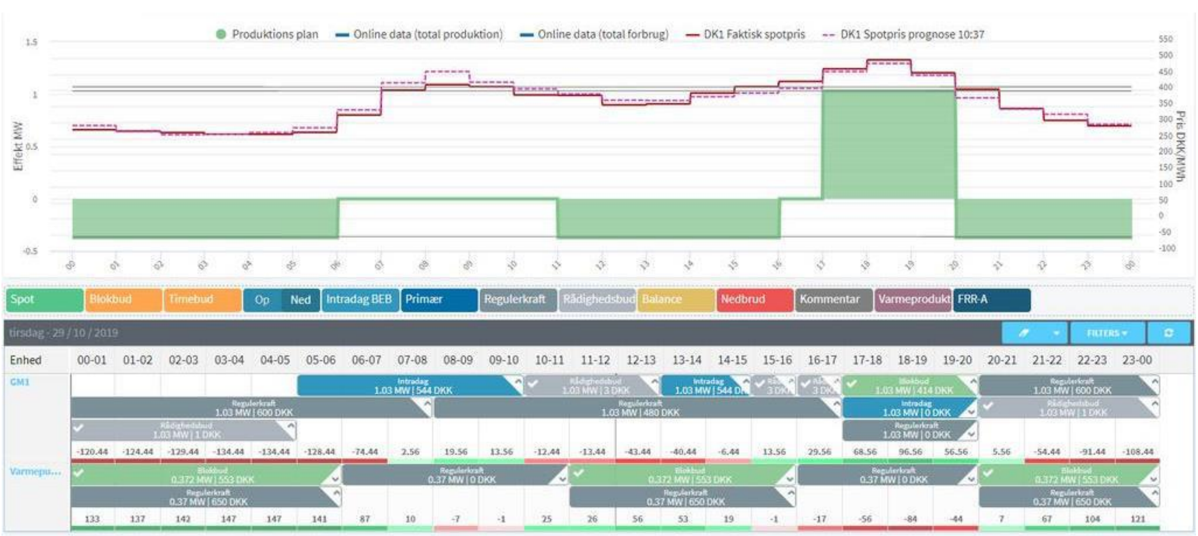

Figure 4. Interface of the energy planning and optimization platform developed by Centrica Energy Trading.

The Centrica Energy Trading tool enables an optimal utilization of several asset types including heat pumps for district heating supply. This tool allows the optimization of energy consumption and production earnings as well as the minimization of expensive imbalances. The platform provides an estimation of the power consumption, heat production, and COP of the heat pump based on forecasted weather variables such as outdoor temperature, humidity, wind direction and speed. In addition, the interface includes estimation of varying marginal prices in different electricity markets. The services provided by the platform include coordinating heating and electricity markets, optimizing heat pumps for the provision of frequency regulation services and guaranteeing electricity prices for large-scale heat pumps.

2.1.5. Climify

Climify has developed a modular digital solution for indoor climate monitoring that works for any building. The platform consists of a data collection and visualization tool for monitoring the indoor climate in buildings and HVAC systems. The platform presents to users an easy-to-understand graphs and visualization to inform the user about the state of the indoor climate in rooms, and to report potential problems/issues of the indoor climate. The service also enables occupants to rate the indoor climate by allowing them to provide feedback through the App “FeedMe”. This is exemplified in Figure 5, where the user can rate the indoor air quality and receive an overview of all the responses received from a particular room.

In the very near future, the software will be able to automatically report potential faults and/or behavioral patterns that may have a negative impact on the indoor environment. Here, users will be immediately informed about such concerns to take preventing or mitigating actions about them. Another future feature is the automatic optimization of HVAC systems’ operation by taking into account indoor climate parameters such as CO2 levels, as well as energy use and electricity prices. Climify does this by performing remote adjustment of e.g. thermostat settings, air supply rates and forward temperatures, in multiple HVAC systems.

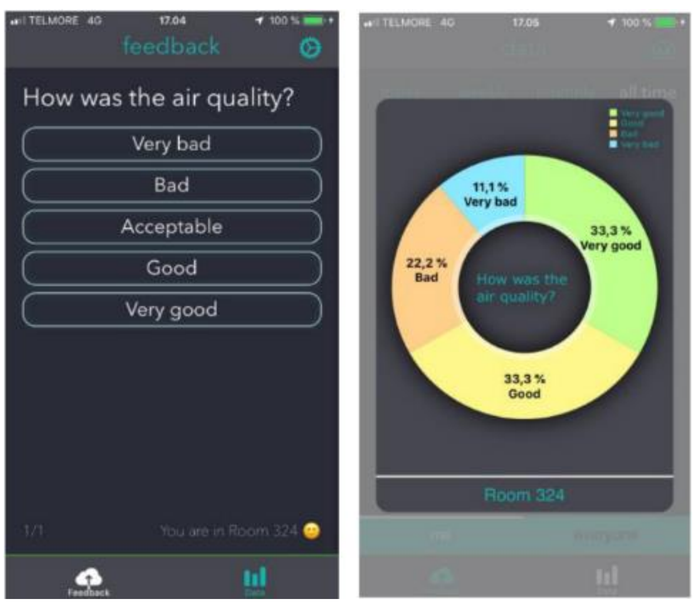

Figure 5. User feedback over Climify phone App.

2.1.6. Nærvarmeværket

Nærvarmeværket is a community owed company which provides solutions for simplified heat as a service based on heat pumps for areas without district heating. The end-users can buy into a co-operative community, which ensures an overall solution with installation, service and maintenance of the heat pump. A one-time fee for the installation cost is paid, together with a smaller annual payment, which guarantees maintenance costs and a free replacement of the heat pump if it breaks down or needs to be changed. In this way, the community structure ensures cheap and reliable green heat for the end-user. Nærvarmeværket cooperates with several heat pump suppliers, e.g. Vailant, Pico Energy, DVI, and HS Tarm.

Figure 6. Complete PVT energy system from Nærvarmeværket.

Nærvarmeværket implements digital and IoT-enabled solutions, where the installed heat pumps are typically monitored remotely. This provides a unique opportunity for low-cost services. As the heat pumps are often installed in remote areas, e.g. on an island, where there is no access to district heating networks, the travel cost for a service technician can be saved. Here, the technician is able to know the existence of a potential fault beforehand and have all necessary spare parts available the first time the heat pump is being serviced.

2.1.7. AI-energy

AI-energy develops products for automating the planning of solar (photovoltaic) plants, optimizing energy market bidding and operation of a portfolio of power and energy plants. AI-energy focusses on two heat pump-related products, namely:

- Market bidding (pooling) of large-scale (central) heat pumps
- Sizing and scheduling optimization of end-user heat pumps.

Bidding of large-scale heat pumps is done based on the forecasted heat demand and prices, using stochastic optimization, shown in Figure 7. The bidding procedure also includes the operation on secondary (balancing) markets. A web-based application then provides an optimized schedule for the operation of a day ahead. Often, it is more lucrative to provide services on different balancing and ancillary service markets than to focus purely on day ahead markets. This is accounted in the optimization algorithm developed by AI-energy.

Sizing and scheduling optimization of end-user heat pumps is also done via a web-based application. This enables the operation optimization of multiple components in a household energy system. Such a system may integrate a heat pump with a PV unit and battery system, and might also include an electric charger for e-mobility usage. The performance of the optimization engine is dependent on the resolution of the available heat and electricity consumption data.

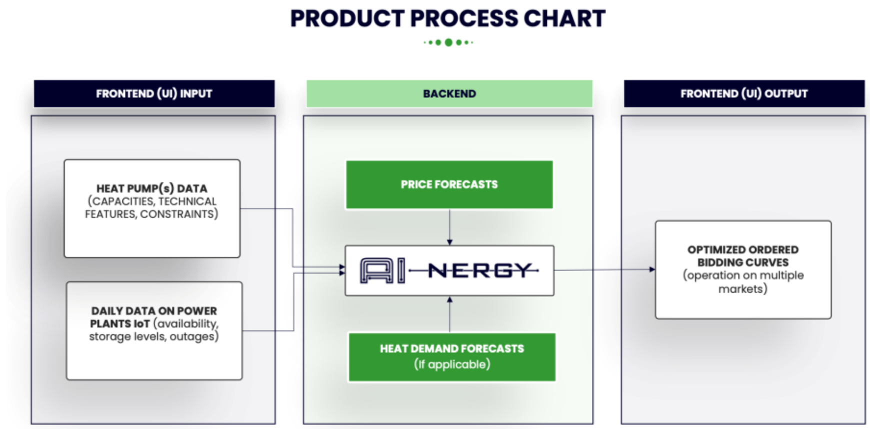

Figure 7. Scheme of the heat pump bidding product from AI-energy.

2.1.8. ENFOR

The energy forecasting and optimization platform developed by ENFOR aims at forecasting energy production from renewable energy sources as well as forecasting electricity demand and heat demand. This platform enables optimal operations of renewable energy production facilities (like and wind and PV) as well as district heating networks. Today, ENFOR provides forecasts of approximately 25 % of the total wind power worldwide. In particular, the module for temperature optimization is able to lower the supply temperature in district heating networks, which will improve the efficiency of heat pumps connected to such district heating supply networks. Furthermore, the temperature optimization module can lower heat losses and fuel costs by optimizing heat pump operation by the use of model predictive control. Several

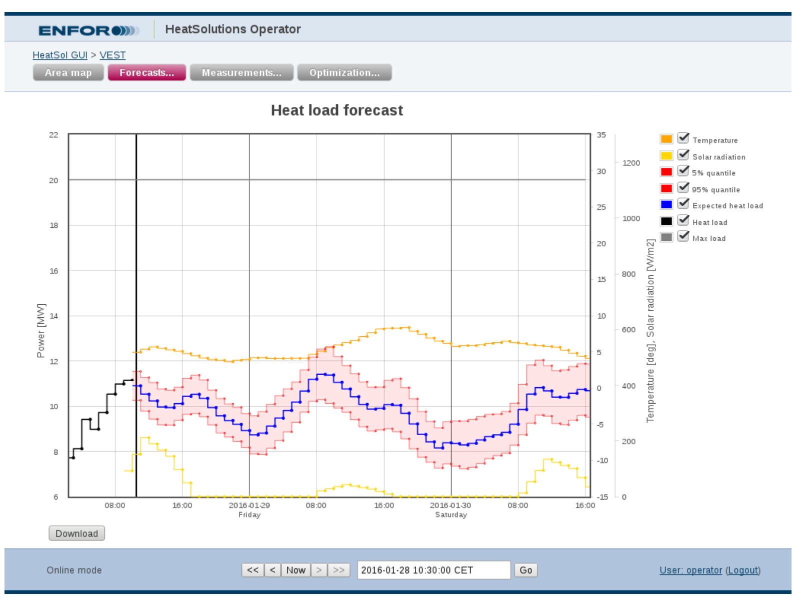

Figure 8. Example of forecast for heat load, temperature, and solar radiation.

Danish district heating supply companies have adopted the energy forecasting and optimization platform from ENFOR, called Heat Solutions, shown in Figure 8.

2.1.9. Center Denmark

Center Denmark is an independent non-profit company that delivers digital infrastructure for different entities in the energy sector to develop novel data-driven solutions that leverage the integration of different sectors, as seen in Figure 9.

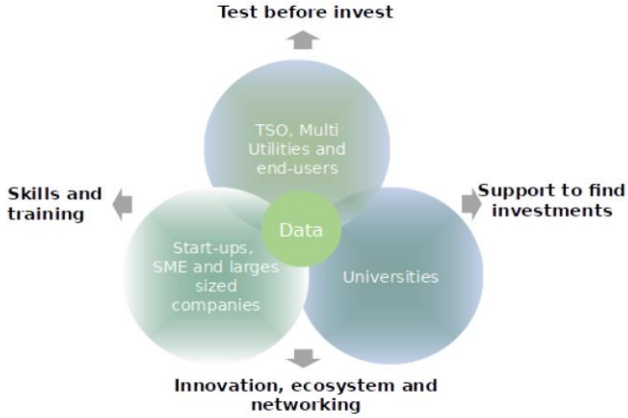

Figure 9. Data is at the core of the development, innovation and business thinking at Center Denmark.

Center Denmark provides a Trusted Data Sharing platform with 24/7 access to energy-related data and digital tools. The platform provides access to historical data using a data lake setup and bi-directional data streaming for smart energy services such as forecasting of electricity prices and control of heat pumps. Using digital tools at the platform, Center Denmark is able to facilitate and support tests and demonstrations in representative and scalable settings. Consequently, Center Denmark is an incubator for digital business models aimed at providing new data-driven services for the energy and water sectors.

2.1.10. EnergyFlexLab

EnergyFlexLab consists of a number of laboratories testing energy components and systems for a future flexible energy system, with increasing demands for smart control systems and sector coupling. EnergyFlexLab uses a digital platform located on its own separate virtual-LAN network within the Danish Technological Institute. The lab setup is testing real life scenarios to analyze the degree of flexibility that coupled technologies can add to an energy system, which include solar panels, battery systems, heat pumps, and electric car chargers.

Figure 10. Main energy components in EnergyFlexLab.

Besides the energy components included in the system, some core features are also integrated and monitored through the IT infrastructure backbone of EnergyFlexLab, which are:

- SQL database where all data and metadata from components are saved for later analysis of historical data.
- Virtual servers with several controlling and analysis-algorithms and feedback loop to optimize the smart control.
- A frontend SCADA developer-tool referred to as YoDa (Your Data), where DTI-employees can share code and develop together. With this SCADA tool online interactive dashboards and control-systems are created and made accessible for external customers.
- A Message Queuing Telemetry Transport (MQTT) data communication protocol that enables fast and asynchronous data communication between components, servers and dashboards.

2.1.11. METRO THERM

MyUpway^{TM} represents METRO THERM's version of the online service platform from its parent company NIBE named NIBE Uplink^{TM}. This service has been commercially available for several years, which has enabled NIBE users to monitor and control their heat pumps to maximize thermal comfort and minimize heating-related costs. The platform myUpway^{TM} provides online monitoring and control services, including surveillance of heat pumps' energy consumption and fault alarms as well as remote control possibilities. This platform is exclusive to METRO THERM products with suitable connectivity specifications, which includes air source and ground source heat pumps. Figure 11 shows the homepage for myUpway^{TM} and the interconnection with a desktop.

Figure 11. Representation of the interconnection between METRO THERM heat pumps and desktop through myUpway^{TM} (left) and homepage of the online-service myUpway^{TM} (right).

Moreover, heat pumps integrated with myUpway^{TM} are smart grid ready. This could be used to optimize remotely the operation of heat pumps based on information from electricity grids and users' consumption patterns to minimize operational costs of heat pumps. The current version of myUpway^{TM} includes a feature called Smart Price Adaption, which enables the automatic adjustment of heat pump operational periods to minimize electricity consumption costs.

2.2. R&D projects

2.2.1. Digital Twins for Large-Scale Heat Pump and Refrigeration systems

This project aims to reduce the effort to develop digital twins for large-scale heat pump and refrigeration systems for monitoring, predicting maintenance and operation optimization purposes. The target groups are supermarket refrigeration systems as well as heat pumps for district heating systems. Figure 12 shows a diagram of the Digital Twin system operator integrated in heat pump or refrigeration system.

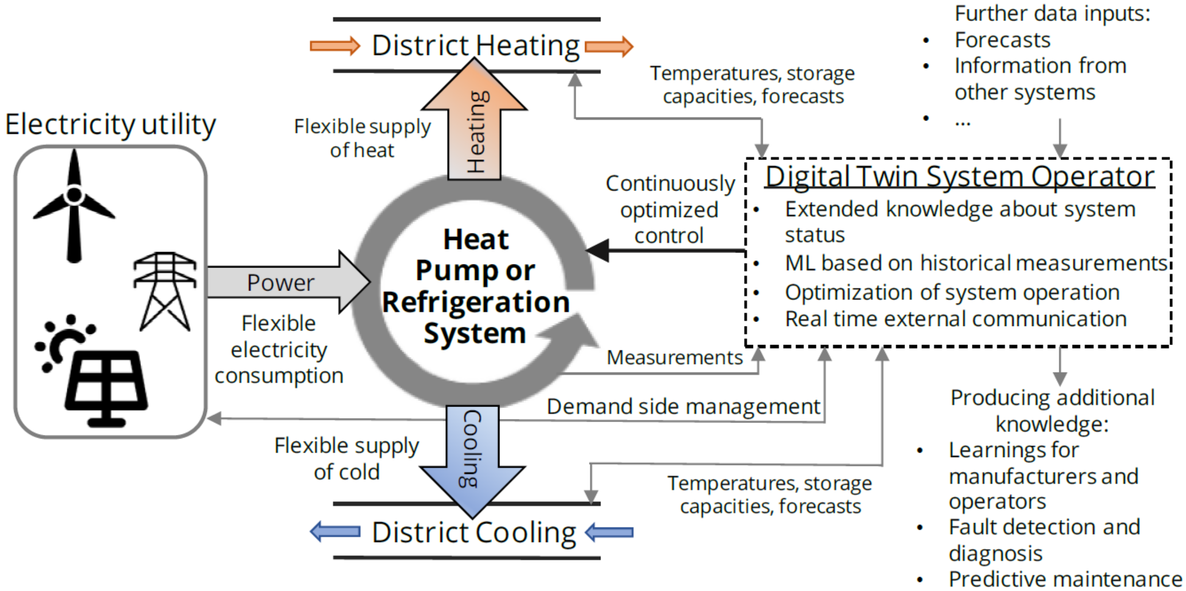

Figure 12. Diagram of the digital twin system operator.

The digital twins developed in the project are expected to have a modular and reusable structure, where physically derived thermodynamic models are integrated with data-driven methods. This is expected to allow the provision of monitoring, predicting maintenance and operation optimization by the use of adaptable models with different levels of complexity. The data used to develop and implement the adaptable models is estimated to be retrieved from wired sensors as well as from IoT-based sensors.

2.2.2. EnergyLab Nordhavn

The project EnergyLab Nordhavn has demonstrated the integration of district heating and electricity systems, as well as energy-efficient buildings and electric transport to achieve smart, flexible and optimize energy systems. In particular, a heat recovery unit has been integrated into the refrigeration system of a supermarket, seen in Figure 13. The supermarket uses a CO_2 refrigeration system. Heat was recovered from the high-pressure side of the refrigeration cycle and supplied to the local district heating grid or to the building itself for space heating and domestic hot water preparation. In this way, energy is recovered, synergies between local energy prosumers are unlocked and the available compressor capacity of the supermarket refrigeration system can be exploited better.

The closed-loop control algorithm for the system was executed in Matlab on a PC at the Technical University of Denmark. The control algorithm decides the optimal operation strategy based on real-time operational data as well as electricity and district heating prices. The connection to the physical system was realized via the Danfoss cloud system that was used to retrieve data to the DTU cloud-based Data Management System (DMS) and to send control commands to the local controller.

Figure 13. Heat is recovered from a supermarket refrigeration system to the local district heating grid in Copenhagen.

2.2.3. Flexheat System - Intelligent and Fast-regulating Control

Flexheat includes a large-scale heat pump system which HOFOR uses to provide heating to a local district heating network in Copenhagen. The system operation is optimized by the use of a linear-optimization model supported by a dynamic model to schedule optimal production with a real-time communication setup to control the heat pump, which is shown in Figure 14. The linear optimization model includes a heat demand forecast with inputs from weather data, complex stratified storage tank modelling, start-up costs for the heat pump, and an electricity price forecast. The optimization model is used to find the minimum cost of heat for the system.

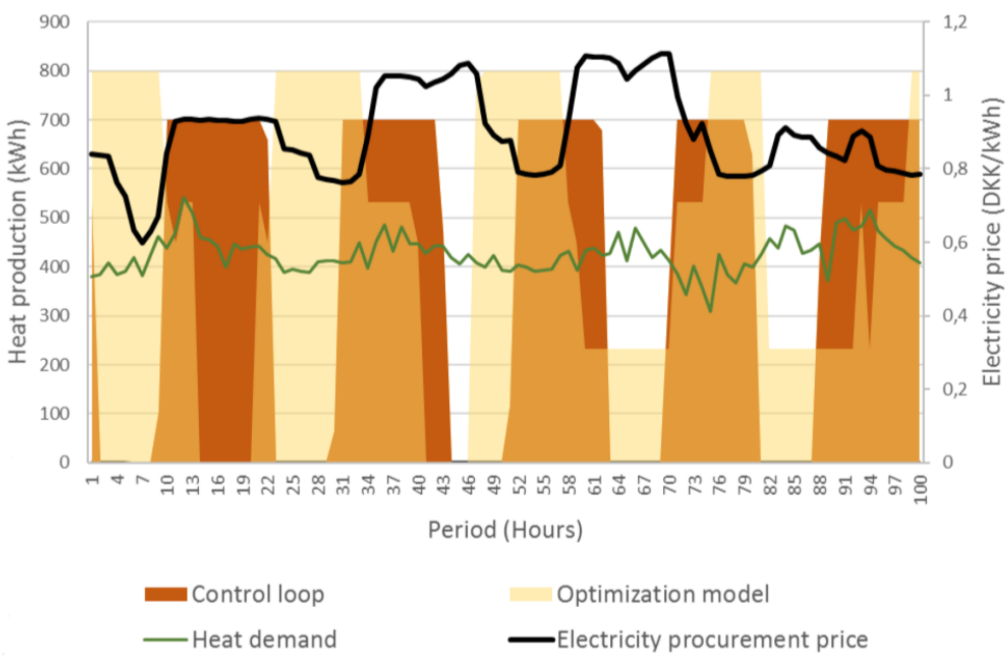

Figure 14. Flexible heat production during 100 hours period. "Control loop" with dark orange columns: Periods with heat production primarily from heat storage, and "Optimization model" with bright orange: Cost optimized heat production from heat pump (800 kW max. production). "Heat demand" is the heat demand in kW for the local district heating grid. Electricity price is seen on the y-axis on the right-hand side.

Furthermore, the heat pump has been modified to provide fast regulation services to the grid. Here, the optimization module (still under development) can additionally plan for the heat pump to deliver this service, where the grid frequency is analyzed, and the module attempts to stabilize it by the adjustment of set points in the heat pump controllers.

The preliminary results indicate that operating costs can be reduced by 7 % when the flexible heat production optimization is applied and an additional cost reduction of 6 % can be achieved by delivering grid services.

2.2.4. Smart-Energy Operating-Systems

The Smart-Energy Operating-System (SE-OS) is a framework for digitalization and implementation of smart energy solutions for heat pumps and other energy systems. This also includes connections to the energy related part of e.g. water and food processing systems. The SE-OS framework consists of both direct and indirect (mostly price-based) control of the electricity and heat load in integrated energy systems, as seen in Figure 15. The system has embedded controllers for handling ancillary service problems in both electricity and heat systems. The entire setup of the SE-OS includes all layers of computing, namely cloud, fog and edge computing. The distributed setup of computing and data includes edge computing near the IoT devices.

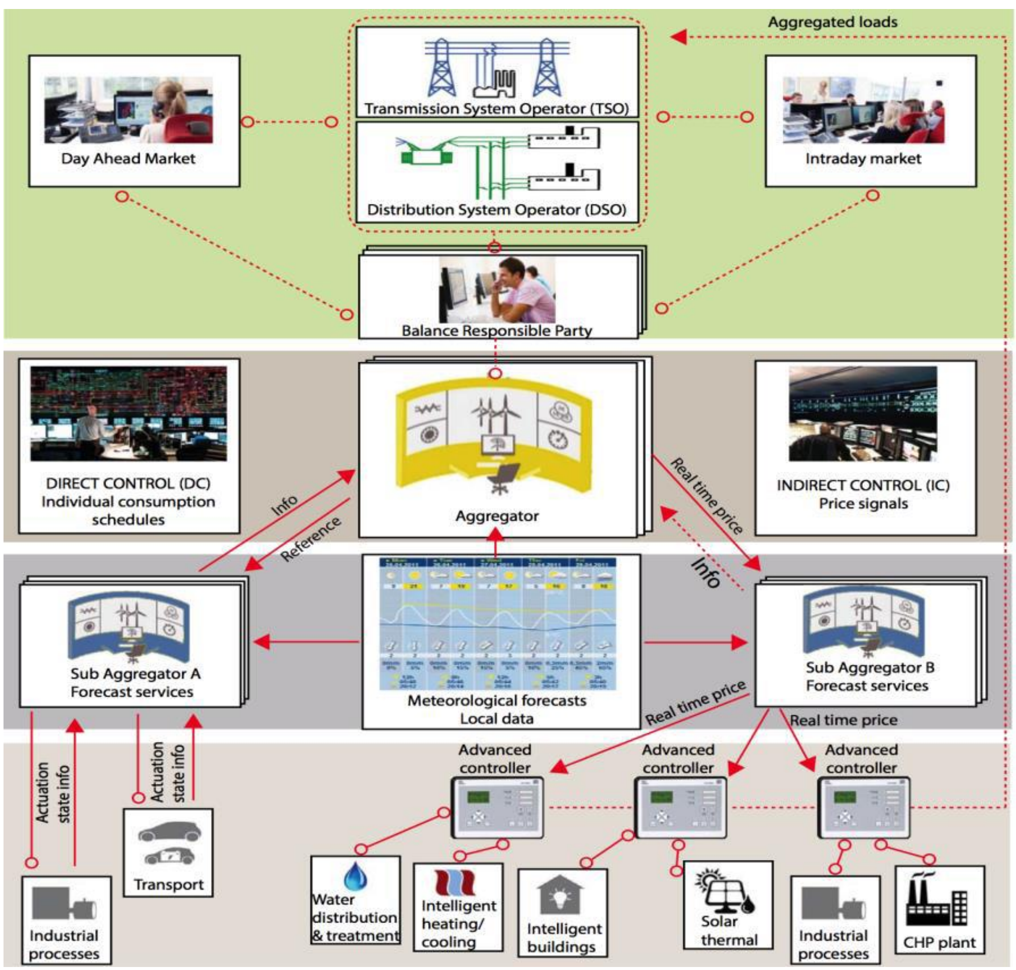

Figure 15. The Smart-Energy Operating-System (SE-OS) for digitalization of integrated energy systems.

2.2.5. OPSYS 2.0

The aim of the project is to increase the efficiency of both existing and new heat pump installations by developing a control kit that can optimize both the forward temperature from the heat pump and the flow rate through heat emitting systems, which is achieved by developing a control system capable of:

- Creating flexibility services for the stabilization of the electricity grid
- Optimizing the self-consumption of PV generated electricity on private houses, represented in Figure 16

Although heat pumps in principle can be controlled according to the amount of renewable energy sources in the system, only little energy flexibility can be provided, as the control of the heat pumps and the heating systems often is not coordinated. The combined optimization of heat pumps and heat emitting systems concept (OPSYS) optimizes the performance of heat pump installations via optimized control of the forward temperature and the flows in the system. This is done by controlling both parameters in accordance with the heat demand, the weather, and the electrical grid requirements.

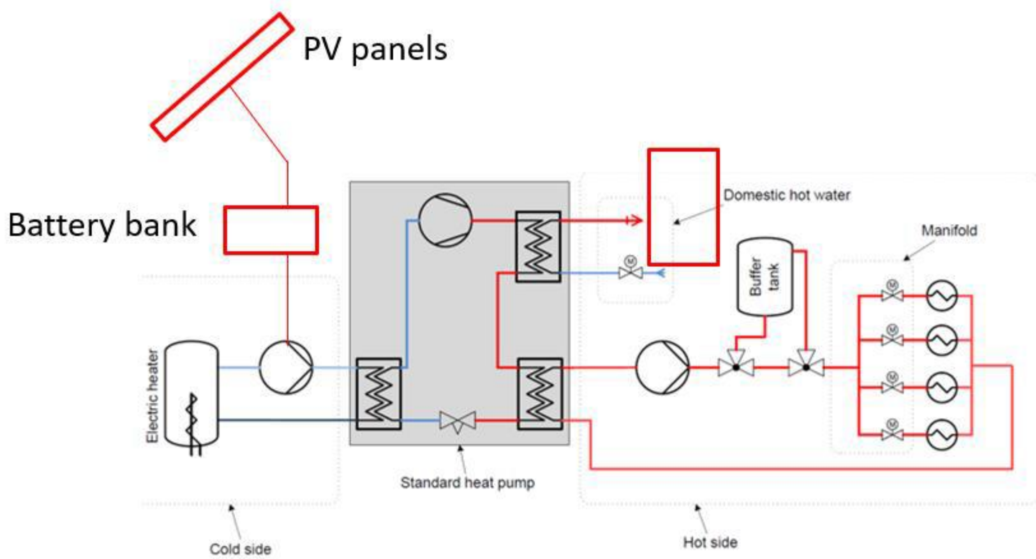

Figure 16. Principle sketch of experimental setup (on the test rig PV and battery are virtual).

2.2.6. Cool-Data

The Cool-Data project focuses on the development, evaluation, and implementation of an AI-based modular, flexible, secure and reliable integrated cooling energy system for data centers. An overview of the application is seen in Figure 17. By the use of an integrated flexible solution, Cool-Data aims at significantly reducing the energy need and cost for cooling data centers and actively contributes to minimizing the carbon footprint of the sector. The integrated cooling solution supports the utilization of electricity from renewable energy sources by storing surplus energy in phase changing materials (PCM) storage units. This allows the decarbonized surplus heat generated by the data centers to be used and valorized in district heating systems by means of heat pumps.

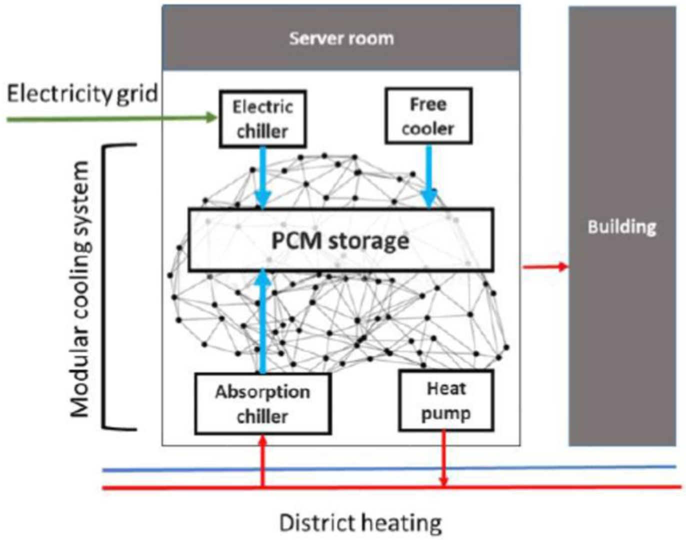

Figure 17. Overview of Cool-Data application.

2.2.7. SVAF phase II

The overall purpose of the project is to accelerate the use of large-scale electric heat pumps (HPs) for district heating (DH) through industrial co-operation, research, and experimental development. A key focus in the project is monitoring and set-point tuning of large-scale HP systems, where two different approaches will be evaluated:

- HP AutoTune - for continuous optimization of operating conditions (see Figure 18).
- HP Doctor - for monitoring purposes and fault detection.

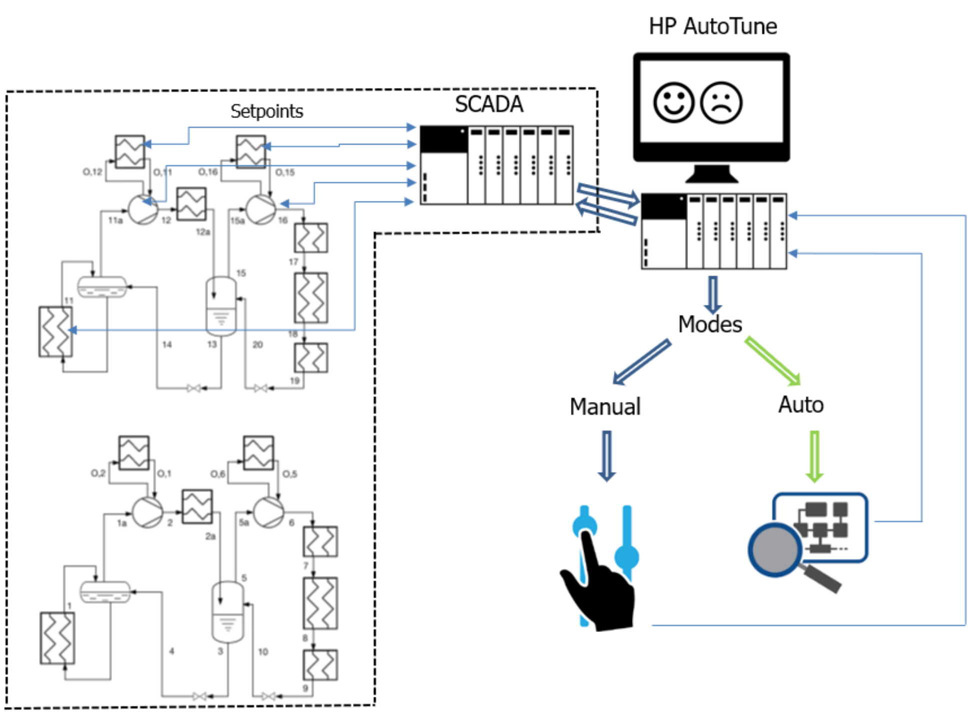

Figure 18. Concept for HP AutoTune.

The idea of the HP AutoTune concept is to adjust the set points for the heat pump, so that the highest possible COP is achieved for a given operating condition. The HP AutoTune will be investigated in the project through different approaches, among other things an approach which is based on invasive weed optimization (IWO).

2.2.8. HPCOM

The main purpose of the project was to strengthen the development and implementation of information and data communication technology (ICT) and infrastructure around individual heat pumps. The project covered data communication from household heat pump installations to the central systems, including distribution system operators, electricity suppliers and other service providers.

The project focused on knowledge sharing and was centered around state-of-the-art research, development, and demonstration (RD&D), standardization and testing facilities which have resulted in a RD&D Strategy and Roadmap for ICT in the heat pump area.

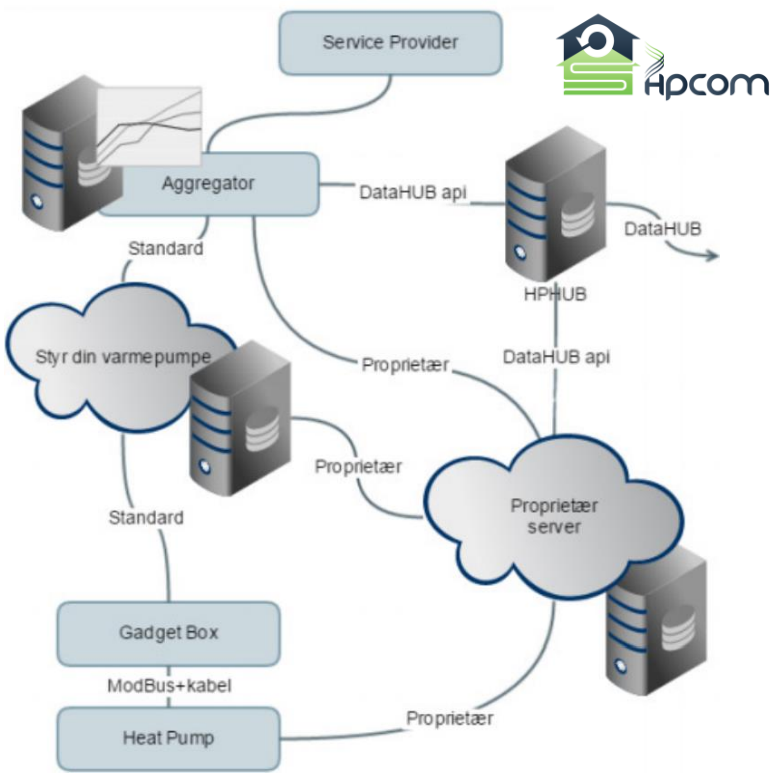

Figure 19. Principle for heat pump datahub (high level) developed in the HPCOM project.

Together with up-to-date knowledge within standardization and RD&D, this roadmap can be utilized by potential new projects within the area. The development of strategy and roadmap were done in close cooperation with the ICT- and heat pump industry, and at the same time, the strategy was conveyed to the broader energy and Smart Grid industry.

2.2.9. Flexible Energy Denmark

The Flexible Energy Denmark (FED) project analyzes large amounts of consumer data and consumer behavior. The aim is to enable the development of digital solutions that are capable of adjusting the power consumption to match the power production – among other things by use of machine learning and different tools for Big Data management. The FED project develops methods for forecasting of wind and solar power production, as well as methods for an efficient integration of the renewable energy production. This is done with state-of-the-art controllers for heat pumps, supermarket cooling, wastewater treatment, district heating operation, and the use of buildings as energy storage solutions in an integrated energy system.

A key focus of the FED project is to deliver a next generation of smart grid solutions, such that the flexibility in integrated energy and water systems that can be used for the provision of grid services. Center Denmark (described in Section 0) is also among the partners in the FED project. Their role is to make the knowledge that the FED project creates available to the entire energy sector in Denmark. This will allow the solutions and results of the project to be applied as widely as possible.

The analysis of a case study included in this project resulted in a reduction between 15 % to 30 % of CO_2 emissions by the use of a smart control developed for heat pumps, where both balancing and grid services could be provided. Figure 20 shows the predicted carbon intensity of electricity production and periods for heat pump operation in the case study installation.

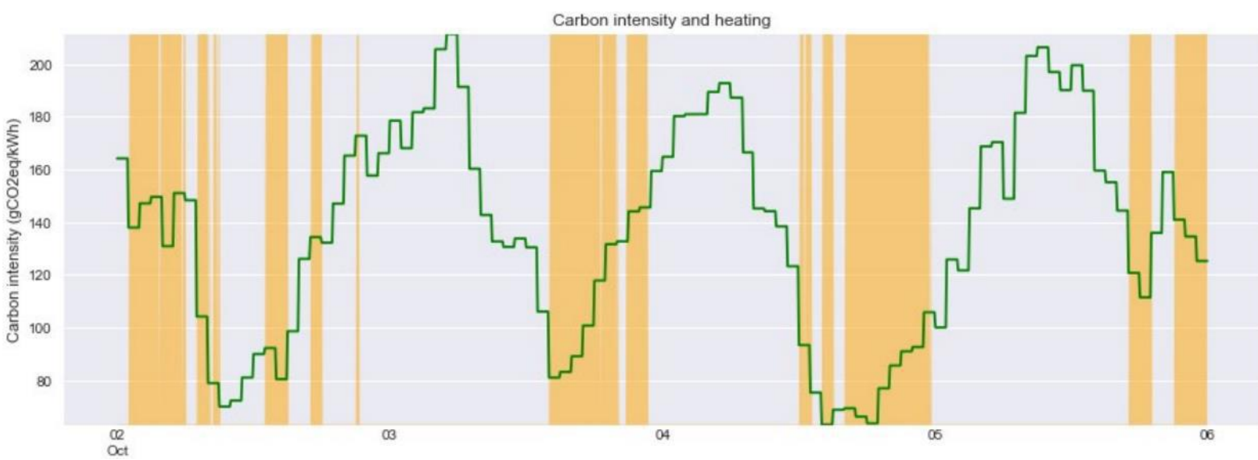

Figure 20. Predicted carbon intensity (green) and periods at which the heat pump is turned on (orange).

2.2.10. Res4Build

RES4BUILD, a Horizon 2020 project, is developing renewable-energy-based solutions for decarbonizing the energy used in buildings. The approach of the project is flexible, where solutions are applicable to a wide variety of buildings, new or renovated, tailored to their size, their type, and the climatic zones of their location. In the heart of the solution lies an innovative multi-source heat pump in a cascade configuration (see Figure 21), including a magnetocaloric (bottom cycle) and a vapor compression heat pump (top cycle). The heat pump will be integrated with other technologies in tailor-made solutions that suits the specific needs of each building and its owners/users.

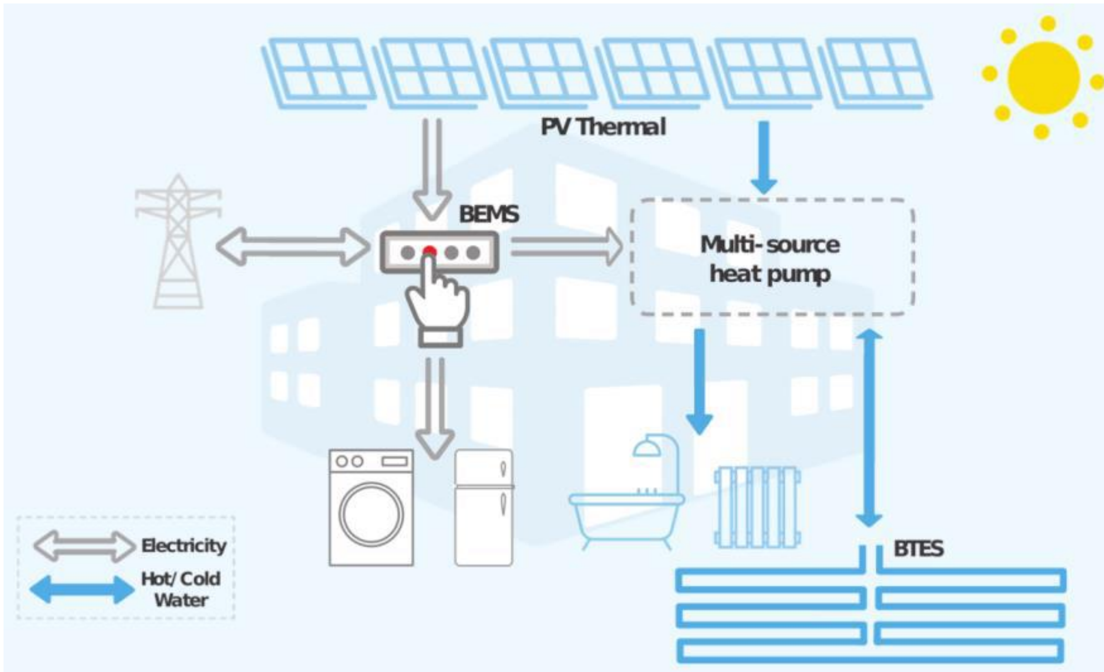

Figure 21. Concept overview for components in the RES4BUILD energy system.

For all solutions, advanced modelling and control approaches will be developed and integrated in a Building Energy Management System (BEMS). This will allow users to select their requirements and optimize the use of the system accordingly, thus exploiting the available potential for demand flexibility.

2.2.11. Development of Fast Regulating Heat Pumps Using Dynamic Models

The project aims at developing software tools that enhance the flexibility of large-scale heat pumps operating in integrated systems with varying operating conditions. This is approached by the development of a holistic control structure and a design procedure that integrates the dynamic characteristics of a heat pump, where it is aimed to reach higher operational performance and lower operational costs. Hence, digital tools are included and used actively in the development of heat pumps systems. Error! Reference source not found. shows the concept for developing fast regulating heat pumps.

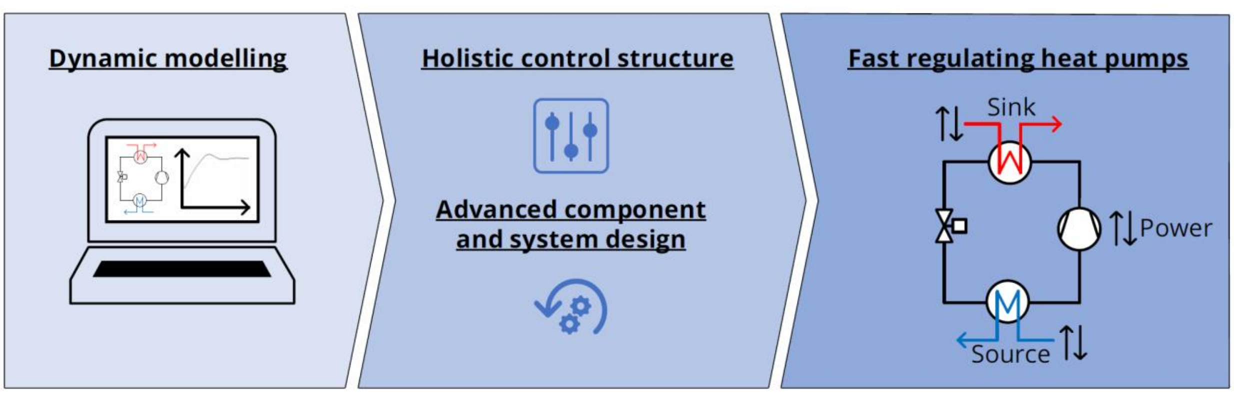

Figure 22. Concept of development of fast regulating heat pumps based on dynamic modelling.

In order to use large-scale heat pump systems effectively and exploit their potential for flexible operation in the context of sector coupling, a sophisticated integration into the given boundary conditions is paramount. The increasingly flexible integration of large-scale heat pumps does imply certain challenges for heat pump components, as short reaction times are required, which is accounted for in this project.

2.2.12. CEDAR

The Cost Efficient heat pumps using DigitAl twins and Reinforcement learning (CEDAR) project studies and develops next-generation technology for optimal control of heat pump systems. In particular, the project aims at constructing an "install-and-forget" type of system for retrofitting residential heat-pump systems.

The simplified flow of the envisioned solution is shown in Figure 23 and is comprised of the following:

1. For a given single-family home, monitor the boundary conditions for the operation of a heat pump (e.g. weather, energy consumption and internal temperature and humidity changes).
2. Use the monitored data to construct a digital twin of the heat pump.
3. Complement the digital twin with auxiliary data-sources related to the future operation of the system (e.g. weather forecast, future energy pricing, user behavior) to create a high-fidelity predictive digital twin.
4. Use state-of-the-art stochastic optimization techniques to generate a strategy for the future control of the heat pump. This process is then repeated over and over ad infinitum.

The two core processes within this project, namely the digital twin estimation and the stochastic optimization, relies on state-of-the-art techniques developed at the Technical University of Denmark (Continuous Time Stochastic Modelling for R) and Aalborg University (Uppaal Stratego), respectively.

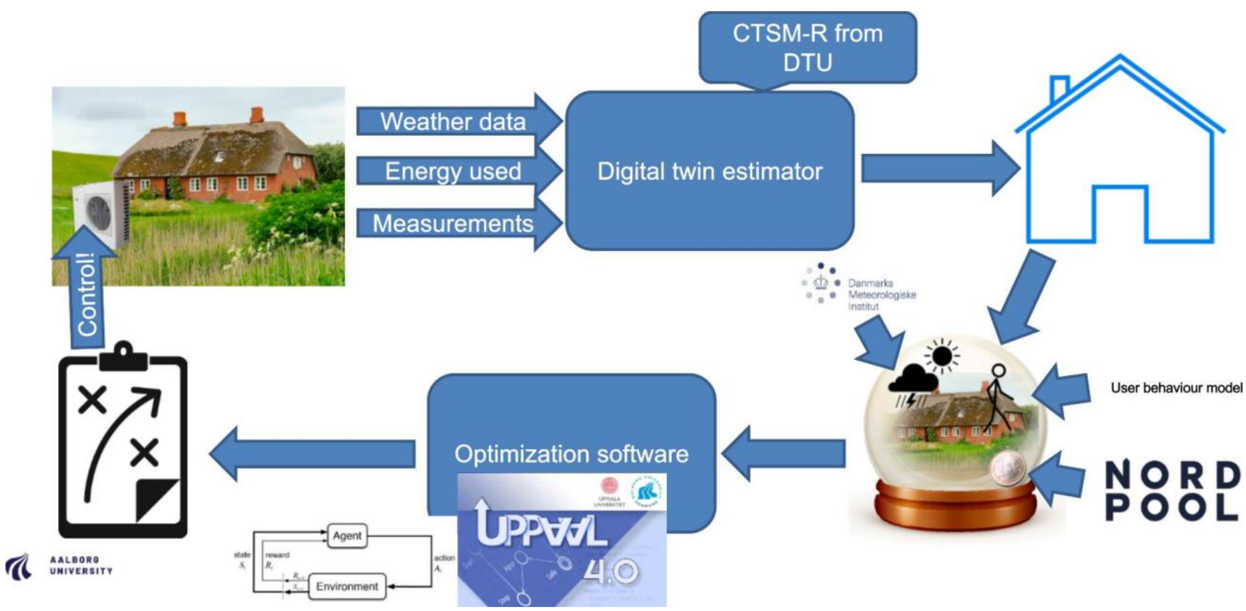

Figure 23. General flow of the approach studied in the CEDAR project.

3. Review of the status of Digitalization and IoT for Heat Pumps in Denmark

The collected information from both product and service suppliers and R&D projects shows that several stakeholders at different levels in the heat pump industry are focusing on enhancing and deploying digital and IoT-enabled solutions for heat pumps in Denmark. There are overlaps with companies being present in more groups, but in general the suppliers and service providers in this review can be grouped as follows:

- Heat pump manufacturers: Energy Machines, Johnson Controls, DVI, and METRO THERM
- Aggregator: Neogrid Technologies
- Service Provider: Climify, Centrica, ENFOR, EnergyFlexLab, AI-Energy
- End-user: HOFOR, Nærvarmeværket
- OEM: LS Control
- Datahub: Center Denmark

In addition to this the authors are aware of various other companies in Denmark working on digitalization and IoT solutions, who did not directly give input to the review. The groups have different roles and interactions between each other, which is visualized in Figure 24. The figure shows a general setup for an IoT-based energy system around heat pump(s) and the involved groups, but it must be emphasized that there are also other possible setups depending on the specific use case.

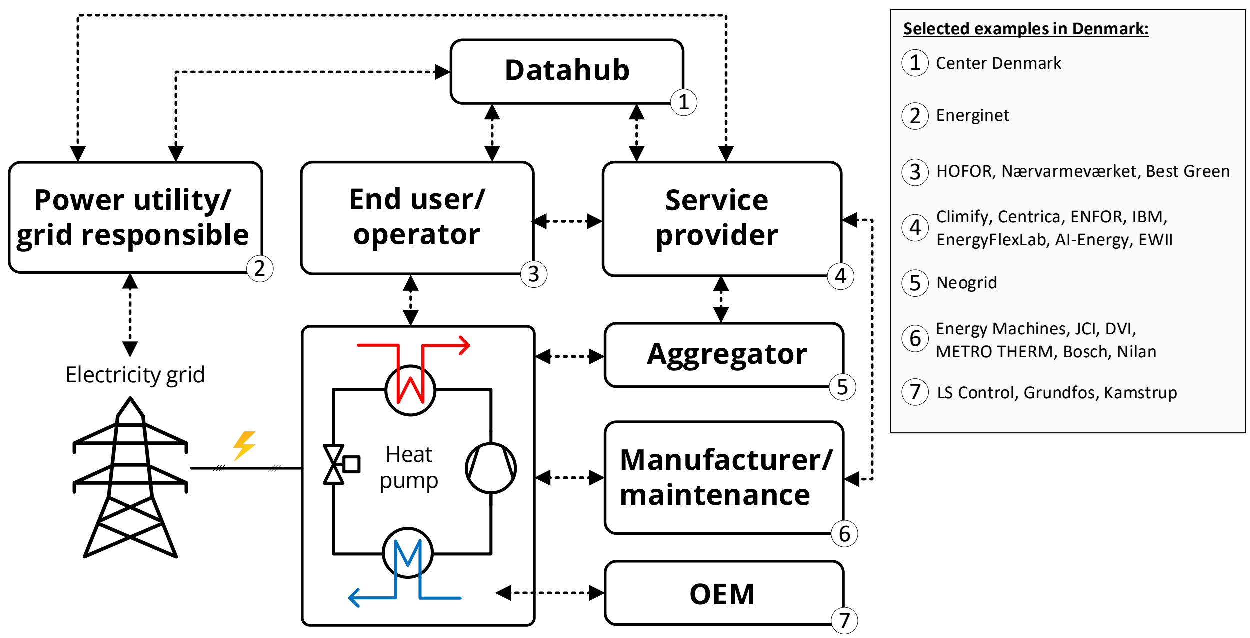

Figure 24. Visualization of supplier groups and examples of associated suppliers in an IoT-based energy system for heat pumps.

In recent years, the number of installed household heat pumps in Denmark has strongly increased. Among other reasons this is due to economic and political incentives supporting electrification and a ban on oil boilers. Moreover, around 66 % of Danish households are supplied by district heating in 2022 [2]. Also in the district heating networks both the number of heat pumps and the total capacity installed has increased significantly in recent years as seen in Figure 25. This is aligned with the target of using heat pumps to supply around one third of the heat in Danish district heating networks by 2030 [3].

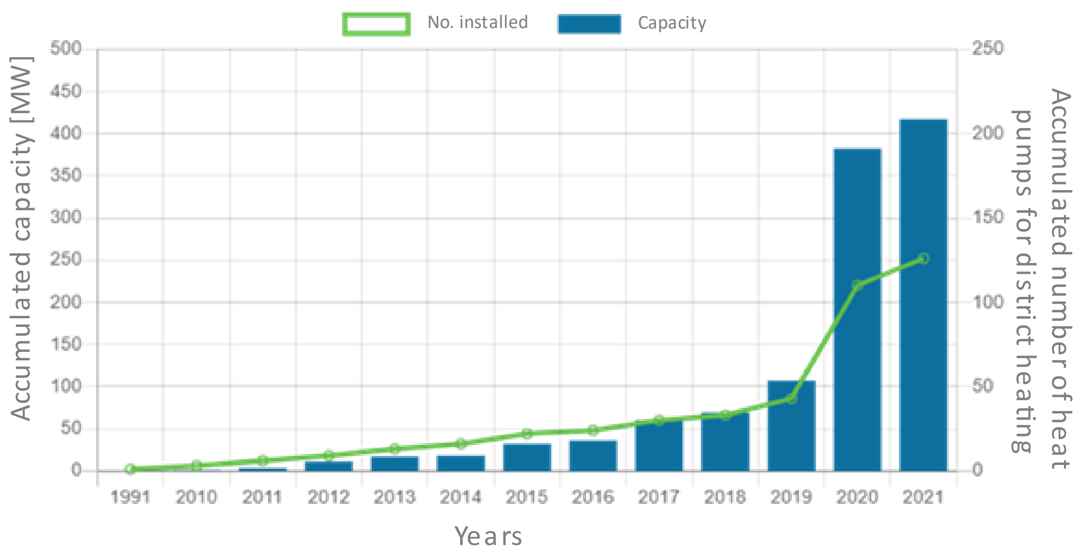

Figure 25. Overview of large-scale heat pumps for the Danish district heating network [4].

In Denmark there are strong incentives to install heat pumps to reduce the dependency of the heating sector on fossil fuels and leverage the increasing amount of renewable (fluctuating) power in the electricity grid, of which the average annual share in Denmark was 47 % in 2021 [5]. Regarding the electricity price different tariffs applies depending on what time of the day it is. The tariff comes on top of other costs such as the spot electricity price and taxes. For example during the evening between 17:00-21:00 in the winter period increasement in tariffs around 1.8 DKK/kWh (0.24 €/kWh) compared to the cheapest period applies [6]. Furthermore, most Danish electricity providers offer their customers to pay hourly adjusted prices, which are settled according to the tariffs and hourly marked spot prices. If the primary heating installation is operating on electricity the consumption above 4,000 kWh for a household can get a reduction in the tax cost for electricity [7]. These measures incentivize the use of smart controls and digital solutions, enabling a high potential to integrate the heating and power sectors by using heat pumps. This is further supported by the Danish Society of Engineers who in a report on how to reach a climate neutral Denmark recommends more interaction between energy consumption and supply in "smart buildings", and encourages to use apps and/or smart meters to control indoor climate and energy consumptions [8].

In this context, a number of technology suppliers such as Neogrid, Centrica, AI-energy, ENFOR and METROTHERM, offer solutions towards the use of heat pumps for sector integration. Here, the most common type of solution is the remote or local adjustment of the heat pump operation based on measured and/or forecasted electricity prices. This enables a reduction of operational costs for users by the use of available low-cost renewable energy resources and the avoidance of periods with limited power supply.

The provision of ancillary services through heat pumps is also possible with some of the technologies currently available in the market. However, in the case of residential heat pumps an aggregator is needed to pool a number of heat pumps, which may raise data security concerns. In the case of district heating heat pumps, their flexible operation has e.g. been analyzed in an R&D project (see Section 2.2.3). This investigation highlights potential opportunities to develop digital solutions that enable the estimation in advance of the constrains related to the provision of ancillary services by means of heat pumps and IoT-enabled frameworks for the remote surveillance of heat pumps under dynamic conditions.

Predictive maintenance of heat pumps complemented by IoT-enabled technologies is already available in several technologies offered in Denmark. This includes the solutions offered by Energy Machines, LS-Control, Neogrid, Nærvarmeværket and METRO-THERM. Remote predictive maintenance enables the reduction of operation and maintenance costs by decreasing the number of times that a heat pump requires the physical assistance of a service technician and by taking preventive measures before it is not possible to avoid or mitigate the negative effects of faults in the heat pump components. R&D projects have also aimed at developing predictive maintenance solutions by means of digital tools. In this case, the technologies under development include digital twins, where the potential effects of fouling can be analyzed and predicted based on adaptive model-based frameworks, as well as advanced data-driven methods that are able to describe and predict the effect of faults by means of real-time measured data.

Accessible data is one of the key elements needed towards the development of digital solutions supporting the sector coupling between electricity and heat sectors. The present review indicated that the digital data platform from the company Center Denmark is used for such a purpose in several projects. The data platform gives consumers in Denmark a direct opportunity for sharing energy consumption and operational data with Center Denmark, and hereby facilitating the development of energy-efficient data solutions in a secure and reliable manner. Service providers or other stakeholders can then purchase anonymized data to develop their solutions. Currently, tens of thousands of Danish households are taking part in this scheme, where e.g. data on electricity, heat, water, and indoor climate are shared.

Throughout the review, especially in the R&D projects, a number of different tools for numerical modelling of heat pumps were identified. This includes approaches such as white-box or physics-derived models, black-box or data-driven models, and grey-box models. The white-box paradigm is often applied when a model is required in the design of a system and/or its components, or to analyze the performance of a system and certain phenomena that can be described straightforwardly with physics. Contrarily, black-box and grey-box models are likely to be applied when simplified representations of reality are sufficient or when it is needed to analyze operational conditions that are difficult or impossible to predict by physically-derived representations, such as faults and performance degradation. Digital twin frameworks, which are under development in multiple R&D projects (see sections 2.2.1 and 2.2.12), may integrate different types of modelling approaches, depending on the data availability, type of service, and communication constraints, among other factors.

In the review, it was identified that different stakeholders will need to interact (fast) through different interfaces, e.g over API interfaces, ModBus, MQTT, end-user-apps, and fog/edge-based computing facilities. This shows that the industry could overall benefit from making standardized interfaces to avoid having various suppliers using and developing each of their own. More standardized interfaces could e.g. include monitored data from the heat pump and the heat demand, but also electricity and heating prices, leading to further possibilities for incorporating comparison schemes between technologies in control and monitoring digital interfaces. Current general issues with this includes a lack for standards across countries, e.g. within the EU, particularly on how price signals shall be communicated to the heat pump. Challenges for those standards include considerations about where to best locate price-forecasts, what format it should have, what should be the cost for access, which areas should be included, and who exactly should control the heat pump without compromising its lifetime? Is it the grid system operator, aggregator, or heat pump manufacturer? The definition of such standards may contribute to answer those questions and may advance towards the improvement of operation of heat pumps and energy systems.

In Denmark there are various industry communities working with the energy system. An example of this is "Intelligent Energi" (https://ienergi.dk/) which is a community for stakeholders who work with advancing an integrated and flexible energy system that provides Danes with safe and green energy at competitive prices. Intelligent Energi supports this development by working on more uniform framework conditions for by being a platform for collaboration within and across electricity, gas, water, and heat sector, and hence also how to best include heat pumps in the energy system.

4. Conclusion

The present report provided a summary of the state-of-the-art digital and IoT-enabled technologies for heat pumps in Denmark. A description of the available technologies and those under development was made, which incorporated information shared by technology suppliers as well as research and development initiatives. The information collected indicated that several products and services that include IoT and digital solutions are already available in the Danish market, which enable the provision of monitoring, predictive maintenance, and ancillary services. Moreover, a number of ongoing research and development projects aim at the improvement of some of those services by means of modelling tools and data analysis and processing methods. Some of the future challenges for a broader implementation of digital and IoT-enabled technologies for heat pumps were identified. These include the definition of standards related to data security, price incentives, and digital interfaces.

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6. Acknowledgements

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7. Appendices – Product and Service Suppliers and Project IoT Case Descriptions

Product and Service Suppliers:

Energy Machines – Energy machines verification

Neogrid – PreHEAT for Heat Pumps by Neogrid Technologies ApS

LS Control - SmartConnect Center

Centrica Energy Marketing and Trading – Energy Planning and Optimization Platform

Climify – Indoor Climate Monitoring Platform

Nærvarmeværket – Community owned Heat Pump Company

AI-nergy – Artificial Intelligence Assisted Products

ENFOR A/S – Energy Forecasting and Optimization Platform

Center Denmark – The Digital Data Platform

EnergyFlexLab

METRO THERM - MyUpway™

IoT Project Cases:

Digital Twins for Large-scale Heat Pump and Refrigeration Systems

EnergyLab Nordhavn - Smart Components

Flexheat – Intelligent and Fast-regulating Control

Smart-Energy Operating-Systems (SE-OS) framework

Combined Optimization of Heat Pumps and Heat Emitting Systems (OPSYS 2.0)

Cool-Data

SVAF phase II

HPCOM

Flexible Energy Denmark

Res4Build - Renewables for clean energy buildings in a future power system

Development of Fast Regulating Heat Pumps using Dynamic Models

CEDAR (Cost Efficient heat pumps using DigitAl twins and Reinforcement learning)

Energy machines verification (EMV)

Energy Machines ApS

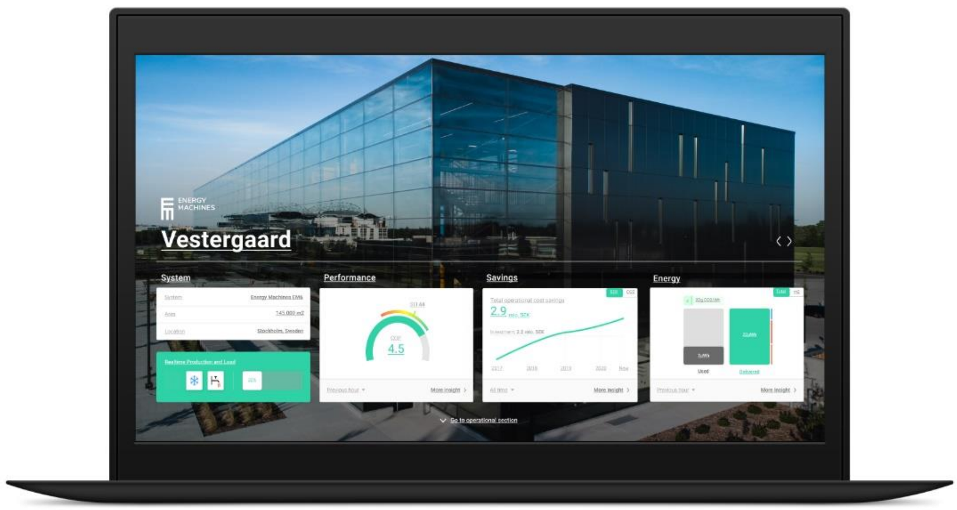

Figure 1: The energy machines dashboard including the EMV with a quick overview of current performance.

Summary of IoT case

Energy Machines™ is a leader in the design, implementation, and operation of integrated energy systems for buildings. Buildings are a growing climate problem, accounting for over 28 % of global CO_2 emissions. We are working to transform them into climate solutions.

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.

Using a reliable and scalable cloud backend (Google Kubernetes Engine), it can be extended to any number of systems.

Data security is taken very seriously, and all services use encrypted protocols (TLS/HTTPS) when exchanging data from client to server. Endpoints require authentication with user permission granularity to access.

Figure 2: An Energy Machines installation. Heat pumps are located on the right. Sensors are placed inside the boxes.

The tool is functioning on most Energy Machines systems, with paying external customers in the portfolio. It is currently implemented through the ControlMachines SCADA service (https://control machines.cloud/), but the API allows flexibility in external access.

Results

Live monitoring of heat pump 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.

As monitoring also includes the compressor efficiency, there's a potential to include early warning systems for predictive maintenance, when for example the compressor efficiencies rise above 100 %, indicating liquid refrigerants cooling the compressor outlet, which can cause breakdown and failure. Combining EMV with data-driven machine learning models, which run as digital twins, may even reveal early signs of deterioration.

FACTS ABOUT THE IOT CASE

IoT category: Online service with analysis of functionality and performance from live measurements of the heat pump COP, energy production and cycle efficiency. In addition to this, service with early warning system for predictive maintenance.

Heat supply capacity: Any.

Heat source: Air and ground.

Analysis method: Sensor measurements of pressures and temperatures are sent to a REST API. Energy balances calculate COP, compressor efficiency, and heating/cooling production, etc. 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).

Modelling requirements: Measurements and knowledge of refrigerant and cycle.

Data required: Temperature, pressure, and compressor power.

Data interface: No specific requirements.

Transmission protocol for data: REST API

Quality-of-Service: Data measured every minute and results provided every minute (real-time).

Technology Readiness Level: TRL 9.

Link to webpage: www.energymachines.com

The latter models, can also be trained using the output from the EMV as input, when the drift over time is interesting to monitor (e.g. refrigerant loss through leakages, fouling of heat exchangers etc.). EMV is not a predictive tool and relies on sensor measurements, nevertheless EMV can also be applied on modelled sensors, and may be interesting to apply for simulations of heat production in system simulations, where multiple heat pumps are connected through a thermal grid. EMV may find usage even in optimization of heat production with respect to balancing electricity prices, demand and thermal reservoir capacity.

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PreHEAT for Heat Pumps by Neogrid Technologies ApS

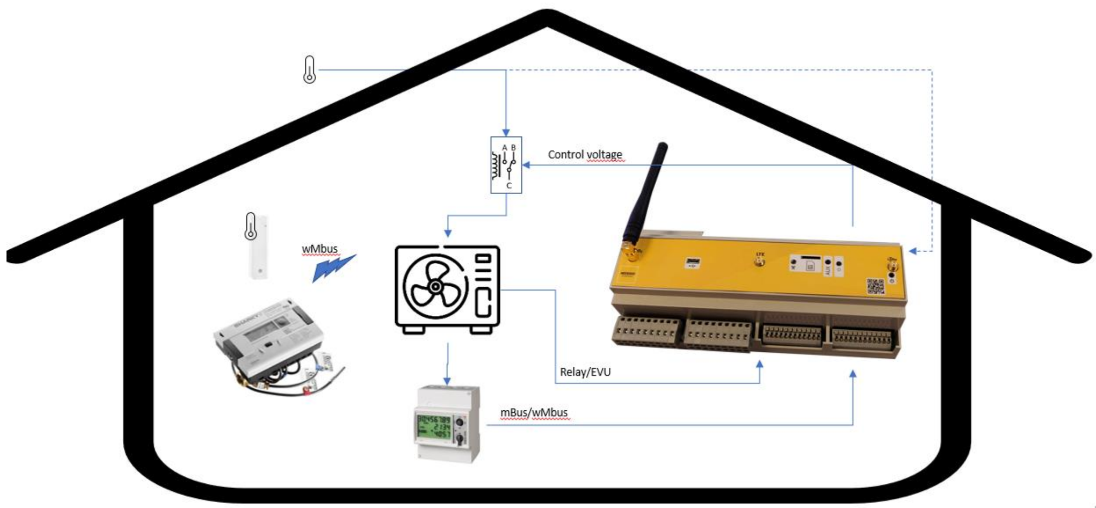

Figure 1: Hardware setup for PreHEAT Heat Pump Controller.

PreHEAT for Heat Pumps is developed by Neogrid Technologies with the purpose to save energy and reduce the cost of heat, by optimizing the heat pump operation in relation to demanded energy from the building and local electricity prices and tariffs. This enables customers to adapt to market flexibility and at the same time to save energy without compromising indoor comfort requirements.

By collecting data from the heat pump, it is possible for Neogrid to deliver three categories of services:

The **first category** are services available as soon as data is collected from the heat pump and connected meters. If external control is activated, extra services like MPC to control, can secure a lower operation cost of the heat pump. This category "only" requires a bilateral agreement with the heat pump owner and a cloud connected operator.
In **category 2** variable prices, tariffs and services to the DSO are taken into account. Variable prices and tariffs are rolled out over most of Denmark, but DSOs flexibility demand to cope with bottlenecks is still limited in Denmark.
In **category 3** specialized services to the electricity markets are delivered. This might be regulating power and frequency reserves. Those services require separate settlement of the electricity to the heat pump and an aggregator is required to pool a number of heat pumps.

From, sensor data like indoor temperature, consumed electricity and delivered heat are collected, and send to Neogrid PreHEAT Cloud.

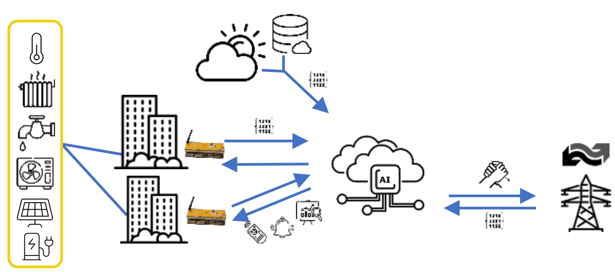

Figure 2: Neogrid PreHEAT Cloud.

In the Cloud, the data is analyzed and optimal operation schedules are send back to the pump.

Establishing connection the heat pump installation, can be implemented in different ways dependent on the type of heat pump. Older and/or simpler heat pumps requires a gateway to provide online access, and to collect all sensor and meter data. Control is established via the heat pumps relay input or by manipulating the outdoor temperature sensor.

Other heat pumps have a communication interface where data and control capabilities are available to access via a local gateway.

Modern heat pumps are "born" online and have the possibility to collect data from external sensors and meters. Here, the heat pump manufacture typically operates a cloud where all data are collected and available for a third-party actor, like Neogrid, via an API.

Neogrid Heat pump aggregator

The aggregator method provided by Neogrid, pools a number of heat pumps together and control the heat pumps as a swarm. I.e. we are allowing / blocking the individual heat pump operation to provide an overall behavior of the pool. This is done by complying with the constraints of each heat pump operation. The pool can then be adjusted according to market changes.

Figure 3 illustrates the installations as a normalized energy storage, where heat pumps are charging/ discharging the storage also fulfilling the run-time constrains of the heat pump.

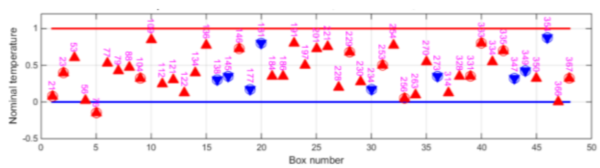

Figure 3: Swarm controller in operation.

Learnings

Heat pumps using the optimized control and flexibility service can provide costumers with energy savings without compromising indoor climate and comfort. Neogrid can optimize a heat pumps energy consumption by 5-15 %.

Multiple factors have an impact on the possible energy savings, but demonstrations have shown that value proposition for the heat pump owners are:

- Online access to key data from heat pump
- Low operation cost
- Improved comfort
- Lower energy bill
- Reduced CO2 footprint

About Neogrid Technologies

Neogrid Technologies have more than 12 years' experience in providing smart energy solutions for cloud-based heating control in buildings, as well as data collection from IoT devices and smart meters.

Neogrid have extensive knowledge within the smart grid and smart energy systems, which have been obtained by participating in a number of research- and demonstration projects both on a national and international level and by performing business development within this field.

The knowledge gained from these projects is used for commercial activities, and PreHEAT by Neogrid is operating commercially in more than 400 buildings in Denmark, with 24/7 active online control and surveillance.

FACTS ABOUT THE PROJECT

IoT Category: Optimized heat pump operation

Goal: Save energy and reduce cost of energy without compromising end user comfort. Deliver real-time monitoring of the heat pump.

Beneficiary: User, Society

Data required: Access to heat pump sensor data, energy and electricity meter and weather forecasts

Analysis method: Data analytics, model- and control engineering

Control method: MPC

Technology availability: TRL 8

Link to webpage: https://neogrid.dk/

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LS SmartConnect Center

LS Control A/S

Figure 1: LS SmartConnect Universe.

Summary of IoT case

The LS SmartConnect Center is a software program with a user interface which enable fleet management of typically residential heat pumps or other ventilation products.

The software has a user interface for PC or app. To function fully it must be used with an LS Control control-platform. But it may be used as a viewing tool with other control platforms if the transmission protocol for data is Modbus and a LS Control gateway is connected.

To ensure the internet security both our controller and the gateways have a security-software integrated. This security-software provides a secure connection between the users' PC, phone, or tablet and the SmartConnect product by use of industry standard cryptography. Each product is given a unique device-id which is used by the client to reach it regardless of dynamic IP-addresses. The security-software provides seamless, direct remote access without firewall or router configurations. The direct connection ensures the best possible performance with minimal overhead and latency. Also important is that all data are kept within the product, the security-software simply performs a PIR-to-PIR bridge enabling the data to be displayed and updated remotely.

LS SmartConnect Center is a fleet management system which provides a swift overview of the performance of all heat pumps or ventilation products licensed by the manufacturer. The overview can be broken down into segments and sold from manufacturers to resellers to janitors to provide a fleet management system for a certain group of products.

Also, the system comes with an end-user app for the consumer to manage their own product. Such as turn on/off and adjust e.g., temperature.

Each product in the overview can be accessed for further investigation and update of software. When reselling licenses, the manufacturer can determine to which level the group of products can be accessed and manipulated.

Benefits

With easy access to each product, errors get detected and corrected very quickly which gives better performance of the product with using fewer hours on service and a better service plan for the product throughout its lifespan.

Often error correction and service can be done from the office which saves a lot of time and milage on the road to the beneficial of everyone, also the environment. The end-user do not have to stay home waiting for a technician, technicians who do not need to spend hours in the service van are more effective for less cost, and finally not driving so many milage saves a lot of CO_2. Also, when service visits are necessary the technician already have a good knowledge of the problem and can bring the right spare parts at the first visit.

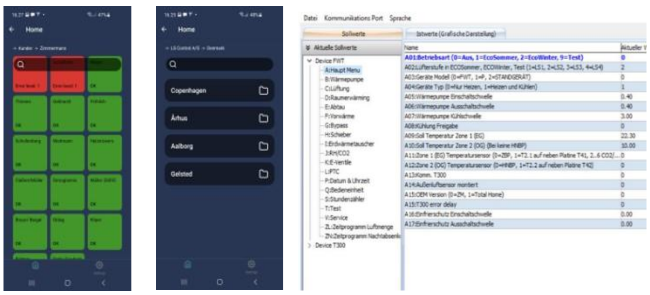

Figure 2: Swift overview of products, product groups and data view.

The security in the LS SmartConnect Center even opens for the possibility to connect to other cloud systems such as Google Home and Apple Home through interfaces like MQTT.

LS SmartConnect Center is not a static tool. It is continuously updated with new features to comply to the newest standards and regulations. E.g., in the up-coming updates to ECO-Design directive 2009/125/EC a new set of monitoring rules for heat pumps are expected to be implemented. The LS SmartConnect Center will then implement the same monitoring standards within the system and end-user apps. These updates are pushed to all users of the LS SmartConnect Center ensuring that when you once have invested in the LS SmartConnect Center you will always stay updated to the newest standards.

Case example

A heat pump manufacturer from Germany is delivering heat pumps with control system from LS Control including integrated internet and LS SmartConnect Center to a new residential neighborhood in England. One of the heat pumps malfunctions and the installation technicians are sure it must be the controller which isn't working correctly, so they replace it. However, the heat pump still malfunctions. The technicians contact the manufacturer in Germany, and they investigate the data transmitted from the heat pump. It turns out that it is a small pressure transducer inside the heat pump which doesn't work. It gets replaced and the heat pump works perfectly.

If this heat pump had not been hooked up to LS SmartConnect Center most likely the technicians had taken down the heat pump and returned it to Germany which would have been very costly and unnecessary.

FACTS ABOUT THE IOT CASE

IoT category: Optimize HP operation, predictive maintenance, performance benchmark and Installation error analysis

Heat supply capacity: Up to 32 kW

Heat source: Air and water

Analysis method Control engineering and fault detections

Modelling requirements: Data-driven

Data required: Operation data, sensor data

Data interface: LAN, Wi-Fi and Local Wireless sensors

Transmission protocol for data: Modbus

Quality-of-Service: Real-time

Technology Readiness Level: TRL 9 (system works and proven in operation)

Link to webpage: lscontrol.dk/en

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Energy Planning and Optimization Platform

Centrica Energy Trading

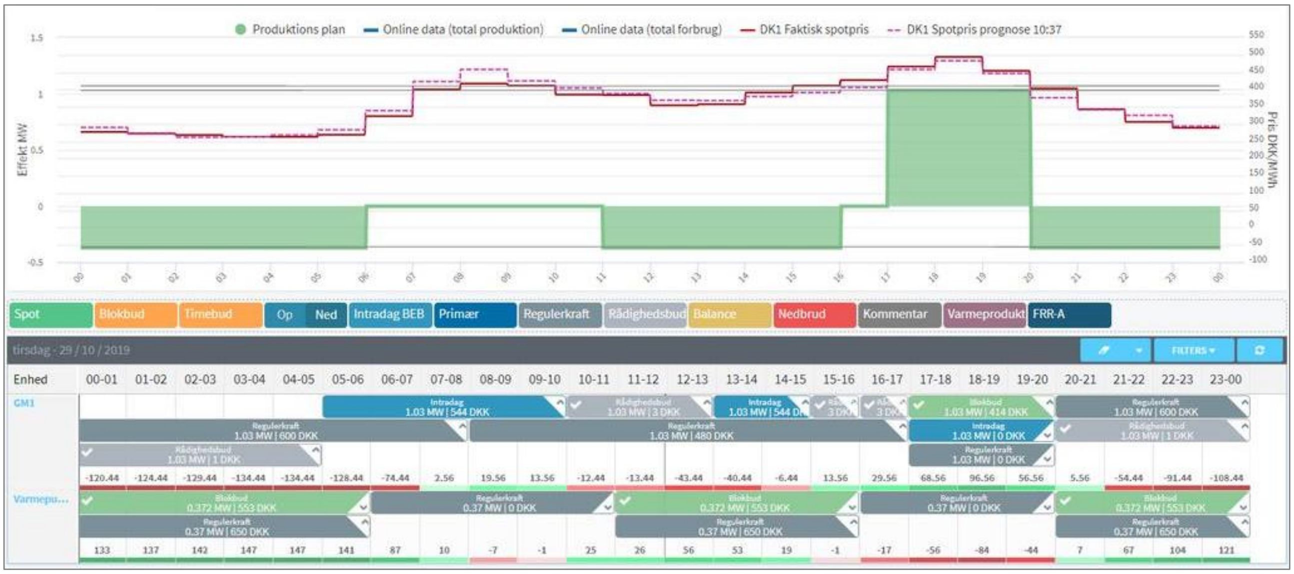

Figure 1: Interface of the energy planning and optimization platform developed by Centrica Energy Trading.

Summary of IoT case

The energy planning and optimization platform developed by Centrica Energy Trading consists of a web-based API with a data warehouse system for energy route-to-market services. The Centrica Energy Trading tool enables an optimal utilization of several asset types including heat pumps for district heating supply. This enables the optimization of energy consumption and production earnings as well as the minimization of expensive imbalances.

The platform provides an estimation of the Power consumption, heat production, and COP of the heat pump based on forecasted weather variables such as outdoor temperature, humidity, wind direction and speed. In addition, the interface includes estimation of the varying marginal prices in different electricity markets.

The services provided by the platform include coordinating heating and electricity markets, optimizing heat pumps for the provision of frequency regulation services and guaranteeing electricity prices for large-scale heat pumps and other consumption systems.

To date, several Danish district heating supply companies have adopted the Energy Planning and Optimization platform developed by Centrica. Electricity prices from the Nordic power exchange Nord Pool are analyzed in the platform, including Day ahead spot, Intraday and frequency regulation markets. The platform has enabled the correct registration at hourly level in the spot market and minimization of electricity and heat imbalances.

Figure 2: Example of the interface used by the platform from Centrica Energy Trading.

Results

Danish district heating companies have been able to maximize their profits by using the platform from Centrica Energy Trading. This was done through the optimization of the operation of heat pumps according to heating and electricity prices, as well as weather forecast indicators.

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FACTS ABOUT THE IOT CASE

IoT category: Grid services.

Heat supply capacity: No specific requirements regarding heating capacities.

Heat source: No specific requirements regarding types of heat sources.

Analysis method: Big data analysis and market models.

Modelling requirements: Data-driven.

Data required: Weather forecast and margin prices for electricity prices markets.

Technology Readiness Level: TRL 7 (system prototype demonstration in an operational environment). TRL 9 expected in Q4-2021.

Link to webpage: www.centrica.com/our-businesses/energy-marketing-trading/

Indoor climate monitoring platform

CLIMIFY

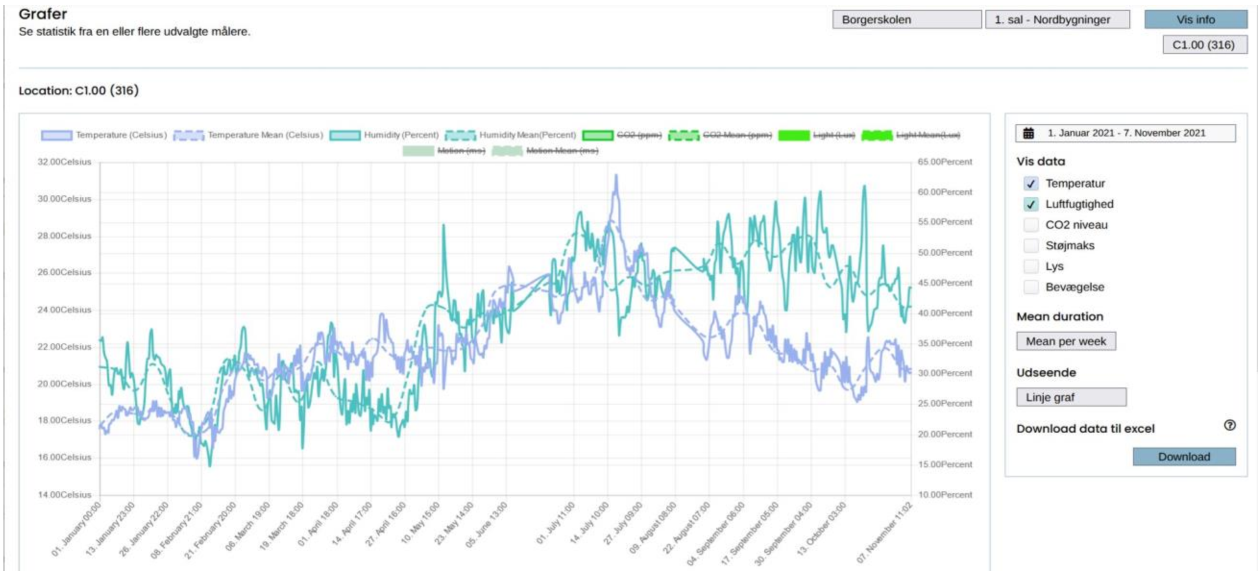

Figure 1: An example of the interface used in Climify: the user is able to zoom in and out in time and display multiple attributes,

Summary of IoT case

The platform developed by CLIMIFY consists of data collection and visualisation for the indoor climate in buildings and all the components in the HVAC system. The platform presents to users an easy-to-understand graphs and visualisation to inform the user about the state of the indoor climate in rooms, and to report potential problems/issues of the indoor climate. The service also enables occupants to rate the indoor climate, to get subjective opinions on its state.

Not only does Climify present to its users objective measurements from IoT-sensors; it also presents the feedback from the occupants, to include subjective measurements on the indoor climate (See screen dumps from the FeedMe app on the next page). The subjective and objective measurements are not necessarily aligned. In the end, it is all about satisfying the occupants while at the same time optimising the buildings' operations.

The software service processes data from indoor climate IoT-sensors located in rooms of interest (plus IoT-sensors collecting data from the heating system, e.g. the heat pump state, forward and return water temperature etc.). The software presents the data to the users and enables them to find rooms that do not reach the required indoor climate standards. E.g. if a room consistently is too cold or suffers from too high concentrations of CO_2.

The user is thus equipped with a software tool that enables him/her to identify problems related to the indoor climate. The software uses data-driven methods to deliver insights and analyses, to inform the user where problems arise as to mitigate them and ensure an optimal indoor climate.

In the very near future, the software will be able to automatically report potential faults and/or bad behavioural patterns of the indoor climate in rooms, in order for the user to know about such problems as soon as possible. Another future feature is automatic optimisation of the operations of the indoor climate w.r.t. parameters such as CO_2-emissions, energy usage, and electricity price. CLIMIFY does this by regulating e.g. thermostats, ventilation system, forward temperatures etc. in order to optimise the operation of the heating, ventilation, and air conditioning systems.

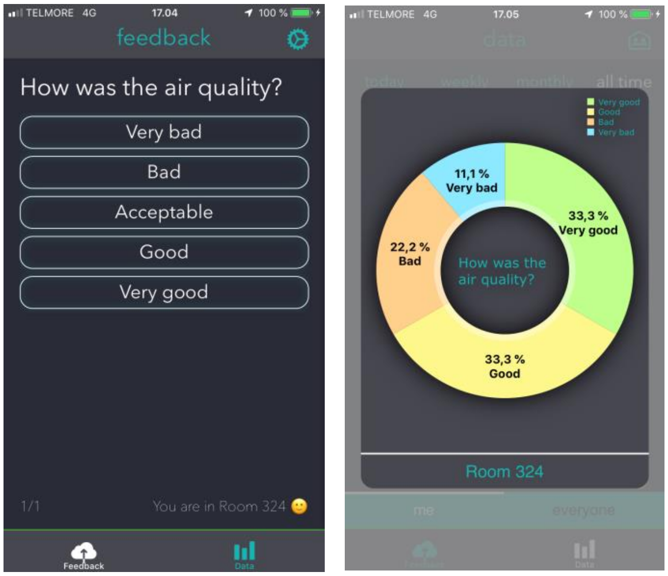

Figure 2: User feedback over phone app.

To date, customers include municipalities that use Climify for schools, to optimise the indoor climate and the learning capabilities of pupils, for gyms, and for other public buildings. Also, Skylab at DTU uses the software to monitor and present to the users with information about the indoor current indoor climate.

Results

End users and building managers are able to monitor and optimise the indoor climate in rooms according to both objective measurements (IoT-sensors) and subjective measurements (feedback from occupants). Thus, the user is able to regulate the heat pump in the building to optimise and satisfy the user's needs, and also being alerted of potential faults in the heating system. In the future, such optimisation and heat pump regulation will be automatic.

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FACTS ABOUT THE IOT CASE

IoT category: Monitoring, fault diagnostics, and optimisation of indoor climate.

Heat supply capacity: No specific requirements regarding heating capacities.

Heat source: No specific requirements regarding types of heat sources.

Analysis method: Data-driven methods.

Modelling requirements: Data-driven.

Data required: Indoor climate data and data on the heating system for the building.

Quality-of-Service: Real-time.

Technology Readiness Level: TRL 8 (system prototype demonstration in an operational environment).

Webpage: https://climify.com/

Community owned heat pump company

Nærvarmeværket a.m.b.a.

Figure 1 – Complete PVT energy system from Nærvarmeværket.

Summary of case

Nærvarmeværket is a community owed company which provides solutions for simplified heat as a service based on heat pumps for areas without district heating. The end-users can buy into a co-operative community which ensures a total-solution with installation, service and maintenance of the heat pump. A one-time fee for the installation cost is paid, together with a smaller annual payment, which ensures the cost of maintenance and a free change of the heat pump if it breaks down or needs to be changed. In this way, the community structure ensures cheap and reliable green heat for the end-user. Nærvarmeværket cooperate with several heat pump suppliers, e.g. Vailant, Pico Energy, DVI, and HS Tarm.

Results

Nærvarmeværket use digitalization as the heat pumps installed typically are connected, so they can be monitored remotely. This provides an unique opportunity for having cheaper service cost. As the heat pumps typically are installed in remote areas, e.g. on an island, where there is no access to a larger district heating network, the travel cost for a service technician can be saved if the technician knows the fault beforehand, and has the spare part available the first time the heat pump is being serviced.

FACTS ABOUT IOT CASE

Category: Heat as a service and predictive maintenance

Heat supply capacity: 3 to 249 kW

Heat source: Air/water and PVT panel.

Analysis method: Error analysis. Simple and cross platform.

Modelling requirements: n/a

Data required: Key operating data from the heat pump.

Data interface: LAN, WLAN, GSM (mobile network)

Transmission protocol: Modbus (open source)

Quality-of-Service: Real time

Technology Readiness Level: TRL 8-9.

Link to webpage: https://www.xn--nrvarmevrket-6cbh.dk/

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Artificial intelligence assisted products

AI-nergy

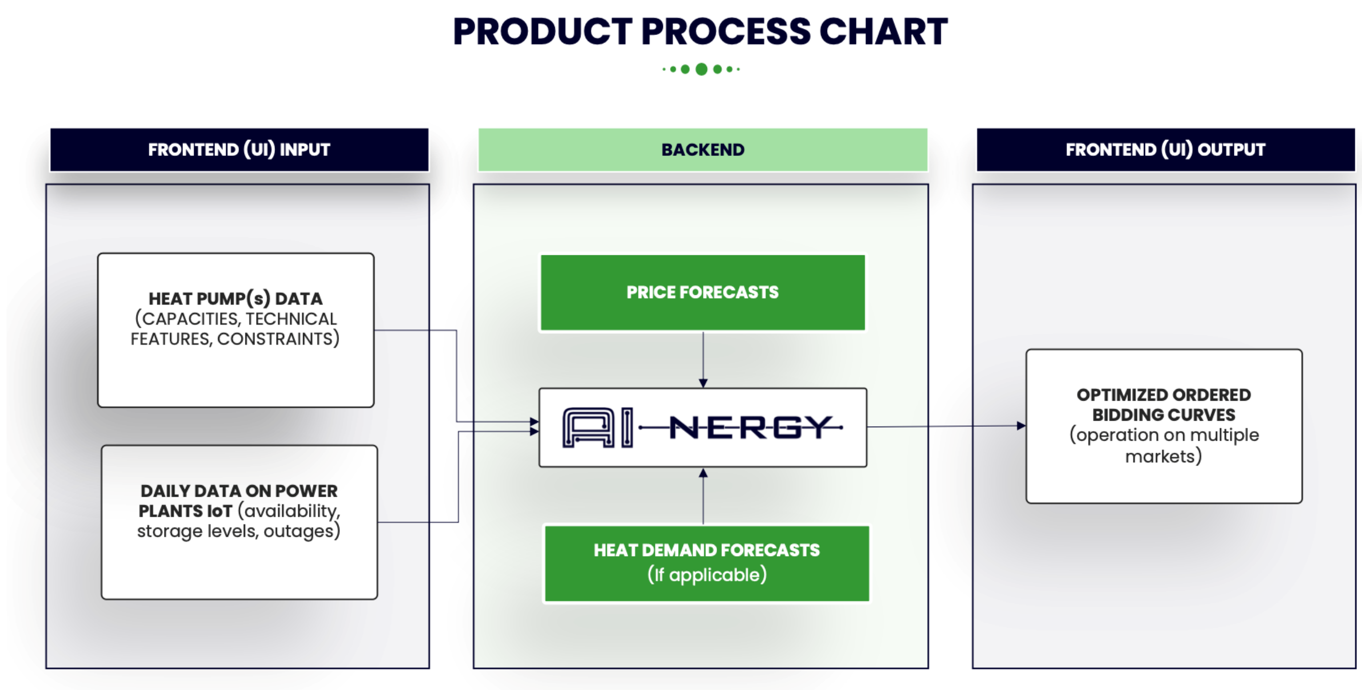

Figure 1: Scheme of the heat pump bidding product.

Summary of IoT Case

Two products from AI-energy focus on:

1. Market bidding (pooling) of large-scale (central) heat pumps,

2. Sizing and scheduling optimization of end-user heat pumps.

Bidding of large-scale heat pumps is done based on the forecasted heat demand and prices, using stochastic optimization. Bidding procedure also includes the operation on secondary (balancing) markets. A web-based application then delivers the optimal schedule for the operation of a day ahead. Often, it is very lucrative to provide services on different balancing and ancillary services markets than to focus purely on day ahead markets and this is what AI-nergy takes into account in its algorithms.

Sizing and scheduling optimization of end-user heat pumps is also done via a web based application. The system can be designed together with the potential PV and battery system for households, as well as with a charger for an electric mobility. The optimization engine improves its accuracy if the heat and electricity con-sumption data is available on a fine resolution.

The platform is run in the cloud, and it can potentially open an API towards the end users. The software architecture includes reading the technology data from databases, accessing the smart meter data via an API, reading IoT data on the status of the heat pumps and automatically generates scheduling procedures.

The technology is currently being tested on different cases, and is currently focused on case studies in Denmark. It is planned to expand to different EU countries in the future.

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FACTS ABOUT THE IOT CASE

IoT Category: Grid services, Optimize heat pump operation, sizing of heat pumps

Goal: Investment costs, operational costs, emissions

Beneficiary: End-users (customers and businesses)

Data required: Forecast, grid prices, energy consumption/demand

Data interface: LAN, WLAN

Transmission protocol for data: RestAPI

Analysis method: Energy balances (real-time), optimization, data-driven methods

Modelling requirements: Data-driven, white-box

Quality-of-Service: Real-time, day-ahead

Technology readiness level: TRL 5

Link to webpage:
www.ai-nergy.net

Energy Forecasting and optimization platform

ENFOR A/S

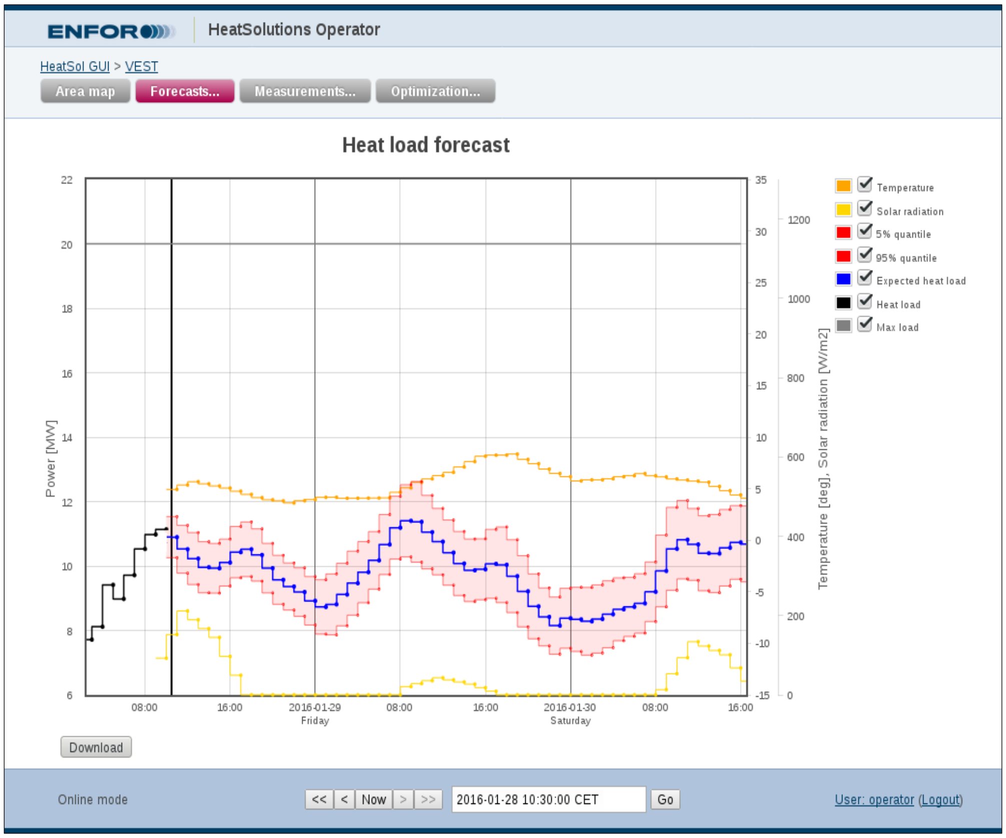

Figure 1 – Example of forecast for heat load, temperature, and solar radiation.

Summary of case

The energy forecasting and optimization platform developed by ENFOR aims at forecasting energy production from renewables as well as forecasting electricity demand and heat demand. This platform enables optimal operations of renewable energy production facilities (like and wind and PV) as well as district heating networks. Today, ENFOR provides forecasts of approximately 25 pct of the total wind power worldwide.

In particular the module for temperature optimization is able to lower the supply temperature in district heating networks, which will improve the efficiency of heat pumps connected to such district heating supply networks.

Furthermore, the temperature optimization module can lower heat losses and fuel costs by optimizing heat pump operation by model predictive control.

The platform provides an estimate of both power production from renewables, as well as electricity and heat demand based on weather variables such as outdoor temperature, humidity, solar irradiance, wind speed, etc.

Several Danish district heating supply companies have adopted the Energy Forecasting and Optimization platform called Heat Solutions.

Results

Danish district heating companies have been able to reduce their fuel consumption 2-3 %, and thereby lowering the heat price for end-customers. This was done through the optimization of the operation of the district heating networks.

FACTS ABOUT

Category: Forecasting and optimization tool (optimize heat pump operation).

Heat supply capacity: No specific requirements regarding heating capacities.

Heat source: No specific requirements regarding types of heat sources

Analysis method: Big data analysis.

Modelling requirements: Data-driven.

Data required: Weather forecast and measurements from district heating network.

Technology Readiness Level: TRL 9.

Link to webpage: https://enfor.dk/services/heat-solutions/

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Center Denmark

The Digital Data Platform

Figure 1: The planned control room at Center Denmark.

Summary of project

The vision of Center Denmark (CDK) is to accelerate the green transition towards 100 % renewable energy in Denmark and Europe through digitalization and sector coupling and thereby unlocking flexibilities needed for an efficient implementation of the weather-driven energy system for the future low-carbon society. CDK is an independent and non-profit organization.

CDK provides a Trusted Data Sharing platform with 24/7 access to energy related data and digital tools. The platform provides access to historical data using a data lake setup, and bi-directional streaming data for providing smart energy services like forecasting of electricity prices and control of heat pumps. Using digital tools at the platform, CDK is able to facilitate and support tests and demonstrations in representative and scalable settings. Consequently, CDK is an incubator for digital business models aimed at providing new data-driven services for the energy and water sectors.

The EU Commission has selected CDK as a European Digital Innovation Hub (DIH). CDK is also an ERA-NET Smart Energy Systems Digital Platform Provider. Consequently, CDK is now acting as a central data and cloud hub for a large number of European projects (see the homepage of Center Denmark for an updated list of ongoing projects). As of today, CDK provides cloud/fog/edge based computing facilities and services for around 11 countries in Europe, and in several cases heat pumps are important elements of the project related demonstrations.

The ambition of CDK is to enable the development of digital solutions that are capable of adjusting the power consumption to fit the power production – among other things by use of Data-driven Digital Twins, Grey-box Modeling, Machine Learning and various tools for handling Big Data. Today, CDK provides methods for an efficient integration of wind and solar power by providing a next generation of methods for forecasting as well as methods for optimized operation of heat pumps, wastewater treatment plants, district heating, Power-to-X plants, supermarket cooling, etc.

A key focus of the Center Denmark platform is to deliver a next generation of smart grid solutions, such that the flexibility in integrated energy and water systems can be used for providing low cost grid and balancing services. The software used by CDK is based on open source technologies such as SPARK MLib, Python, Java, and Grafana. The interface with end-users is typically set up using APIs.

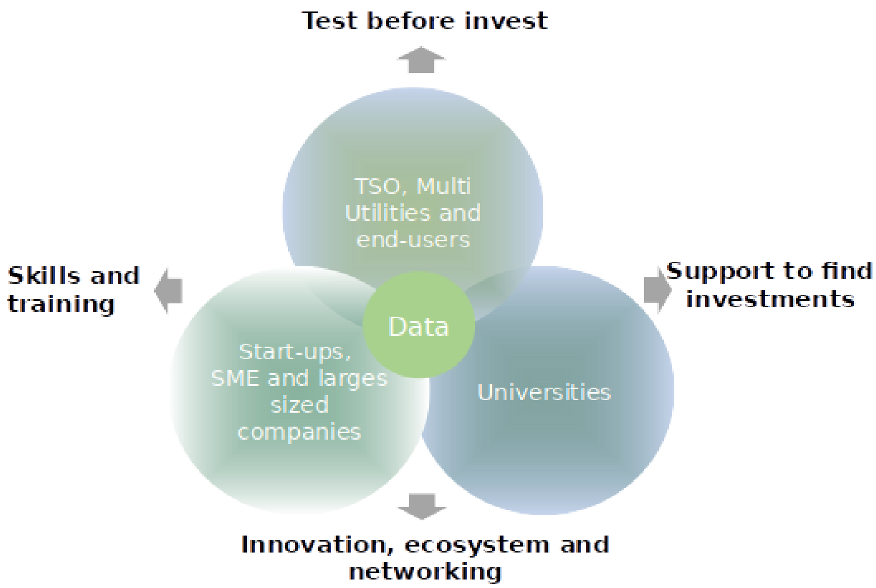

Figure 2: Data is at the core of the development, innovation and business thinking at Center Denmark.

Smart-Energy Operating-System

At Center Denmark the core idea is to adopt a spatio-temporal thinking where the models, forecasts, etc. are coherent across all spatial and temporal aggregation levels; see Figure 3. This is also reflected in the layout of the control room (see Figure 1). The setup is taking advantage of a so-called Smart-Energy Operating-System (SE-OS) framework, which is an operating system for testing and implementing integrated energy systems for data-driven operation at all aggregation levels.

Conventional electricity markets are static curves relating the prices to the volume of produced or consumed electricity, and the flexibility is described by the elasticity, which then presumably is assumed constant over time. However, if a supermarket has provided flexibility for, say, 30 minutes, then it might not be able to provide the same flexibility for the coming 30 minutes due to e.g. temperature constraints of the products in the freezer.

At Center Denmark the Smart-Energy OS facilitates a link between the high-level conventional energy and electricity markets, based on bidding and clearing, and the low-level flexibility at supermarkets, houses, industry, etc. The concept of a flexibility function, based on models and optimization, is used to establish the link between the high-level markets and the low-level physics; see Figure 3.

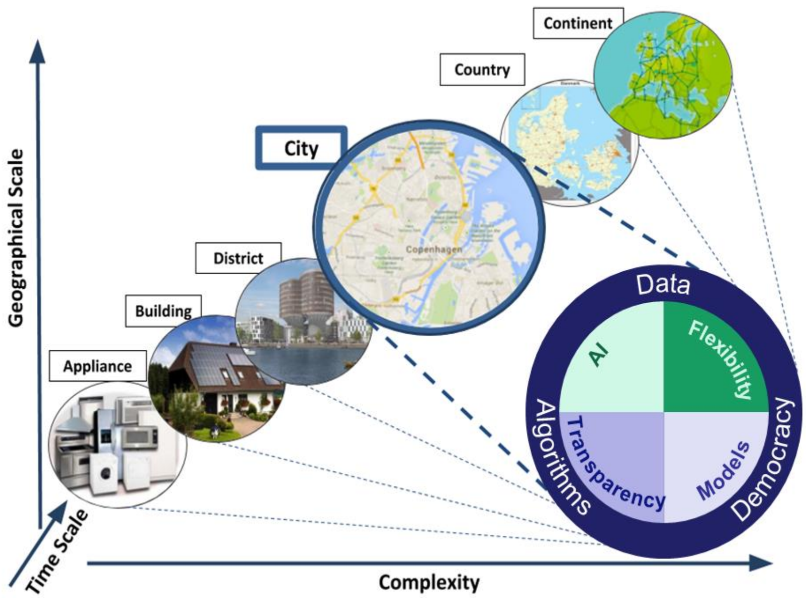

Figure 3: A spatio-temporal hierarchy is the core of the Smart-Energy Operating-System.

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Project: EnergyFlexLab

Figure 1: Main components in EnergyFlexLab.

Summary of project

EnergyFlexLab consists of a number of laboratories testing energy components and systems for a future flexible energy system, with increasing demands for intelligent control and sector coupling. The lab setup is testing real life scenarios of how much flexibility coupled technologies such as solar panels, battery systems, heat pumps and electric car chargers can add to our energy system.

The EnergyFlexLab test environment is a platform supported by smart grid and smart energy system knowledge and linked to a number of existing laboratories:

- Battery lab with accredited safety tests, single cell and pack level lifetime test facilities and grid connected Battery Energy Storage Systems (BESS).
- Heat Pump labs with testbeds for both small and large heat pumps and thermal storage.
- Electric Vehicle-lab with EV-chargers and test facility for EV-batteries.
- Energy efficiency labs e.g. EnergyFlex-House with solar panels, which is a high-tech laboratory where complete, innovative energy solutions for the building industry can be developed, tested and demonstrated.

The infrastructure for EnergyFlexLab allows manufacturers of intelligent and embeddable energy components to have testing performed which supports a wide range of activities such as:

- Flexibility testing of intelligent components e.g. the optimization of simultaneously operated heat pump, PV inverter and EV charger.

- Data harvesting from industrial areas, ports, airports, construction sites etc.
- Household battery system dynamic testing for annual efficiency, flexibility etc.
- Testing of the ability of intelligent components to be controlled / controlled remotely.
- Simulation and models for flexible energy systems to optimize operating economy, combined energy efficiency, climate effect and component life.
- Knowledge and testing that supports integration with cloud- based solutions such as weather services, electricity market etc.

Hence the test facilities in EnergyFlexLab provides an opportunity to investigate how heat pump most optimally is to be used in future energy systems where the share of heat pumps are expected to increase. E.g. it can be investigated how better sector coupling between solar panels, batteries, and heat pumps can be done.

One of the concepts with EnergyFlexLab is that the components are self-protected, hence inputs for changing setpoints is only allowed within a certain range with safe operation.

Data, communication, and interfaces

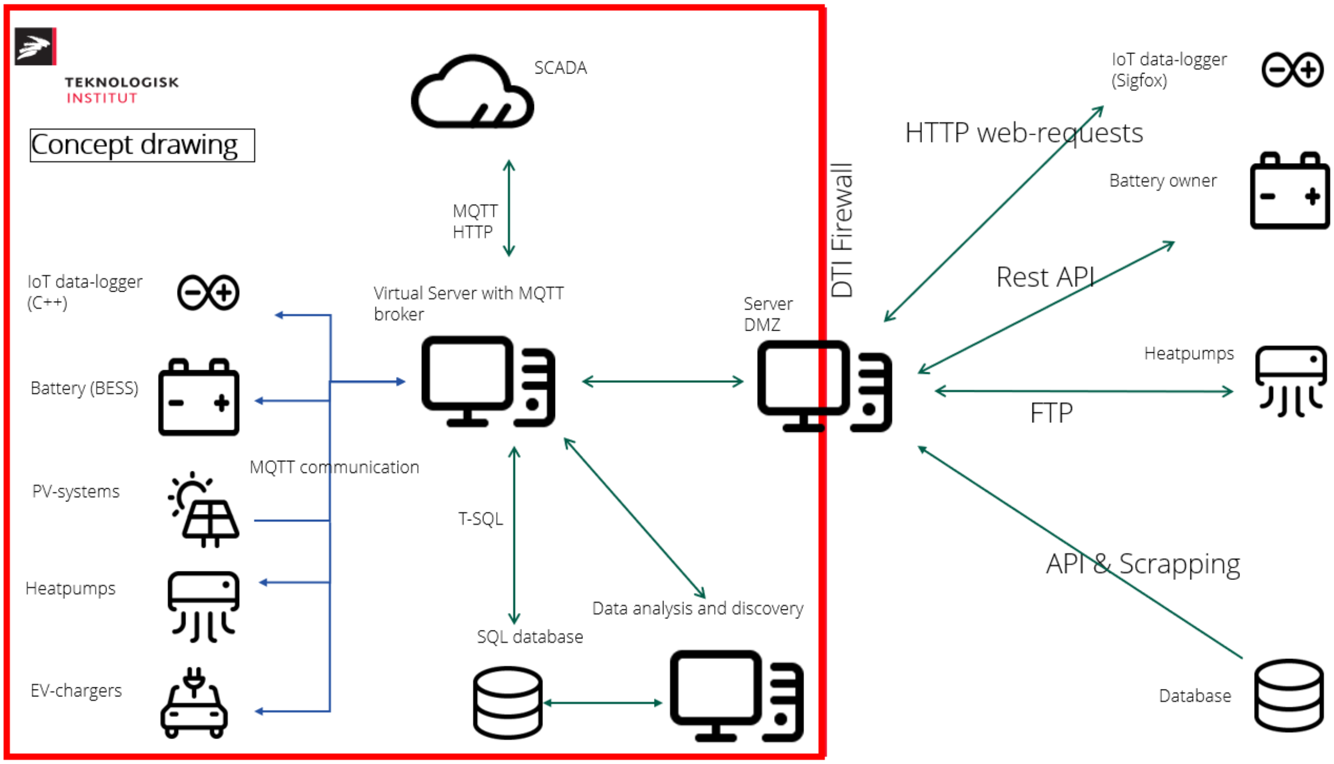
A key-feature of the EnergyFlexLab digital infrastructure is a modular setup that enables easy installation of new components and/or digital services “on-the-fly”. Adding a new component and/or digital services does therefore not interrupt currently running tests at the EnergyFlexLab platform.

EnergyFlexLab as a digital platform located on its own separated virtual-LAN network within the IT system of Danish Technological Institut (DTI). This gives some extra benefits in both security and performance:

- Only systems with a granted access to the EnergyFlexLab LAN can see and control communication between components.
- A dedicated bandwith for fast and efficient data-communication between components whether they are located at DTI facilities in Aarhus, Odense or Taastrup.
- Dedicated access control for external customers who can get access to interact with specific components in EnergyFlexLab – and nothing more.
- The possibility to allow specific dataflow between EnergyFlexLab and external data-sources e.g. REST API, FTP-servers, Sigfox devices and more.

Besides energy components some core features are connected to the virtual-LAN as the IT-infrastructure backbone of EnergyFlexLab (please see Figure 2):

- SQL database where all data and metadata from components are saved for later analysis of historical data.
- Virtual servers with several controlling- and analysis-algorithms and feedback-loop to optimize the smart control.
- A frontend SCADA developer-tool referred to as YoDa (Your Data), where DTI-employees can share code and develop together. With this SCADA tool online interactive dashboards and control-systems are created and made accessible for external customers.
- A MQTT data communication protocol that enables fast and asynchronous data communication between components, servers and dashboards.



Concept sketch – EnergyFlexLab.

- Custom made data-acquisition devices that connects external components to the EnergyFlexLab platform for "Hard-ware -in-the-loop test".

This backbone of EnergyFlexLab makes the digital platform highly scalable, flexible, and easy to use across employees on DTI. The platform fills the needs of both DTI and the customers and partners, with whom DTI is working with.

Example

An example of the use of EnergyFlexLab is in the project "Future Green Construction sites", where a setup for intelligent electricity to a construction site is developed and demonstrated. Compo-nents in this energy system is e.g. electric vehicles, solar panels on the site hut, which is being heated by heat pumps, and energy storages which reduces the expenses by charging outside normal working time. This project helps to support the standards for how a construction site optimizes both its energy supply and use.

Another use of EnergyFlexLab is in the EU Horizon2020 project "ALIGHT" where European airports and stakeholders in the field of aviation together create the tools for a sustainable future of aviation. The project leader of "ALIGHT" is Copenhagen Airport, Denmark, which also act as the demo-site of the 4-year long project. One goal in the project is the implementation of a "Smart Energy Management System" for efficient and optimized use of sustainable energy from PV-systems by controlling e.g. BESS, buildings (electricity and HVAC) and electrified vehicles chargingpoints. The "Smart Energy Management System" is currently being tested in Energy-FlexLab to help the creator (a danish SMV) to optimize and test the control-algorithms before implementation in the real-life application.

FACTS ABOUT THE PROJECT

IoT Category: Grid services and optimized heat pump operation.
Goal: Provides opportunity for test of heat pumps systems in future flexible energy systems with sector coupling.
Beneficiary: Manufacturer and operator
Data required: Operating data for components in energy system and forecast inputs.
Analysis method: Analysis of heat pump operation during dynamic changing operating conditions.
Modelling requirements: An example is to use a dynamic model of a heat pump made in Dymola (Modelica) using the TIL library from TLK as starting point. Communication between model and EnergyFlexLab can be made with a Functional-mock-up-unit (FMU).
Quality-of-Service: Real-time
Project participants: EnergyFlexLab facilities is e.g. used in the Horizon project "Smart Island Energy Systems (SMILE)" and "ALIGHT".
Time schedule: EnergyFlexLab facilities can be used continuously.
Technology availability: TRL 7-9 (depends on ernegy component)
Link to webpages:
https://www.dti.dk/energyflexlab-and-8211-testing-flexible-and-intelligent-energy-components/42286?cms.query=energyflexlab

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MyUpway^{TM} – Online heat pump control

METRO THERM A/S

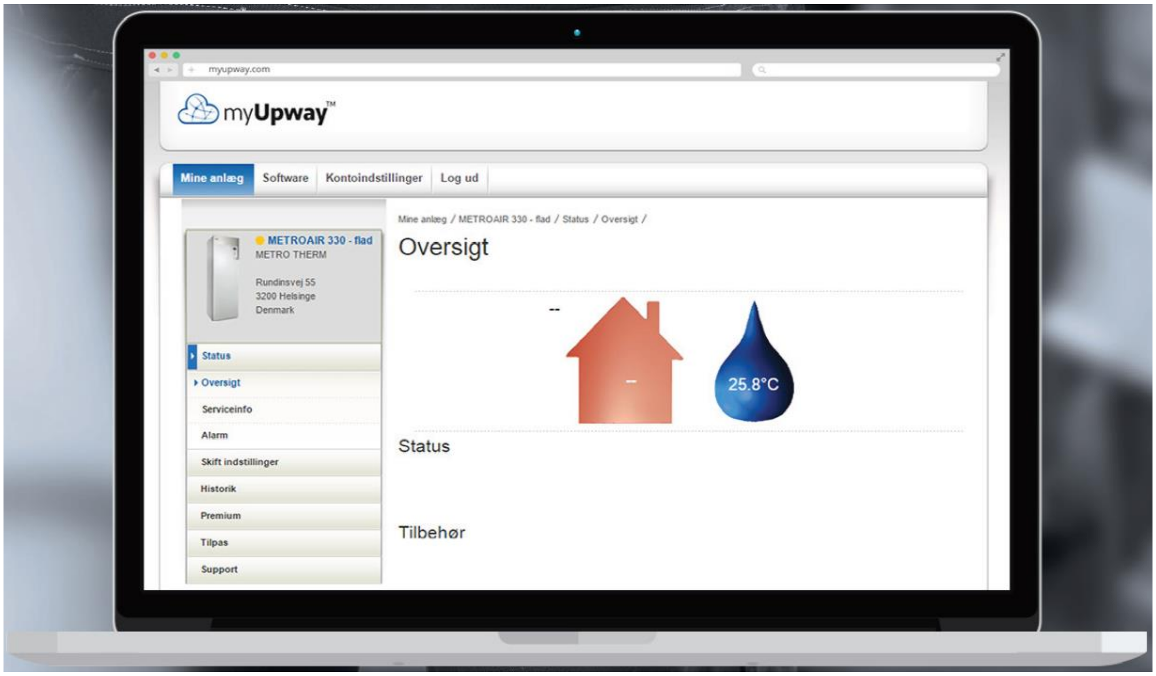

Figure 1: Homepage of the online-service myUpway^{TM} where overall heat pump information is displayed.

Summary of IoT case

The platform myUpway^{TM} provides online monitoring and control services, including surveillance of heat pumps energy consumption and fault alarms as well as remote control possibilities. This platform is exclusive to METRO THERM products with suitable connectivity specifications, which includes air source and ground source heat pumps.

Moreover, heat pumps integrated with myUpway^{TM} are smart grid ready. This could be used to optimize remotely the operation of heat pumps based on information from electricity grids and users' consumption patterns to minimize operational costs of heat pumps. The current version of myUpway^{TM} includes a feature called Smart Price Adaption, which enables the automatic adjustment of heat pump operational periods to minimize electricity consumption costs.

MyUpway^{TM} is available in two different functional levels, namely a basic level and an advanced level. The basic level includes services such as operation monitoring, fault alarms and access to one month of historical data with a limited number of parameters. The advanced level includes the same functionalities as the basic level and the option of changing the configuration of the heat pump. Moreover, with the advanced level, users can access to historical data from more variables compared to the basic level and over the entire operational life of the heat pump. Heat pump users are able to retrieve such historical data and apply their own advanced data analysis methods (e.g. by means of machine learning), which are not included in the platform.

MyUpway^{TM} represents METRO THERM's version of the online service platform from its parent company NIBE named NIBE Uplink^{TM}. This service has been commercially available for several years, which has enabled NIBE users to monitor and control their heat pumps to maximize thermal comfort and minimize heating-related costs.

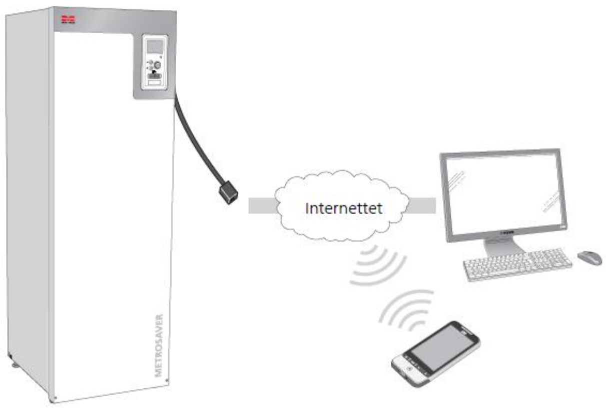

Figure 2: Representation of the interconnection between METRO THERM heat pumps and desktop through myUpway™.

Results

- Users of myUpway™ are able to receive insights about heat pump status and indoor climate, control temperatures related to space heating and domestic hot water supply, and get suitable support from service providers.
- Users can reduce their electricity bills as a result of the Smart Price Adaption feature. Here, the operation of heat pumps is automatically reduced during hours with high electricity prices, without sacrificing comfort requirements.
- Service providers connected to myUpway™ can avoid unnecessary physical assistance to heat pump users and get remote assessment of multiple units.
- The possibility of third-party remote control of heat pumps through myUpway™ may in the future increase their performance and provide ancillary services to electricity grids. However, this feature has not been applied in commercially available units yet.
- As a future possibility, the data retrieved through myUpway™ could be used for performance forecasting and advanced fault diagnosis methods.

FACTS ABOUT THE IOT CASE

IoT category: optimize HP operation and predictive maintenance

Heat supply capacity: up to 20 kW

Heat source: air and ground

Analysis method big data analysis

Modelling requirements: Data-driven

Data required: operation data

Data interface: LAN and Wireless

Transmission protocol for data: Modbus

Quality-of-Service: Real-time (online control)

Technology Readiness Level: TRL 9 (system works and proven in operation)

Link to webpage: https://www.metrotherm.dk/support/varmepumper/online-styring-af-varmepumpen

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Project: Digital twins for large-scale heat pump and refrigeration systems

EUDP
The Energy Technology Development and Demonstration Programme

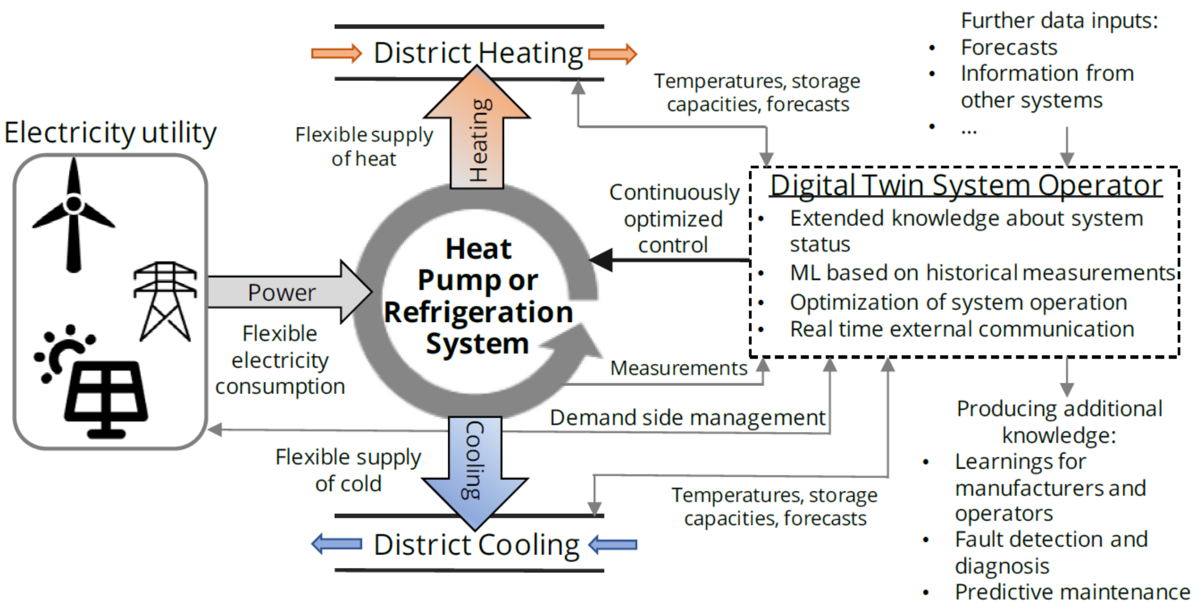

Figure 1: Diagram of the digital twin system operator.

Summary of IoT case

Digital twins can be described as adaptable models that are able to adjust their structure based on measured data from the system they represent. This project aims to reduce the effort to develop digital twins for large-scale heat pump and refrigeration systems. The target groups are supermarket refrigeration systems as well as heat pumps for district heating systems.

The digital twins developed in the project are expected to have a modular and reusable structure. This will be used to provide services such as advanced system monitoring, operation optimization as well as fault detection and diagnosis. The data used to develop and implement the adaptable models may be retrieved from wired sensors as well as from IoT-based sensors.

Digital twins are conceived as a combination of two modelling frameworks, namely physics-based and data-driven models. The first type includes simulation models that incorporate mass and energy balances, and empirical correlations of heat transfer coefficients and pressure drops. On the other hand, data-driven models are comprised of statistical models and machine learning. Such models will be especially useful to describe performance degradation of components, predict system performance and optimize set points as well as operation schedules.

Two large-scale heat pump systems are applied as case studies to develop and test the digital twins. These systems have rated heating capacities of approximately 4 MW and 1 MW and are used for supply of district heating. One system use seawater as heat source and ammonia and water as working fluids in separate cycles. These cycles include reciprocating and turbo compressors, respectively. The second case study is an ammonia system with reciprocating compressors that uses industrial excess heat as heat source.

Measured data from the case study heat pumps is retrieved from data collection systems used for monitoring and control. Currently, the digital twins that are under development in this project use measured data from wired sensors only. However, it is expected that future

Figure 2 - Seawater and NH_3 heat pump system at Aarhus Ø (AVA) used for case study I.

applications of such models will also include data from wireless sensors based on IoT.

After the project is finalized, it is expected that the frameworks developed during the project will be applied in multiple heat pump and refrigeration systems. It is estimated that the digital twins will be implemented as a software that use measurements from existing monitoring and control systems, e.g. SCADA systems.

Learnings and results

- Dynamic simulation models of the case study heat pump systems were developed, which are expected to provide an accurate description of their performance.
- Predictive maintenance and operation optimization are estimated to be potential outcomes from the implementation of the digital twins developed in the project. This can be used as a basis for creating digital twin-based services. As an example of this, a framework for performing continuously set-point optimization has been developed for case study I.
- Advanced fault detection and diagnosis services provided by digital twins will be included in a framework to assess the potential of heat pumps for flexible operation.
- It is projected that the effort to develop new digital twins for large-scale heat pump and refrigeration systems will be reduced as a result of this project.

FACTS ABOUT THE IOT CASE

IoT category: Optimize heat pump operation, predictive maintenance, and performance monitoring

Goal: Reducing the effort for creating digital twins in order to improve services for large-scale heat pumps and refrigeration systems

Beneficiary: End-use and operator.

Analysis method Numerical simulations and data analysis.

Modelling requirements: Design system specifications and real-time measured data for the development and adjustment of dynamic simulation models (made in Dymola) and data-driven models.

Data required: Operational data from heat pumps, weather forecast and electricity prices

Data interface: No specific requirements yet.

Transmission protocol for data: No specific requirements yet.

Quality-of-Service: Real-time and hourly for online monitoring and control.

Technology Readiness Level: TRL 5.

Project participants: DTI, DTU, TLK-Thermo GmbH, AK Centralen, Superkøl, Danfoss, Affaldvarme Aarhus, TU Braunschweig

Time schedule: 2020-2024

Link to webpage: http://digitaltwins4hprs.dk/

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EnergyLab Nordhavn – Smart Components

Figure 1: Heat is recovered from a supermarket refrigeration system to the local district heating grid in Nordhavn, Copenhagen.

Summary of project

Within the project EnergyLab Nordhavn – Smart Components a heat recovery unit has been integrated into the refrigeration system of a supermarket (Figure 1). The supermarket uses a CO2 refrigeration system. Heat was recovered from the high pressure side of the refrigeration cycle and supplied to the local district heating grid or to the building itself for space heating and domestic hot water preparation. In this way, energy is recovered, synergies between local energy prosumers are unlocked and the available compressor capacity of the supermarket refrigeration system can be exploited better.

It was studied how the supply of cooling to the supermarket and heating to the district heating system could be decoupled by adaption of the gascooler pressure and by addition of an extra air-source evaporator. Simulations showed that these measures would allow to exploit the available compressor power and to increase the flexibility of heating and cooling supply.

Further, the control of the heat recovery system according to dynamic price signals has been demonstrated. It was shown that the implementation of the proposed control structure led to increased heat recovery during periods of low energy prices. Thereby this method could be useful for maximizing the revenue for the supermarket owner by an optimal real-time decision on selling the recovered heat to the district heating grid or self-consumed for space heating and domestic hot water of the supermarket.

The corresponding closed-loop control algorithm was executed in Matlab on a PC at the Technical University of Denmark. The control algorithm decides the optimal operation strategy based on real-time operational data and electricity and district heating prices. The connection to the physical system was realized via the Danfoss cloud that was used to retrieve data to the DTU cloud-based Data Management System (DMS) and to send control commands to the local controller. A sketch of the system is shown in Figure 2.

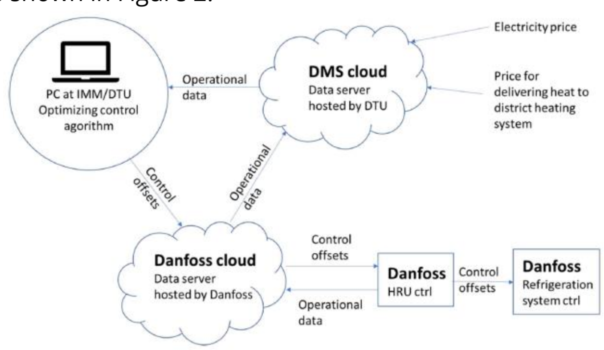

Figure 2: Sketch of the communication framework used for demonstration of the control of the heat recovery unit according to dynamic price signals.

Overall, it was shown how heat from supermarket cooling equipment can be exported to the district heating network, and how this heat export can be controlled in a smart way based on online data exchange so that the system contributes as decentral peak load capacity for the district heating utility, while generating an additional income to the supermarket system operator.

Learnings and results

-The supply of district heating from the heat recovery unit integrated with the CO2 refrigeration system of the supermarket has been successfully demonstrated by Danfoss.

-Through system simulations, it was shown that the production of cooling for the supermarket appliances and heating to the local district heating grid can be decoupled cost efficiently by adapting the gas cooler pressure or by using an additional air-source evaporator. The first version results in cheaper heat supply cost, especially at lower gas cooler pressures and ambient temperatures. Providing additional heat using an additional air-source evaporator (e.g. part of the gascooler) is more efficient if the evaporation pressure level is independent from the MT cabinet pressure. This solution becomes feasible, when high gascooler pressures are required (due to high ambient temperatures or heat demand internally in the building).

-It was shown how heat from supermarket cooling equipment can be exported to the district heating network, and due to the nature of the CO2 based technology, this heat export can be controlled so that the systems contribute as decentral peak load capacity for the district heating utility, reducing the need for fossil fueled peak load boilers.

-The business case has been investigated (using 2019 prices) and it was found that by selling district heating to the local district heating company HOFOR, a payback time of 3-4 years for the heat recovery system may be achieved. The yearly profit for the supermarket were fund to amount to 11,600 €/year. In case, the supermarket was only to pay for its net heat consumption, the profit would be significantly higher.

-The heat recovery unit has been introduced as a product in combination with CO2 refrigeration systems by Danfoss and the marketing has started. Today solutions are implemented in the control systems that already now enable the possibility to utilize excess heat for district heating or building heating. The products also support the use of spare compressor capacity for providing extra heat. The implementation of these solutions is expected to follow the adaptation of CO2 for supermarkets refrigeration which is expected to increasingly spread globally during the coming 3-4 years – following the legislative requirements for use low GWP (Global Warming Potential) refrigerants.

-A range of data streams and data series have been made available on an online platform supporting secure real-time data sharing between the stakeholders. In this way, a smart energy system encompassing electricity, heat, buildings, transport, and residents can be realized. The

FACTS ABOUT THE PROJECT

IoT Category: Heat as a service
Goal: Unlocking synergies between small-scale excess heat sources and district heating networks
Beneficiary: Supermarket owner, District heating utility
Data required: Operational data, electricity prices, marginal heat generation cost
Analysis method energy engineering, control engineering
Modelling requirements: Simple energy balances, control algorithm
Quality-of-Service: real-time
Project participants: Danfoss - DHS Application Centre, Danfoss Refrigeration and Air-Conditioning, DTU Wind and Energy Systems - Center for Electric Power and Energy, DTU Construct – Section for Thermal Energy
Time schedule: 2016-2020
Technology availability: 9
Link to webpage: http://www.energylabnordhavn.com/

ability of the system to support real control applications was demonstrated.

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FlexHeat – Intelligent and Fast-regulating Control

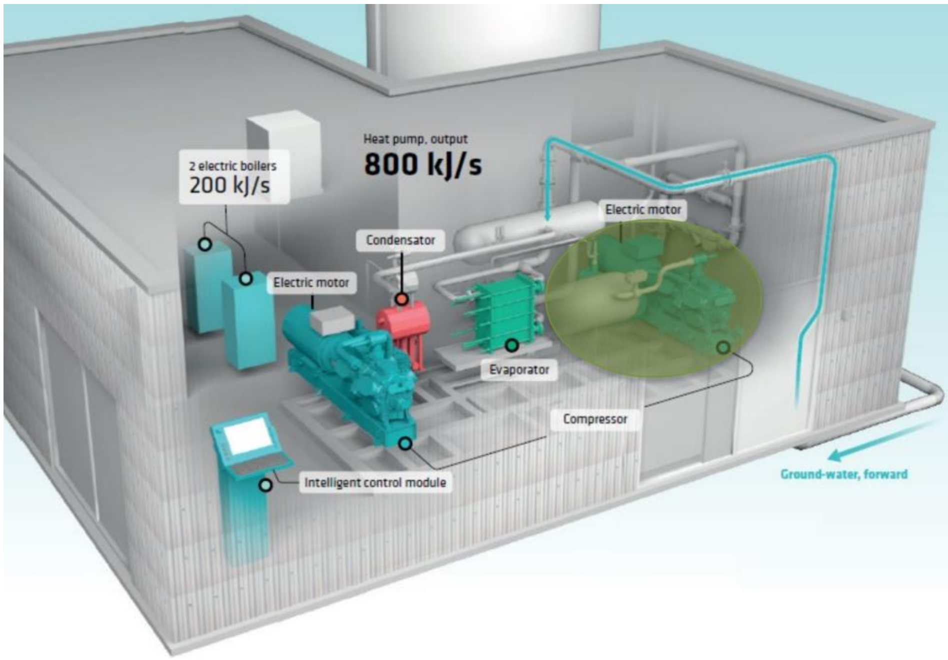

Figure 1: 3D drawing of the energy system with the most important [HOFOR, communication department, 2021]

Summary of project

A flexible energy system consisting of an 800 kJ/s ammonia-based ground-water heat pump with reciprocating compressors, 200 kJ/s electric boiler and a thermal storage tank of 100 m^3. This system delivers heat to 4 customers in an island district heating grid, which were supplied by oil-fired boilers previously.

This system is optimized by a linear-optimization model supported by a dynamic model of the heat system to schedule optimal planning production with a real-time communication setup to control the heat pump accordingly, see figure 2. The linear-optimization model includes heat forecast with inputs from weather data, complex stratified storage tank modelling, and start-up costs for the heat pump, and an electricity price forecast is supplied to find the minimum costs for the system.

On top of this, the heat pump has been modified to provide fast regulation services to the grid – here, the optimization module can additionally plan for the heat pump to deliver this service, and, still under construction, a setup is implemented to read the grid frequency and stabilize this accordingly by changing the set-points of the heat-pump.

The preliminary results indicate that operating costs can be reduced by 7 % by introducing intelligent operation with the linear optimization model, and an additional 6 % costs reduction can be achieved by delivering grid services.

Learnings and results

The most important finding here is that ammonia-based heat pumps can regulate fast enough to deliver the FCR-N service (frequency stabilization service).

It was found that this would compromise the COP due to pre-heating of the suction line and compressor blocks as well as the increased overheating from the evaporator, and that a control scheme where you would only do this if you were asked to deliver a grid service would be optimal – hence, the overall COP of the facility is not compromised, unless you choose to do so, and here you could be making money delivering a grid service.

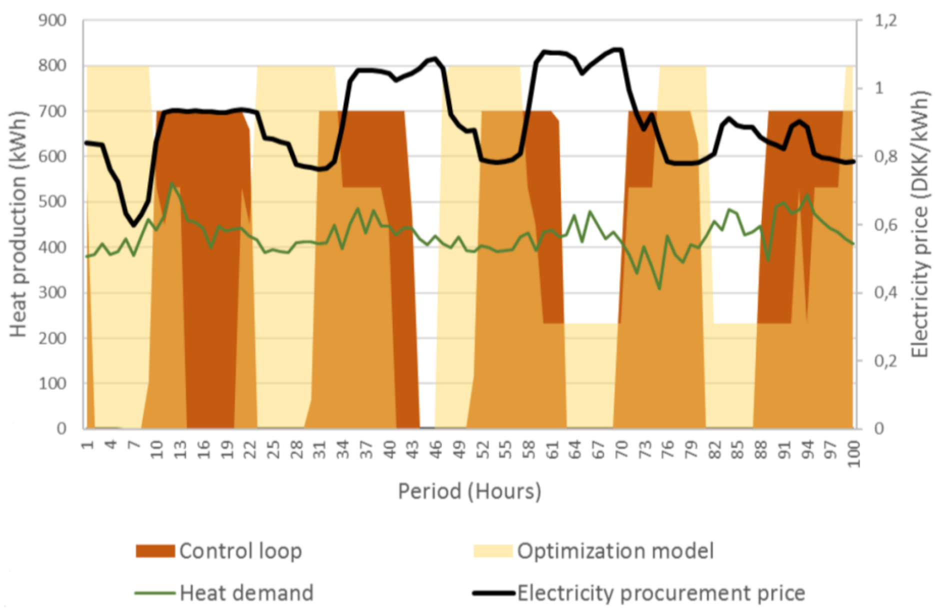

Figure 2: Flexible heat production during winter [HOFOR, 2021]

These results give an idea of asking manufacturers for a fast-regulation option in the design and control of the heat pump, the next time HOFOR build a heat pump. HOFOR have seen the feasibility of doing so, and more compressor types and refrigerants should be tested – so it is ensured, that heat pumps can help out the electricity grid now and in the future, to the benefit of the electricity system and the district heating customers.

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FACTS ABOUT THE PROJECT

IoT Catagory: Grid services.

Goal: Reduced heat production costs for the system and ensure that heat pumps can help stabilize the current and future electricity system.

Beneficiary: User, TSO and the heat pump manufacturer.

Data required: Weather forecasts, electricity price forecasts, heat pump operation data, grid frequency measurements.

Analysis method Control engineering.

Modelling requirements: Primary model is a linear-optimization model, which has been backed up by a dynamic model to support the constraints implemented.

Quality-of-Service: Real-time control signals and 24-hour optimization schedules.

Project participants: HOFOR, DTU MEK, Johnson Controls (Factory and Enterprise), COWI

Time schedule: 2018-2020

Technology availability: TRL 7.

Link to webpage:

http://www.energylabnordhavn.com/deliverables.html (see deliverable 5.5a)

Smart-Energy Operating-System (SE-OS) framework

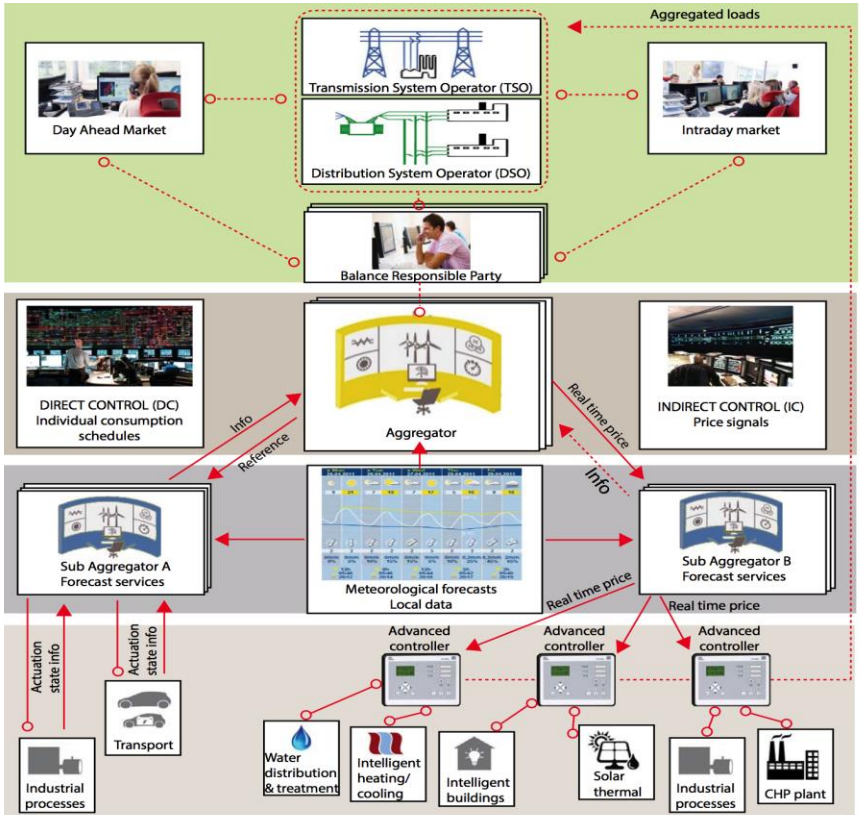

Figure 1: The Smart-Energy Operating-System (SE-OS) for digitalization of integrated energy systems.

Summary

The Smart-Energy Operating-System (SE-OS) is a framework for digitalization and implementation of smart energy solutions, including the use of heat pumps. Also connections to the energy related part of e.g. water and food processing systems are included. The SE-OS framework consists of both direct and indirect (mostly price-based) control of the electricity load, heat load, etc. in integrated energy systems. The system has embedded controllers for handling ancillary service problems in both electricity and heat grids. The entire setup of the SE-OS includes all levels of computing (cloud, fog, edge). The distributed setup of computing and data includes edge computing near the IoT devices. The SE-OS framework is used in the central data and cloud hub Center Denmark which is an European Digital Innovation Hub that is used for digital business models aimed at providing new data-driven services for the energy and water sectors (https://www.centerdenmark.com/en/)

A hierarchy of optimization and control problems

The SE-OS, as shown in Figure 1 (this version of the SE-OS has a focus on electricity), is built as a hierarchy of four nested stochastic optimization and control layers representing aggregated consumption on various spatial and temporal scales. Today, the framework is used in several European projects for optimized operation of heat pumps and IoT devices. Within e.g. the CITIES project (https://smart-cities-centre.org/), the SE-OS has been used to implement flexible and smart grid enabled solutions for heat pumps, wastewater treatment plants, super markets, HVAC systems, indoor comfort, etc. Please see the homepage for specific examples.

Multi-level control and markets

Ultimately the purpose of the future smart energy system is to establish a connection between the controllers related to IoT devices operating at local scales, and high-level markets, which obviously is operating at large scale. Essentially a spectrum of all relevant spatial aggregation levels (building, district, city, region, country, etc.) has to be considered. At the same time control or market solutions must ensure that the power system is balanced at all future temporal scales. Consequently, data-intelligent solutions for operating flexible electrical energy systems have to be implemented on all spatial and temporal scales.

Traditionally power systems are operated by sending bids to a market. However, in order to balance the systems on all relevant horizons several markets are needed. Examples are day-ahead, intra-day, balancing and regulation markets. The bids are typically static consisting of a volume and duration. However, the Smart-Energy OS provides new and efficient methods for activating low-level flexibility. Given all the bids the so-called supply and demand curve for all the operated horizons can be found. Mathematically, these supply and demand curves are static and deterministic. Merit order dispatch is then used to find the optimal cost and volume. However, if the production is from wind or solar power, then the supply curve must be stochastic. In the future demand response will play an important role, and on the demand side the needed electricity depends on the history. If, for instance, a supermarket has reduced the electricity load for an hour, then the temperature constraints of the freezers etc. implies that the supermarket might have difficulties in reducing the electricity for the next few hours. Consequently, the demand flexibility has to be described dynamically. Mathematically, a so-called Flexibility Function is introduced, and this function is a core element of the SE-OS framework.

Summing up, new digitized markets need to be introduced, which are dynamic and stochastic, and instead of using a large number of markets for different purposes (frequency, voltage, congestion, etc.) and on different horizons, a concept based on the flexibility function and stochastic control theory is suggested. Zooming out in space and time, i.e. and consider the load in a very large area on a horizon of days, or maybe next day, then both the dynamics and stochasticity can be eliminated, and hence, a conventional market principles as illustrated in Figure 2 can be used. Zooming in on higher temporal and spatial resolutions (like for instance a house), the dynamics and stochasticity become important, and consequently the use of control-based methods for the flexibility is suggested.

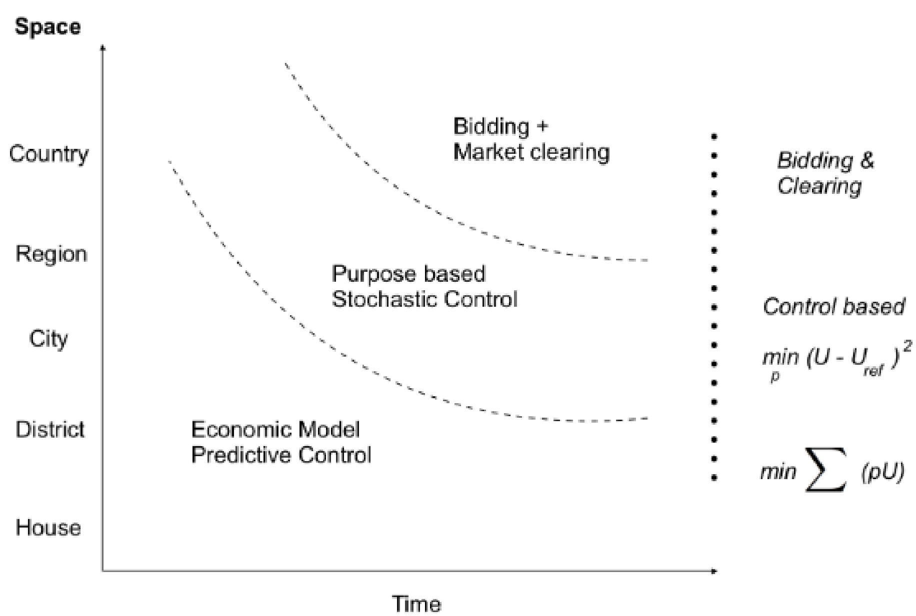

Figure 2: Hierarchical control and markets.

The total setup consists of a combination of all these options, and the best option depends on the zoom level. The conclusion is that a new future digitized refined market principles is needed, which operate as a hierarchy of conventional market-based bidding and clearing on the higher levels and control-based approaches on the lower level.

All these principles for forecasting, control, and optimization are included in the Smart-Energy Operating-System (SE-OS), which is used to develop, implement and test solutions (layers: data, models, optimization, control, communication) for operating flexible electrical energy systems at all scales.

Data-driven digital twins (grey-box models)

The models used for forecasting, control and optimization within the SE-OS framework are most often so-called data-driven digital twins or grey-box models. These models are optimized for real-time operations, and most importantly these models are optimized for assimilating information from available sensors into the model parameters.

This is illustrated by the red dashed line on Figure 3 which aims at illustrating that the used data-driven digital twins or grey-box models are simplified models of the considered system (building, wastewater treatment plant, heat pump, etc.). Please see the references for more information.

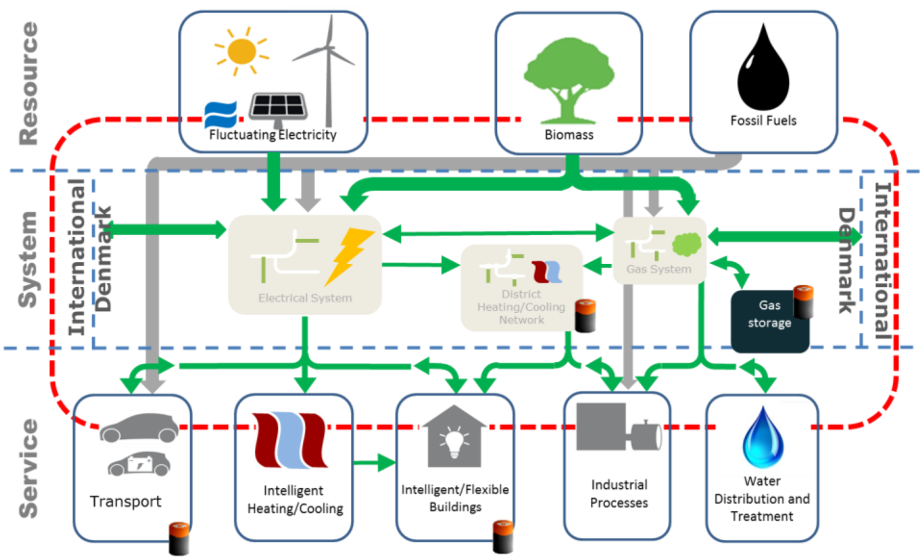

Figure 3: Grey-box models and data-driven Digital Twins.

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Project: Combined Optimization of Heat Pumps and Heat Emitting Systems (OPSYS 2.0)

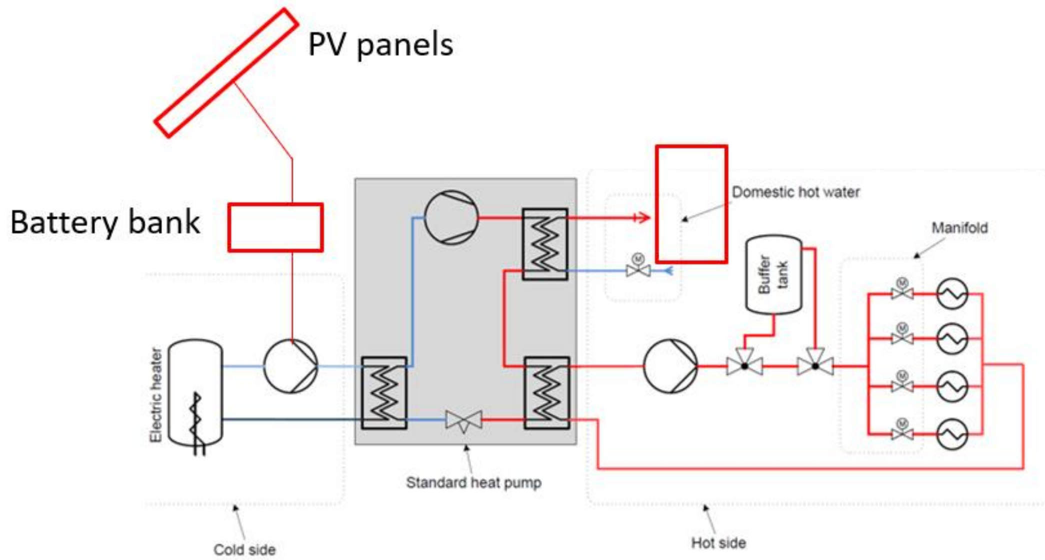

Figure 1: Principle sketch of experimental setup (on the test rig PV and battery are virtual).

Summary of project

The aim of the project is to increase the efficiency of both existing and new heat pump installations by developing a control kit that can optimize both the forward temperature from the heat pump and the flow rate through the heat emitting system, which is to be done by developing a control system capable of:

- Creating flexibility services for the stabilization of the electricity grid.
- Optimizing the self-consumption of PV generated electricity on private houses and/or avoid curtailment.

Heat pumps are intended to play a major role in the transition to renewable energy sources (RES) due to their high efficiency and ability to provide energy flexibility for stabilization of the future energy system with much RES. However, a survey has showed that only around 16 % of the heat pumps installations could be categorized as "good", as e.g. the regulation of the heat pump is not optimal as the forward temperature often is too high.

Although heat pumps in principle can be controlled according to the amount of RES in the system, only little energy flexibility can be provided, as the control of the heat pumps and the heating systems often is not coordinated. The Combined Optimization of Heat Pumps and Heat Emitting Systems concept (OPSYS) optimizes the performance of the heat pump installations via optimized control of the forward temperature and the flows in the system by controlling both parameters in accordance with the heat demand, the weather, and electrical grid needs.

Another important feature of the OPSYS concept is that it may increase self-consumption from on-site PV systems. The goals for the project include system-wide optimization of a house as energy

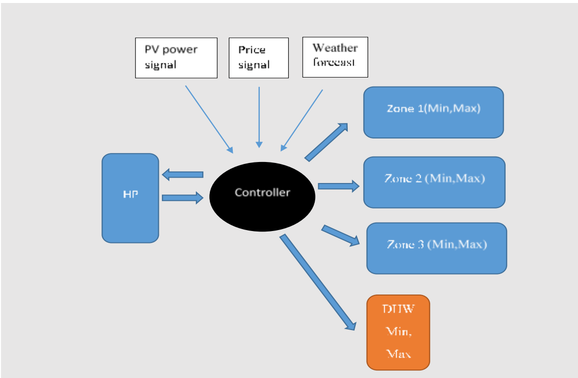

Figure 2: Simple representation of the controller.

consumer and producer by using control strategies for optimizing the self-consumption of PV electricity. The concept also includes utilization of storage in thermal mass and electric batteries.

The setup for the OPSYS test rig, can be seen in Figure 4. It can here be seen how the temperature control is performed by inputs from floor and room models, with feedback from the physical system. The house model (see figure 3) is developed in Dymola (Modelica) and imbedded in a python script as a FMU (Functional Mock-up Unit). 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.

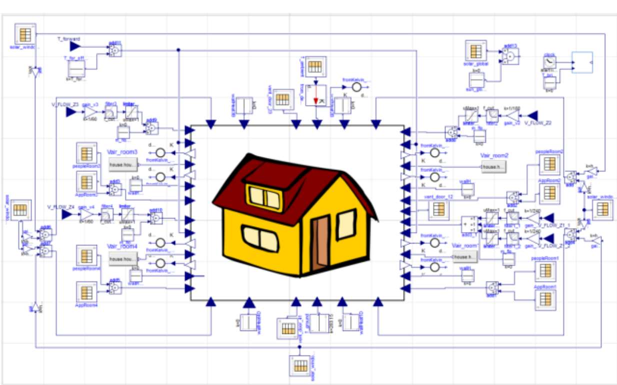

Figure 3: House model in Dymola.

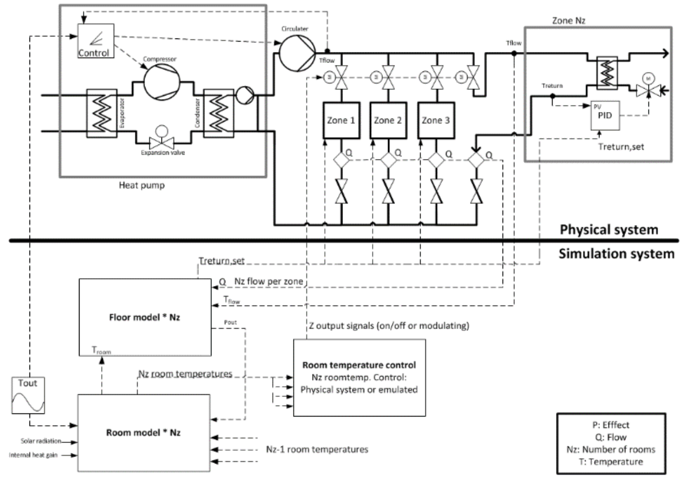

Figure 4: Physical and simulation system.

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.

Learnings and results

The experimental platform at DTI has been modified and adjusted to overcome some regulation instability issues. It was necessary to install a large brine buffer tank and after that the test rig is operational, however the PV system is yet to be simulated in detail.

The controller has also been installed in a real house with heat pump and a PV system. A number of practical problems related to communication with sensors has been observed. This house has been monitored for a while and results compared with the theoretical room temperatures calculated in the FMU house model. The project has been extended to allow measurements through a full heating season.

One part of the experiments is with pulsed operation of the regulation valves in the heating system which has been successfully carried out. The preliminary results showed a little advantage compared to on/off operation.

Contact information

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FACTS ABOUT THE PROJECT

IoT Catagory: Optimize heat pump operation
Goal: The goals for the project include system-wide optimization of a house as energy consumer and producer by using control strategies for optimizing the self-consumption of PV electricity.
Beneficiary: End-user.
Data required: Electricity prices, dynamic carbon intensity of power, grid tariff signals, weather data, operating data from heating system.
Analysis method: Model predictive control strategy
Modelling requirements: Dynamic self-learning models.
Quality-of-Service: Real-time.
Project participants: Danish Technological Institute, Neogrid, Aalborg University, Wavin, Bosch
Time schedule: 2019-2023.
Technology availability: TRL8 for control kit and TRL7 for the optimized control for grid interaction and increased self-consumption of PV electricity
Link to webpages:
https://www.teknologisk.dk/projekter/projekt-opsys-2-0/40581

Cool-Data

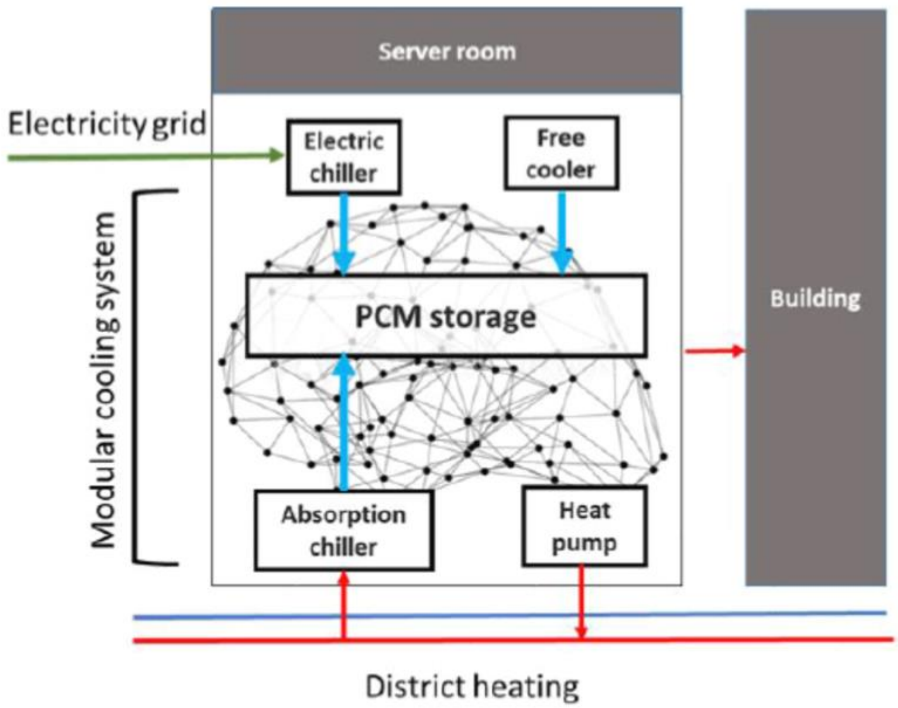

Figure 1: Cool-Data Overview

Summary of IoT case

Cool-Data develops, assesses, and implements an AI-based modular, flexible, secure, and reliable integrated cooling energy system for data centers.

With the integrated flexible solution, Cool-Data aims at significantly reducing the energy need and cost for cooling data centers and actively participates to minimizing the carbon footprint of the sector. The integrated cooling solution supports the utilization of electricity from renewable energy sources by storing surpluses in time in PCM (phase changing materials) storage units. This allows the decarbonized surplus heat generated by the data centers to be used and valorized in district heating with the help of heat pumps.

By using Artificial Intelligence and smart controllers that connect the cooling equipment and the PCM storage, a modular cooling solution capable of responding to reliability requirements in data centers and minimizing the cost for cooling is obtained. By doing so, the Cool Data project targets up to 80 % energy efficiency gains in data centers, resulting in severely limiting the current impact of this sector's growth on carbon emissions.

Moreover, Cool-Data enables UPS systems to access a new revenue as Frequency Containment Reserve in the balancing market. There is the possibility to sell UPS reserve power and storage that is not used for the data center operation as FCR while ensuring the reliable operation of the data center. The pro of operating as FCR is that prices are favorable, but the main downside is the difficulty to forecast the balance market.

Cool-Data also assess the business and environmental benefits of scaling up the solution in terms of energy efficiency, flexibility, excess heat utilisation, and CO_2 reduction.

Cool-Data is a research project funded by Innovation Fund Denmark led by DTU Compute and involving 8 partners in Denmark:

- 3 research groups: DTU Compute, DTU Civil Engineering, DTU Management
- 1 non-profit research institute: Center Denmark
- 2 Danish manufacturers: EnergyCool and Purix
- 1 air traffic controller: Naviair
- 1 Danish district heating utility: GEV

Learnings and results

A reinforcement learning algorithm was successfully developed, and it managed to keep the server rack temperature at 30 °C by using the cooling equipment in an efficient way.

A pilot storage set up using paraffin has been already studied. It consists of 8 kWh storage capacity and 115 liters of PCM. Currently, the design is being optimized further.

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FACTS ABOUT THE PROJECT

IoT Catagory: Optimize heat pump operation
Goal: Reducing the energy need and cost for cooling data centers and actively minimize the carbon footprint of the sector.
Beneficiary: Data centers
Data required: Data center cooling requirements, balancing market prices
Analysis method: energy balances and control engineering
Modelling requirements: stochastic MILP
Quality-of-Service: nearly real time
Project participants: DTU Compute, DTU Civil Engineering, DTU Management, Center Denmark, EnergyCool, Purix, Naviair, GEV
Time schedule: 01/09/2020 → 31/08/2023
Technology availability: TRL 6
Link to webpages:
https://cool-data.dtu.dk/
https://www.linkedin.com/company/cool-data/

Project: Experimental development of electric heat pumps in the Greater Copenhagen DH system (SVAF phase 2)

Figure 1: 5 $MW_{thermal}$ heat pump system for district heating in Copenhagen [Source: HOFOR].

Summary of project

The overall purpose of the project is to accelerate the use of large electric heat pumps (HPs) for district heating (DH) through industrial co-operation, research and experimental development. The project is the second phase of the total project, which includes large-scale HP investments carried out to demonstrate optimal design, smart system integration, cost efficiency and climate benefits.

Large electric HPs are expected to play an important role towards CO_2 neutral DH systems. The HPs can make up a significant supplement to heat production on biomass, and furthermore, electric HPs, when operated in a smart way, can support wind power integration in the overall energy system.

This project addresses the main barriers in order to accelerate the use of HPs using natural refrigerants in the DH sector through the development of optimized HPs for system integration with improved cost efficiency and with potential for scaling up concepts to 50-100 MW. The demonstration heat pump built can use both seawater and waste water as heat sources, and can be seen in Figure 1. The system consists of two parallel 2-stage heat pumps with NH_3 as working fluid.

A key focus in the project is monitoring and set-point tuning of large-scale HP systems, where two different approaches will be evaluated:

- HP AutoTune - for continuous optimization of operating conditions (see Figure 2).
- HP Doctor - for monitoring purposes and fault detection (see Figure 3).

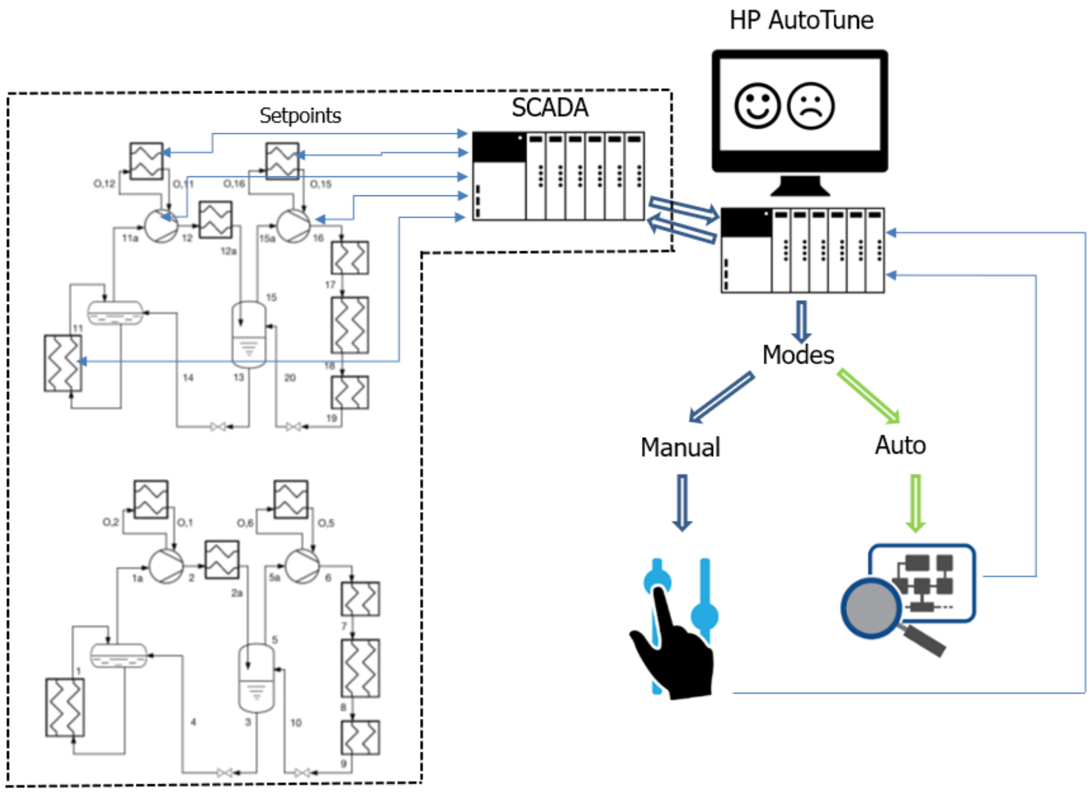

Figure 2 – Concept for HP AutoTune.

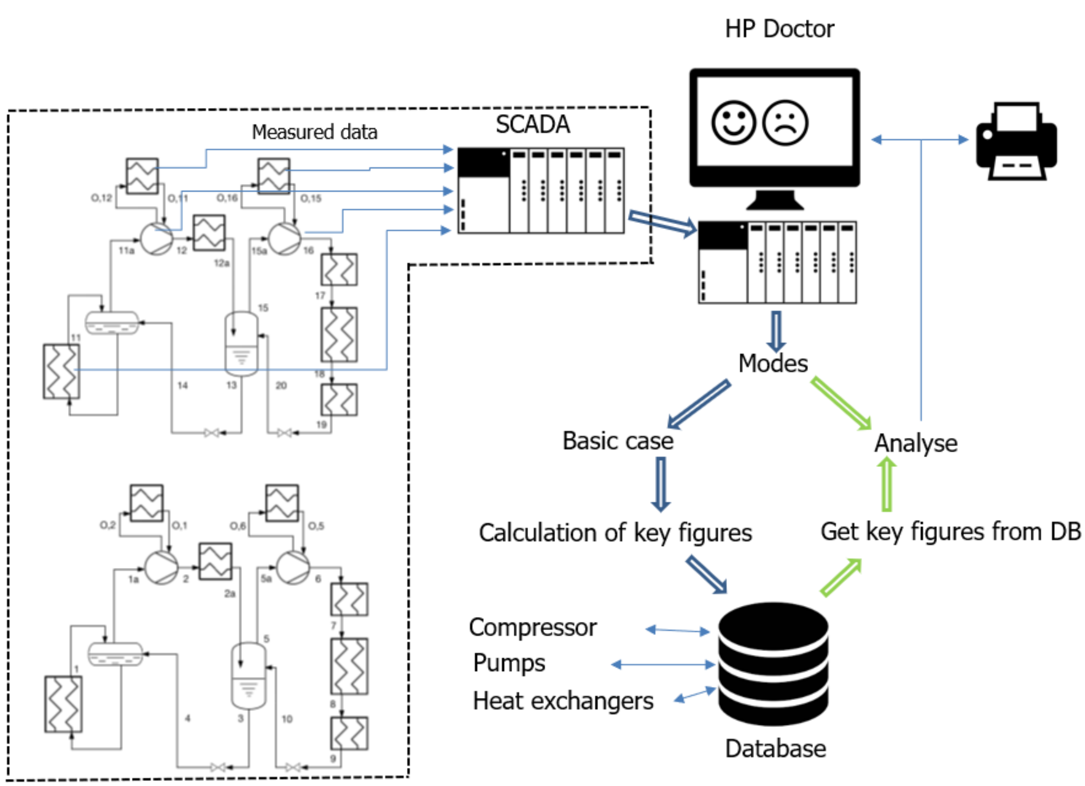

Figure 3 - Concept for HP Doctor.

The HP AutoTune concept to be developed in the project is to guide the heat pump installation to always have the highest available COP, and through all operating conditions. The HP AutoTune will be investigated in the project through different approaches. The first is based on IWO (Invasive Weed Optimization) approach and the second on use of analytical equations:

HP AutoTune - IWO

In this approach, a number of system control loops have been chosen. Each of these control loops have a set point which is accessible from the IWO. The main goal is to optimize the COP at all times, and this is done by the IWO by changing one set point at a time and register the change in COP. If the result is improved COP, the change is kept and otherwise the set point is returned to the original value. The IWO then cycle through the selected set points and thereby gradually optimize the total COP of the system aiming at finding the top of the COP curve in the allowed operating domain (see Figure 4).

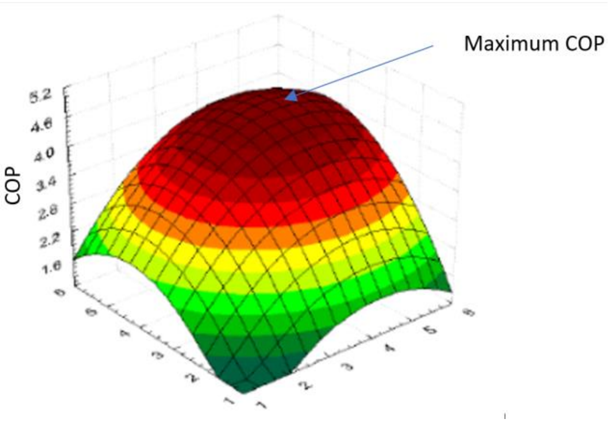

Figure 4 - Concept for optimum COP based on IWO.

HP AutoTune – Analytical

The second approach is to develop equations for the components included in the control loops e.g. heat exchangers, compressors, pumps etc. The equations consist of constants independent of operating condition and variables dependent of the running conditions. By differentiating the equation and set equal to zero a general equation can be developed for the optimum condition of the control variable. This equation contains constants and variables. At start-up of the heat pump plant with the system tuned in to the design conditions, the coefficients in these equations can be found. When running with the system off design, the equations with the established constants is used to calculate the optimum set points. It is also an option to investigate set-point tuning done in manual model.

The HP Doctor concept is intended to monitor the heat pump running with highest COP adjusted by the HP AutoTune. At start up with new and clean system a start-up procedure is performed where the heat pump runs through the operating range and collects measured values for the different components in the heat pump and saves them to a database. Equations for the efficiency of different components are developed and the efficiency for each component is calculated and stored in the database. Later, when the heat pump is released to normal duty the HP Doctor will continuously calculate the efficiency and compare the stored values. The HP Doctor can then alert the operator of possible loss of efficiency or of a threatening system failure.

A test campaign has been carried out in Q1 2022 to evaluate HP AutoTune. These tests were *short term tests*, in which one parameter was changed at a time and its influence on COP was measured. In total 6 different parameters were studied, from which flows in different heat exchangers and load repartition between stages of the heat pumps. A difficulty encountered was the fluctuation of the COP throughout the day. Indeed, short term tests were carried out during up to 3 days, and the influence of a specific value of a parameter was observed on a few hours. The COP being highly dependent on other conditions, such as temperatures of the sources and of the district heating (DH) water, a method should be found to isolate the studied parameters influence. A regression of COP during normal operation (outside tests) was made to compare COP during tests with expected COP (as it should be during normal operation). This regression is dependent on temperatures on the source side and on the DH side, as well as the compressors capacity.

With this expected COP, it was much easier to evaluate the impact of one parameter on the COP. For example, as presented on Figure 5, the impact of the water flow through the desuperheater of heat pump 2 was studied. The results show that the higher the flow, the higher the performance.

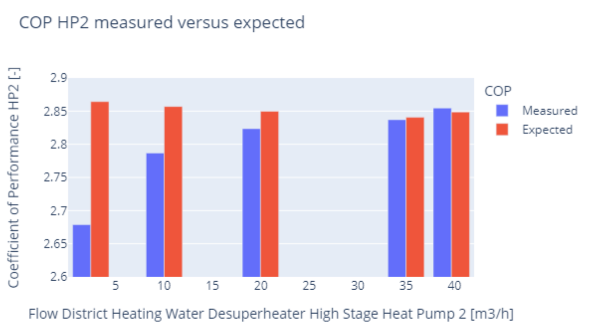

Figure 5 - Use of the regression to evaluate influence of water flow through desuperheater

Other short-term tests will be run in Q4 2022 in order to study the influence of other parameters, such as liquid level in evaporator separator or water flows on the source side.

A test campaign for evaluating HP AutoTune and HP doctor is planned for Q1 2023.

FACTS ABOUT THE PROJECT

IoT Catagory: Optimize heat pump operation and predictive maintenance.
Goal: The goals for the projects includes development of concepts regarding optimizing the operating conditions of the heat pump and monitoring of the heat pump in order for giving notifications when the heat pump is ill and points out the component causing the illness.
Beneficiary: Operater.
Data required: Operating data for the heat pump.
Analysis method Invasive Weed Optimization and development of analytical equations for COP optimization based on operation in design point.
Modelling requirements: Development of equations for components included in the control loops
Quality-of-Service: Real-time.
Project participants: Danish Technological Institute, HOFOR, CTR, VEKS, Vejlegårdens Fjernvarmecentral, COWI, Innoterm, Dansk Miljø- og Energistyring, Alfa Laval, and DTU.
Time schedule: 2016-2023.

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HPCOM

Figure 1: Project about RD&D Strategy and Roadmap for Information- and communication technology in the heat pump area.

Summary of project

The main purpose of the project was to strengthen the development and implementation of information and data communication technology (ICT) and infrastructure in the area of individual heat pumps. Hence, the project covered data communication from household heat pump installations to the central systems – at distribution system operators, electricity suppliers and other service providers.

The project focused on knowledge sharing and was centered around state-of-the-art research, development, and demonstration (RD&D), standardization and testing facilities which have resulted in a RD&D Strategy and Roadmap for ICT in the heat pump area.

Together with up-to date knowledge within standardization and RD&D, this roadmap can be utilized by potential new projects within the area. The development of strategy and roadmap were done in close cooperation with the ICT- and heat pump industry, and at the same time the strategy was conveyed to the broader energy and Smart Grid industry.

The projects consisted of 5 work packages:

- WP1: Inputs to standards. Mapping of relevant standards, and inputs for future standardization work.
- WP2: Test environments. Field test and mapping of relevant test facilities in Europe.
- WP3: Development of datahub for heat pump.
- WP4: Knowledge sharing about ICT within R&D projects and development of roadmap and strategy.
- WP5: Future organization of activities and within the co-operative "Andelsselskabet Intelligent Energistyring".

Learnings and results

WP1:

The participants are involved in various national and international working groups about standardization and ecodesign directives, and would like to influence the existing standards in order to better take smartgrids and data communication for heat pumps into account. Focus in WP1 was especially on existing testing standard should support one combined test of the heat pumps energy performance together with the products data communication. Some of the most important standards identified were:

- IEC 61850-8-2, Standard for data communication: Communication networks and systems for power utility automation – Part 8-2: Specific Communication Service Mapping (SCSM) – Mapping to Extensible Messaging Presence Protocol (XMPP)
- DS/EN14511: Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling
- DS/EN14825: 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
- DS/EN16147: Heat pumps with electrically driven compressors - Testing, performance rating and requirements for marking of domestic hot water units

Beside these standards the interesting "SG Ready" specification from Bundesverband was introduced at this time, which specifies the communication between a heat pump and a service provider. This specification is however not standardized. From the review it was concluded, that both data communication standards and conformance testing standards need to be addressed as soon as possible as a joint European standardization effort, which was communicated to the committee CEN/TC113 on Heat pumps and air conditions units.

From the mapping it is was furthermore concluded that if a heat pump shall be used for other business services, the heat pump manufacturers need to open op for more API's, in order for external stakeholders to obtain an extended communication with the heat pump.

It was also identified that the Danish standard DS 469, which states that heat pump must be able to cover the heating demand for a house down to 7 °C without the use of a heating element, in some cases can lead to a lower efficiency. In other cases it can lead to a faster response to a smart grid as the heat pump is designed with a higher capacity than before.

FACTS ABOUT THE PROJECT

IoT Category: Mainly grid services.
Goal: Improved information- and data communication infrastructure within the area of individual heat pumps to support flexible operation in smart grid systems.
Beneficiary: User, aggregators, DSO.
Data required: HP operation data, grid prices.
Analysis method: Data analytics, model- and control engineering.
Modelling requirements: Dynamic models, diagnostics, data-driven.
Quality-of-Service: Real-time.
Project participants: Insero, Eurisco, Danish Technological Institute, Neogrid Technologies Andelsselskabet Intelligent Energistyring Amba.
Time schedule: 2014-2017.
Technology availability: TRL 7.
Funding: ForskVE (Energinet.dk)
Link to webpage:
https://energiforskning.dk/en/node/15330

WP2:

In WP2 a field test was made for a heat pump with the "SG Ready" specification. According to the specification the heat pump must be equipped with 2 digital control signals (2 bit protocol) which control the heat pump to operate in one of the following four modes:

- Normal operation
- Must stop
- High
- Must max

The SG Ready specification specifies that the "Must stop" mode as a maximum can be 2 hours, but other than that there are no details about how the electrical behavior of the heat pump in the transition between the different operation modes.

Ideally, an aggregator with authority to remote control the heat pump would like the heat pump to immediately react on a control signal, to accommodate the demands for regulation of the electrical grid. In practice, there is however some challenges with this when using the SG Ready specification, for example that the specification does not specify a reset of the blocking of the heat pump after a shutdown, which the manufacturer has encoded in the heat pump. If the aggregator controls a pool of heat pumps this is not necessarily a problem, however if only one heat pump is controlled it would not be able to participate in the grid event on the desired point in time.

In the field test it was tested how the heat pump reacted when the "must stop" operation was switched off. In general the SG Ready specification does not specify details how the heat pump should react on the control signal, and it is up to the heat pump manufacturer themselves to define this. This means, the aggregator needs to modify its smart grid control to many different products which is not optimal.

The result from the field test showed that the 2-bit control concept is applicable to remote control a heat pump, however, some issues were observed during the field test. Among other things, that the heat pump after a shutdown was locked for 20 min in all conditions, and that the integral function of the degree minutes (a measurement of the current heating requirement in the house) was reset.

From the field test it was concluded that to be able to efficiently control the time for operation and electrical power use in the heat pump the SG Ready specification was inadequate. Only the Must stop function guarantees a reduction in power use. The increase in power uptake when switching to "High" or "Must max" only increased the power use momentarily if certain internal requirements was met in the heat pump, and if there is a heating demand in the house. The tested heat pump was an on/off controlled heat pump. If a frequency-controlled heat pump was used, it is expected that the heat pump better would be able to increase its power consumption instantaneously. It is however still required that there is a heating requirement in the house in order to be able to take up the heat from the heat pump. This problem could be reduced if the SG Ready specification also set requirement to a certain heat storage capacity for the heat pump installation, in order to issue a SG Ready specification for a heat pump.

WP3:

The developed principle for the datahub made in WP3 is shown in Figure 2.

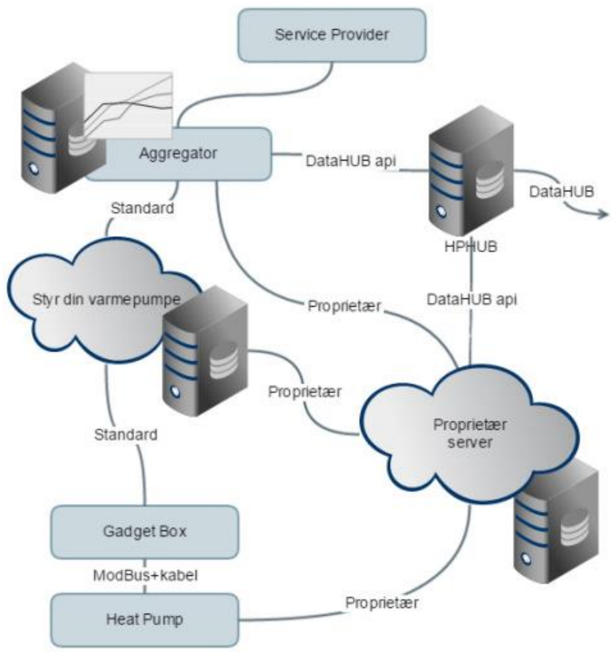

Figure 2: Principle for heat pump datahub (high level).

The developed principle includes several stakeholders with the following roles:

- End-user: Seeks optimal indoor climate with low cost and high energy efficiency.
- Manufacturer of heat pump: Needs remote data for maintenance of heat pump
- Aggregator: Owns and operate an IT system which can automatize the technical data collection and control the pool of heat pumps.
- Service provider: Sells services to the end user, e.g. smart control of the heat pump in relation to comfort and the electricity market.
- Balance responsible for the electricity grid: Has access to the electricity market regarding production and consumption, and hence is connected to the service provider.
- Heat pump datahub: Central data register with user accessible data for the heat pump.
- National datahub: Central and independent IT system to handle measurement data and business processes.
- Net company: Responsible for reading and sharing of measurements from electrical meters to the national datahub.

WP4:

In the strategy and roadmap work for expanding heat pumps potential for flexible use of electricity, the following points were identified as key enablers:

- Increased economic incentives with higher focus in variable electricity prices.
- Simplified administration and procedures for separate final settlements of heat pumps energy production and use.
- Implementation of standards for communication on an international level.
- Smart grid hardware and software needs to be developed further, and integrated in the control of the heat pumps and be a requirement for subsidies.

WP5:
The activities and knowledge base from HPCOM were in a longer period continued on the homepage www.hpcom.dk. However, the co-operative "Andelsselskabet Intelligent Energistyring was not continued after the project, as the electricity market at the time of the end of the project (2017) had relatively small variations. In addition to this, the legislation at this time did not create a high enough push for this kind of platform. Instead the heat pump manufactures have to a higher degree developed each of their own smart grid solutions, compared to a more shared platform.

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Project: Flexible Energy Denmark (FED)

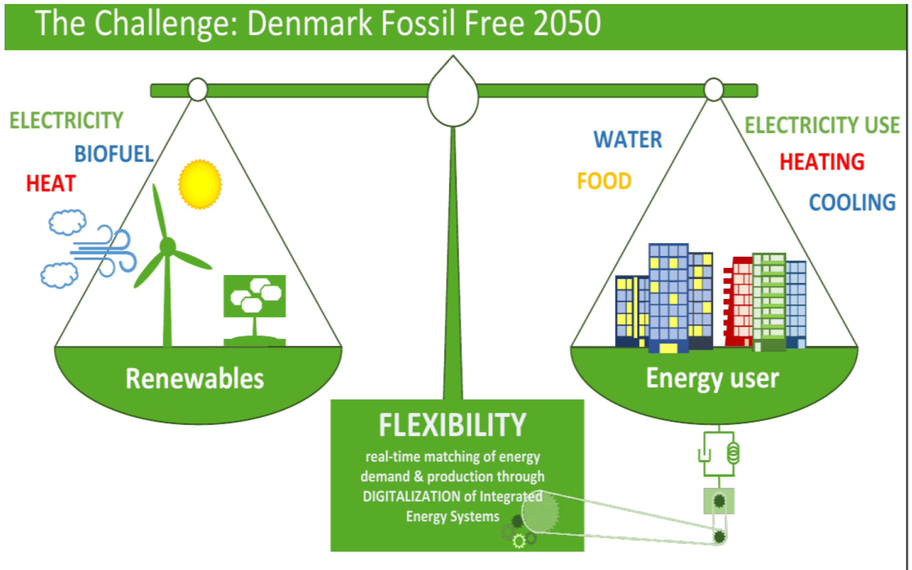

Figure 1: Flexible Energy Denmark establish the tools and solutions for enabling the end-user flexibility for large-scale integration of wind and solar energy.

Summary of project

In the FED project we analyze large amounts of consumer data and consumer behavior. The ambition is to enable the development of digital solutions that are capable of adjusting the power consumption to fit the power production – among other things by use of Machine Learning and different tools for handling Big Data. In FED we develop methods for forecasting of wind and solar power production, as well as methods for an efficient integration of the renewable energy production by a next generation of controllers for heat pumps, supermarket cooling, wastewater treatment, district heating operation, and for using buildings as energy storage solutions in an integrated energy system.

A key focus of the FED project is to deliver a next generation of smart grid solutions, such that the flexibility in integrated energy and water systems can be used for providing grid services.

As a result, Denmark's new national research for green transition, Center Denmark, is also among the partners in the FED project. Their role will be to make the knowledge that the FED project creates available to the entire energy sector in Denmark. This will allow the solutions and results of the project to be applied as widely as possible.

Example: Heat pumps in summer houses with a swimming pool

In 2020 in Denmark, approximately 10 % of the available wind power generation was lost, and in 2021 the fraction of lost green energy production will increase; for the last few months about 16 % of the available wind power was lost.

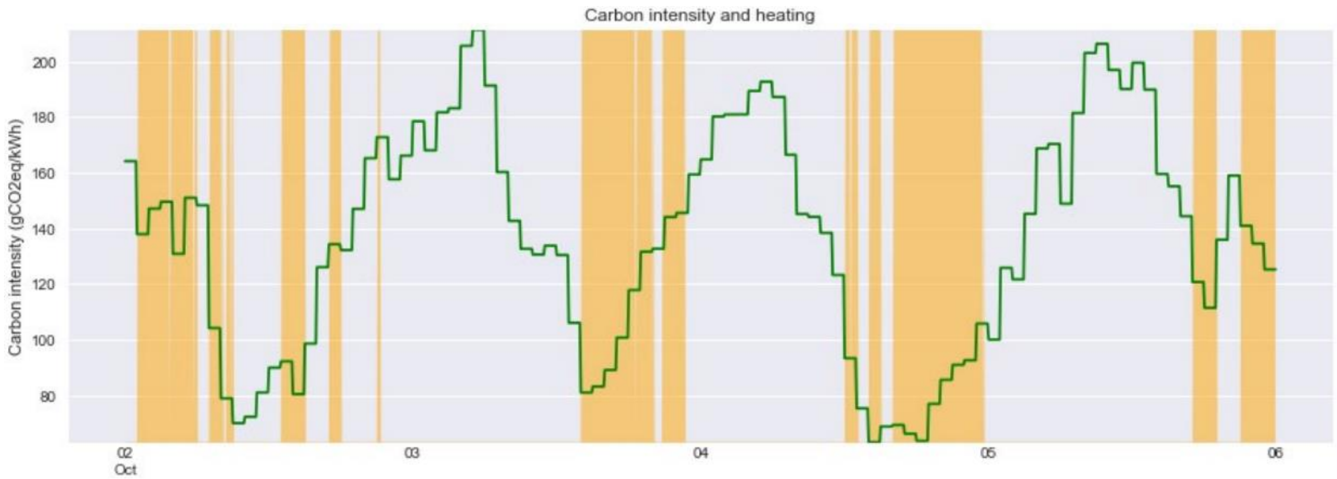

Figure 2: Predicted carbon intensity (green) and periods at which the heat pump is turned on (orange). The installation is located in Denmark.

Summer houses with a swimming pool consume substantial amounts of electricity for the heating and humidity control. In the FED project we are using the flexibility of summer houses to lower the carbon emission and for providing grid services.

The electricity demand from summer houses is particularly flexible. For example, swimming pools have a large thermal mass, thus, the load to heat pool water can be disconnected or shifted with little consequences on the comfort of the occupants. This makes them particularly well-suited to the provision of ancillary services and balancing. Field testing of the proposed setup involves a small but representative number of summer houses. For this living lab in FED it has been decided that 15 houses, located in Blåvand in Denmark, would be enough proof-of-concept.

Using the Smart-Energy OS (SE-OS) the CO_2 - or price-based indirect control provides a setup for storing excess wind and solar power, and at the same time the setup can provide services for the smart grids. Here the Distributed Energy Sources (DERs), i.e., swimming pools, after receiving the control signals, calculate: i) the optimal consumption profile within the forecast horizon, and ii) the set-point for the thermostat of each individual summer house. The control signal is based on the grid load forecasts, electricity price or CO_2 forecasts, weather forecasts from ENFOR (forecast provider), and booking information from NOVASOL (summer house rental company).

The results show that, depending on the actual layout of the summer house, we are able to save 15-30 % CO_2 emission or similar cost savings with the smart control of the heat pump, and at the same time we can provide both balancing and grid services. Please see figure 2 for predicted carbon intensity and periods for heat pump operation.

The energy consumption may at the same time increase with 5 % - but in a low CO_2 emission or cost period.

A similar technology can be used to control heat pumps e.g. in district heating networks. Using forecasts and model predictive control the water is heated when the CO_2 emission or price is low.

The setup is a part of Uni-Lab.dk under Center Denmark, and a living lab under the Flexible Energy Denmark project.

FACTS ABOUT THE PROJECT

IoT catagory: Grid services, optimize heat pump operation, grid services, cloud-based solutions.

Goal: Minimize cost and emission while optimizing the comfort.

Beneficiary: Many options.

Data required: Weather forecasts, CO_2 emission, price and load forecasts.

Analysis method: Cloud based solution using forecasting and model predictive control.

Modelling requirements: Grey-box or data-driven digital twin models are needed.

Quality-of-services: Near real-time.

Project participants: Several network operators and balance responsible parties. Forecasting and control providers.

Time schedule: 2019-2023

Budget: 45 mio. DKK.

Technology availability: TRL 7

Link to webpage:

https://www.flexibleenergydenmark.com/

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Project: RES4BUILD - Renewables for clean energy buildings in a future power system

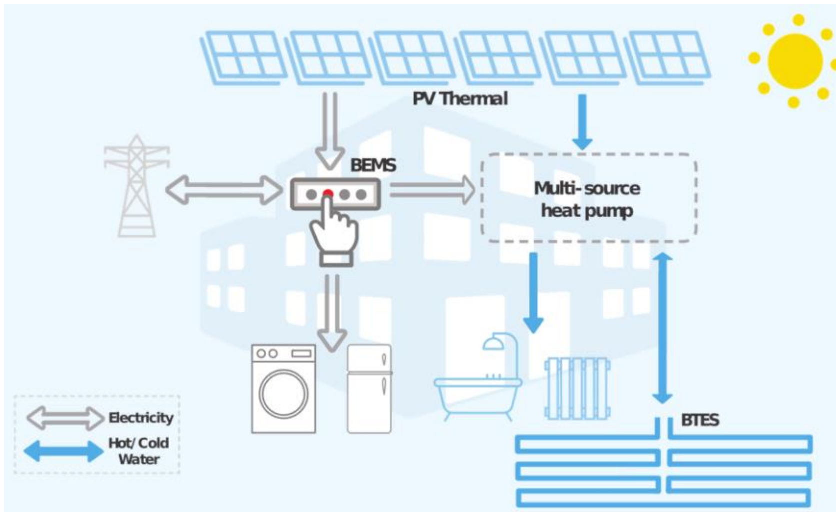

Figure 1: Concept overview for components in the RES4BUILD energy system.

Summary of project

RES4BUILD, a Horizon 2020 project, is developing renewable-energy-based solutions for decarbonizing the energy used in buildings. The approach of the project is flexible, so that the solutions are applicable to a wide variety of buildings, new or renovated, tailored to their size, their type and the climatic zones of their location.

In the heart of the solution lies an innovative multi-source heat pump with a cascading configuration, including a magnetocaloric (bottom cycle) and a vapor compression heat pump (top cycle). The heat pump will be integrated with other technologies in tailor-made solutions that suit the specific needs of each building and its owners/users.

These technologies will be selected on a case-by-case basis from a mix of standard equipment available in the market and from novel components that will be specifically explored within the project.

The novel components include innovative collectors that integrate in one panel photovoltaic cells with solar thermal energy collectors (PV/T), a borehole thermal energy storage (BTES) and a Magnetocaloric heat pump (MCHP). For all solutions, advanced modelling and control approaches will be developed and will be integrated in a Building Energy Management System (BEMS). This will allow the users to select their objectives and to optimize the use of the system accordingly, thus exploiting the full value of their demand flexibility.

The project adopts a co-development approach, where the end-users and other relevant stakeholders are engaged in an interactive and iterative process, resulting in a co-designed RES4BUILD system that meets technical and non-technical user and installer requirements. In parallel, a full life cycle assessment (LCA) and life cycle economics (LCE) analysis will be carried out, showing from an early stage the real impact of each proposed design. The diverse consortium and the dedicated

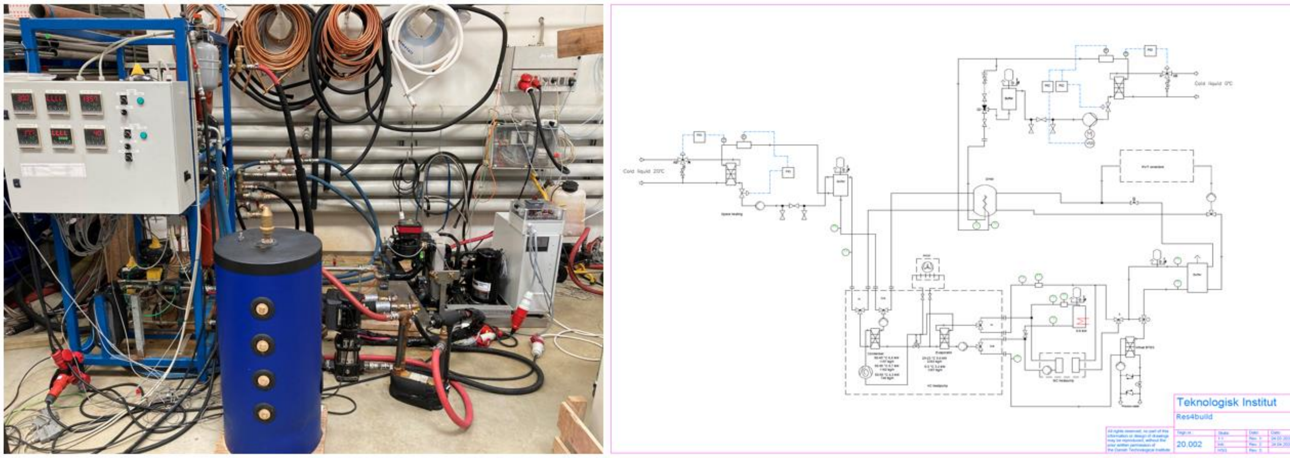

Figure 2: Preliminary test setup with the multi-source heat pump at Danish Technological institute.

exploitation tasks will connect the project with the market, paving the way for wide application of the developed solutions.

Two pilot systems will be constructed focusing on integrated systems where the innovative components of RES4BUILD are combined with the advanced control delivered by Thermovault. The two pilot systems will be developed in Denmark and Greece, respectively at the Danish Technological Institute (DTI) and at National Center for Scientific Research Demokritos (NCSRD).

The two pilot systems have many similarities since the general purpose is to validate the concept in two locations with different building energy needs and climate conditions. A major difference between the two pilot systems will be the heating/cooling demand, since the pilot system at NCSRD will be a real building corresponding to a small office building, while the pilot system at DTI will be installed in the laboratory and therefore the demand will be simulated with the use of a virtual building, modelled in Modelica by the company VITO Energyville. Both pilot systems will be tested over a one-year time frame.

FACTS ABOUT THE PROJECT

IoT Catagory: Optimize heat pump operation
Goal: Decarbonizing energy consumption in buildings by developing integrated renewable energy-based solutions for achieving the EU energy and climate goals.
Beneficiary: Operater and end-user.
Data required: Operating data and weather conditions.
Analysis method Performance analysis of overall pilot systems and validation of the building management system.
Modelling requirements: Dynamic model of the building made in Modelica, and made available as a Functional-Mock-up unit.
Quality-of-Service: Real-time.
Project participants: 15 partners from 8 countries
Time schedule: 2019-2023
Technology availability: Mix of novel and standard equipment.
Link to webpages:
https://res4build.eu/

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Project: Development of fast regulating heat pumps using dynamic models

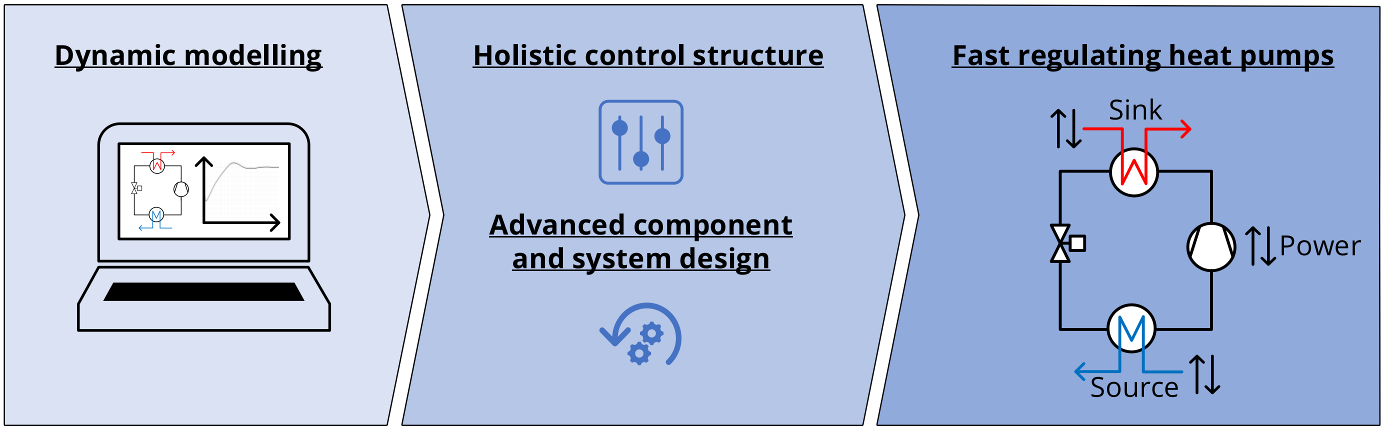

Figure 1: Concept of development of fast regulating heat pumps based on dynamic modelling.

Summary of project

The project develops software tools that enhance the flexibility of large-scale heat pumps operating in integrated systems with varying operating conditions. This is approached by the development of a holistic control structure and a design procedure that is considering dynamic aspects, yielding higher overall performances and lower operating cost. Hence, digitalization is included and used actively in the development of heat pumps system.

In order to use large-scale heat pump systems most effectively and exploit their potential with regards to sector coupling, a sophisticated integration into the given boundary conditions is paramount. The increasingly flexible integration of large-scale heat pumps does, however, imply certain challenges for the equipment, as short reaction times are required.

This project provides an advantage when designing and operating heat pumps, which are to be integrated in the energy system. The platform for modeling the transient operation enables Johnson Controls to create a digital representation of their systems to perform troubleshooting for site and plant specific interactions.

Furthermore, the dynamic modelling platform will provide the basis for integrating digital modelling approaches more thoroughly in the design process of Johnson Controls heat pumps, which is expected to imply significant advantages compared to the conventional design procedures.

Johnson Controls is the overall project manager and leads the application and demonstration activities. Danish Technological Institute leads the development, implementation and validation of component and system models, which will serve as the basis for the development of advanced design procedures and a holistic control structure, which is led by the Technical University of Denmark (DTU Construct, Section of Thermal Energy).

Figure 2: Johnson Controls Heat pumps with UniSAB III controller.

Learnings and results

Dynamic models of various heat pump systems are developed in Dymola (Modelica) and visualized in DaVE, where the results are compared and validated with operating data from a reference plant, see Figure 3.

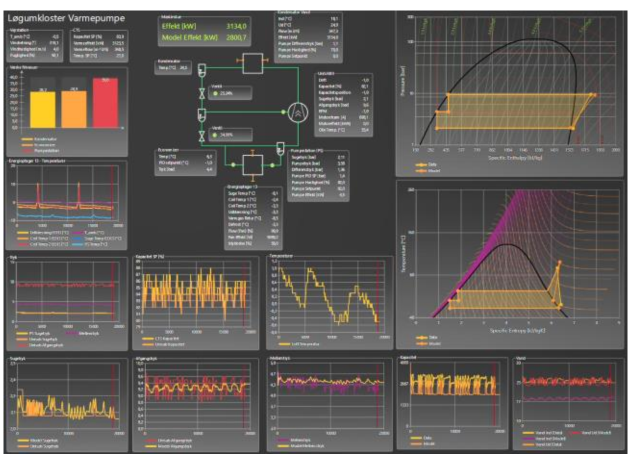

Figure 3: Initial comparison of operating data and simulation data.

One of next steps in the project is to simulate various scenarios during fast changing operating conditions, e.g., a sudden change in temperature on the sink side of the heat pump, where different control strategies then will be tested for accommodating this.

Demonstration of the developed control strategies is planned for the reference plant in the final phase of the project.

FACTS ABOUT THE PROJECT

IoT Catagory: Optimize heat pump operation and installation error analysis
Goal: Support development of large-scale heat pump systems for faster response time and hence e.g. exploit their potential with regards to sector coupling
Beneficiary: Manufacturer and operator
Data required: Operating data and datasheets for heat pumps components
Analysis method Visualization and analysis of modelling results for heat pump operation during dynamic changing operating conditions. Simulation model first requires validation based on real time operating data
Modelling requirements: Dynamic model made in Dymola (Modelica) using the TIL library from TLK as starting point. Models includes data-driven submodels.
Quality-of-Service: Real-time
Project participants: Johnson Controls, DTU Construct, Section of Thermal Energy, and Danish Technological Institute
Time schedule: 2020-2023
Technology availability: TRL 6-7
Link to webpages:
https://www.johnsoncontrols.com/en_sg/industrial-refrigeration/chillers-and-heat-pumps
https://www.dti.dk/dynamic-modelling/42634
https://construct.dtu.dk/Sections/thermal-energy

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CEDAR

Cost Efficient heat pumps using DigitAl twins and Reinforcement learning

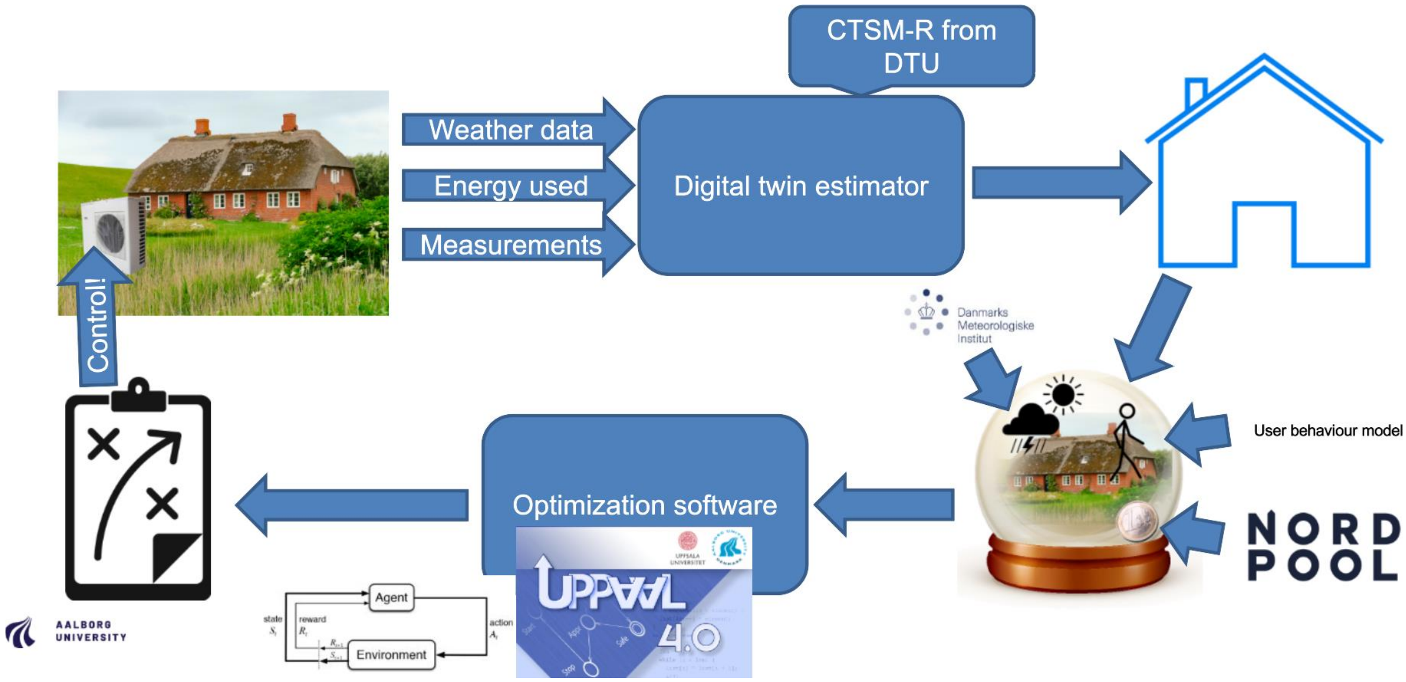

Figure 1: General flow of the approach studied in the CEDAR project.

Summary of project

The CEDAR project studies and develops next-generation technology for optimal control of heat-pump systems. In particular the project aims to construct a “install-and-forget” type of system for retrofitting in residential scale heat-pump systems.

The simplified flow of the envisioned solution is depicted in Figure 1. Given a single-family home, (1) observe the circumstances of the house (weather, energy consumption and internal temperature and humidity changes). Then (2) utilize the monitored data to construct a digital twin which is (3) decorated with auxiliary data-sources of the future context (weather forecast, future energy pricing, user behavior, ...) to create a high-fidelity predictive digital twin. State-of-the-art stochastic optimization techniques (4) is then used to generate a strategy (5) for the future control of the heat pump. This process is then repeated over and over ad infinitum.

Internally the two core processes, namely the digital twin estimation and the stochastic optimization, relies on state-of-the-art techniques developed at the Technical University of Denmark (CTSM-R) and Aalborg University (Uppaal Stratego), respectively.

The novelty and strength of the approach lies in avoiding approximations and simplifications of the building dynamics to fit a specific Model Predictive Control (MPC) Framework. Instead the CTSM-R tool is utilized to estimate high-quality higher order thermodynamic models of a given building from the observed data – a model which also includes measures of disturbance from e.g. solar radiation. Importantly, such building models can be extracted with little or no knowledge of the physical building layout.

Conventional MPC frameworks require that such a model is abstracted or simplified into e.g. a linear model such that classical optimization techniques (Linear Programming) can be used. Instead, Uppaal Stratego provides a toolsuite for optimizing control of switched-control non-linear, stochastic differential equation systems.

In particular, Uppaal Stratego utilizes a novel partition-refinement extension of classical reinforcement learning algorithms to provide near-optimal controller synthesis. The synthesis process itself is flexible with respect to the optimization criterion. This implies that the trade-off between cost and comfort can be adjusted freely according to any user specified function. In turn this opens for introducing pump-control flexibility such as temperature set-backs and target-bands which the optimization procedure can exploit towards an even higher savings by e.g. lowering the temperature at night.

A similar benefit of applying Uppaal Stratego is the ease at which peripherals such as accumulation tanks and photovoltaic power generation can be included as factors into the optimization problem; e.g. local power generation can be utilized when economically profitable, depending on the future energy demand of the house. As such, this project is in part envisioned as a stepping stone towards a holistic domestic energy optimizer for modern “prosuming” residential buildings.

In practical terms, the project is realized using off-the-shelve IoT sensor networks and edge-computing. We envision utilizing the inexpensive ZigBee family of devices for sensing and relying on low-powered mini-computers for the optimization and identification procedures. This facilitates a near offline application, ensuring robustness and stability.

Learnings and results

Preliminary studies using virtual house models demonstrate an up-to 30 %-40 % cost savings using the proposed method compared to a naive controller. Introducing user-specified flexibility (e.g. set-backs and target bands) an additional 11 %-point reduction has been demonstrated.

The CEDAR project aims to continue this work by (1) validating the laboratory results, (2) maturing the technological platform from research grade to consumer grade, and (3) further improve the technology of the digital twin estimation and the stochastic optimization procedure to ensure a robust and optimal control of heat pump units.

FACTS ABOUT THE PROJECT

IoT Category: Optimize heat pump operation
Goal: A self adapting and self optimizing cost efficient heat pump control. In particular facilitate that the heat pump control adapts to changes in the thermodynamics and changes in user behaviour.
Beneficiary: User, heat pump producers, Society
Data required: Weather forecast, day-ahead energy prices, sensors of the heat pump, temperature, and humidity sensors of the house.
Analysis method: Model generation via Continuous Time Stochastic Modelling and optimization via reinforcement learning on Euclidean Markov Decision Processes.
Modelling requirements: Fully data driven.
Quality-of-Service: Near real-time (minutes).
Time schedule: 2023-2024
Technology availability: TRL4 at project start.

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Appendix B

Topical article – HPT Magazine

Opening the black-box: A case study of a borehole thermal storage

Opening the black-box: A case study of a borehole thermal storage

Tobias Dokkedal Elmøe, Denmark

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 perform analysis on historically logged data. Here we present a case study where a combination of this tool and energy-meters are used on an existing plant to de-convolute the system COP and the negative energy balance of a borehole thermal storage (BTES), which may predict, and prevent potential long-scale temperature drops inside the BTES.

Energy Machines (EM) is a leader in the design, implementation and operation of integrated energy systems for buildings. EM uses standardized component designs, which not only reduce complexity for control systems but, more importantly, ensure quality and functionality as the designs consist of reusable and scalable modules. Through simulation platforms, EM is developing digital solutions for heat pump systems. Hence, EM has a key focus on the digitalization of heat pumps and is, in relation to that, also a part of the Danish working group in the HPT Annex 56 on "Digitalization and IoT for Heat Pumps".

Ground source heat pumps, which take advantage of borehole thermal storages (BTES), are some of the most flexible heat pumps which provide high energy efficiency [1]. When designing a new BTES, care must be taken to avoid the dropping of temperatures below freezing. The lifetime of the underground storage is typically designed for 25 years. In practice, this is controlled on-site by dumping excess building heat in free-cooling mode during spring/early summer and excess heat from the hot side into the borehole in warm summer months during active cooling. Thermal energy-meters can be placed around the site to estimate the power going into the boreholes, but they are expensive and in most applications, the energy meters are therefore limited to only measuring the building interface (heating/cooling side).

Here, we present a case study of an Energy Machines (EM) installation located in Sweden, where we wish to investigate the total heating/cooling production from the installation, as well as examine the imbalance between heat storage and heat recovery from the BTES connected to this site. We do this by applying the Energy Machines Verification tool (EMV), in combination with the preexisting energymeters, to open up the "black-box" of the energy flows of the heating/cooling system. EMV relies on multiple, simultaneous measurements of the refrigerant pressure and temperature, as well as a knowledge of the thermodynamic properties of that refrigerant, as illustrated in Figure 1. EMV comes as an optional "out-of-the-box" with all EM installations since the machines already have all the necessary sensors equipped. It functions primarily as an automated real-time cloud service but can also be invoked to analyze historical data and give inputs to energy engineers, building property managers, or others who might have an interest in the performance of their heating/cooling system.

The purpose of this study was to gain more insight into the performance of the EM installation, in particular with a focus on the total heat and cooling production vs the measured heating and cooling from the energy-meters, and the imbalance imposed on the borehole storage. This insight can improve the control of the system to prevent long-term freezing of the boreholes, as well as help, understand the actual system COP.

Case study

The system examined in this case study consists of three heat pumps (HP1, HP2, and HP3), two of which are in parallel, and one which has its heat source connected to the outlet of the two parallel ones. A very basic sketch can be seen in Figure 2. Currently, at the plant, thermal energy-meters are placed at the inlet, measuring $Q_{i,\ building}$, as well as $Q_{o,\ building}$. There are also electrical energy meters measuring the electrical power used for each of the three compressor pairs ($Q_{c,1}$, $Q_{c,2}$, $Q_{c,3}$) (two circuits with two compressors/circuit each per heat pump). With EMV, we can estimate the power to the evaporator and the power released in the condensers. Because of the configuration of the system, only $Q_{i,1}$ and $Q_{i,2}$ need to be determined from EMV, as the input source to heat pump 3 is part of the output from heat pumps 1 and 2.

The EMV algorithm requires input measurements of pressure and temperature throughout the heating cycle,

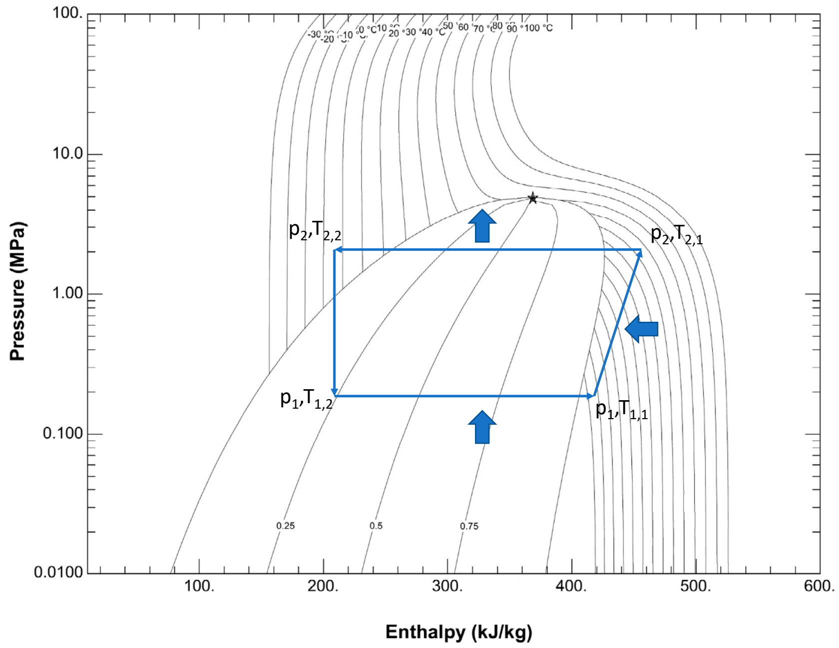

Figure 1. p-h diagram for R410A, showing the thermodynamic cycle of the heat pump, indicating the necessary measurements of the temperatures/pressures for EMV. Energy Machines heat pumps have all relevant sensors installed per default, so the EMV option can be enabled without additional installations required.

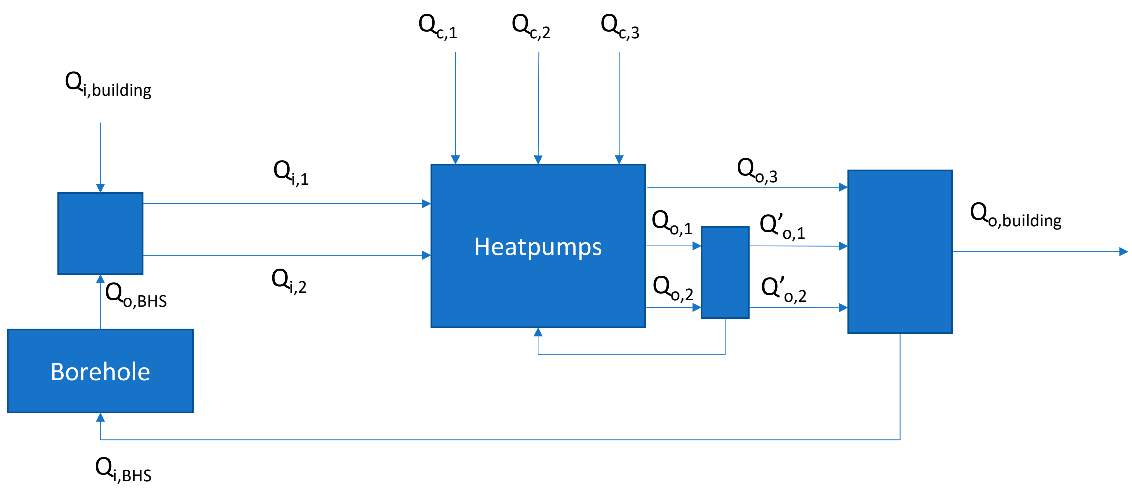

Figure 2. Sketch showing the heat flows in the system. Energymeters monitor the building energy flows ($Q_{i,\ building}$/ $Q_{o,\ building}$), while electricity meters measure the compressor powers ($Q_{c,1}$ to $Q_{c,3}$), and EMV is used to calculate the heat source $Q_{i,1}$ and $Q_{i,2}$. Some output energy from HP1 and HP2 is recycled as input to HP3. Energy balances can then be used to determine $Q_{o,\ BHS}$ and $Q_{i,\ BHS}$, the outlet and inlet from the borehole storage, respectively.

which are logged with 1-minute resolution and are available using our energymachines.cloud platform, which logs and monitors all EnergyMachines installations. Figure 3 shows the energy flows in terms of heating and cooling in the system, as an example of the output data from EMV. Many more outputs can be derived, such as COP, refrigerant flow and compressor efficiency, which given the right data analysis, may help diagnose/predict potential performance issues.

A summary of the COP, heating- and cooling energies can be seen in table 1, which is estimated by EMV, and

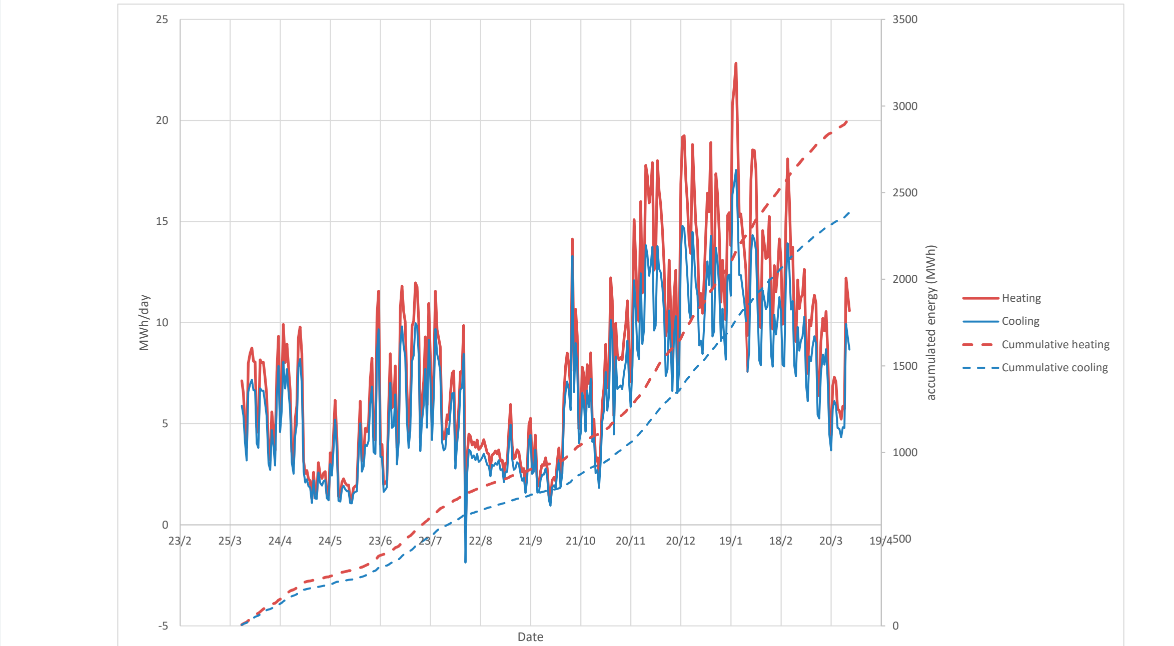

Figure 3. Heat (bold solid, red lines) and cooling (solid, blue lines) energy delivered per day (in MWh, left axis), as well as the accumulated energy (from start, broken lines right axis).

Table 1. Accumulated values for the case studied system calculated by EMV using temperature/pressure sensors located around the heat pump refrigerant circuit(s).

Heating energy delivered at condensers +subcoolers [MWh]	Cooling energy delivered at evaporators [MWh]	COP heating	COP cooling
2928	2385	5.01	4.09

COP was calculated from the total compressor energy used, which was measured by electrical meters to be 584 MWh.

Table 2. Accumulated values for the case studied system calculated energy meters located at the building interface (heating/cooling).

Measured heating energy delivered to building	Measured cooling energy delivered from building	COP heating	COP cooling / COP cooling energy balance
1815	699	3.10	1.20 / 2.10

COP was calculated from the total compressor energy used, which was measured by electrical meters to be 584 MWh. The energy balance is not fulfilled using energy meters alone because the borehole contributes significantly to the cooling energy delivered to the evaporators. COP cooling, therefore, has to be corrected for this (1.20 vs 2.10).

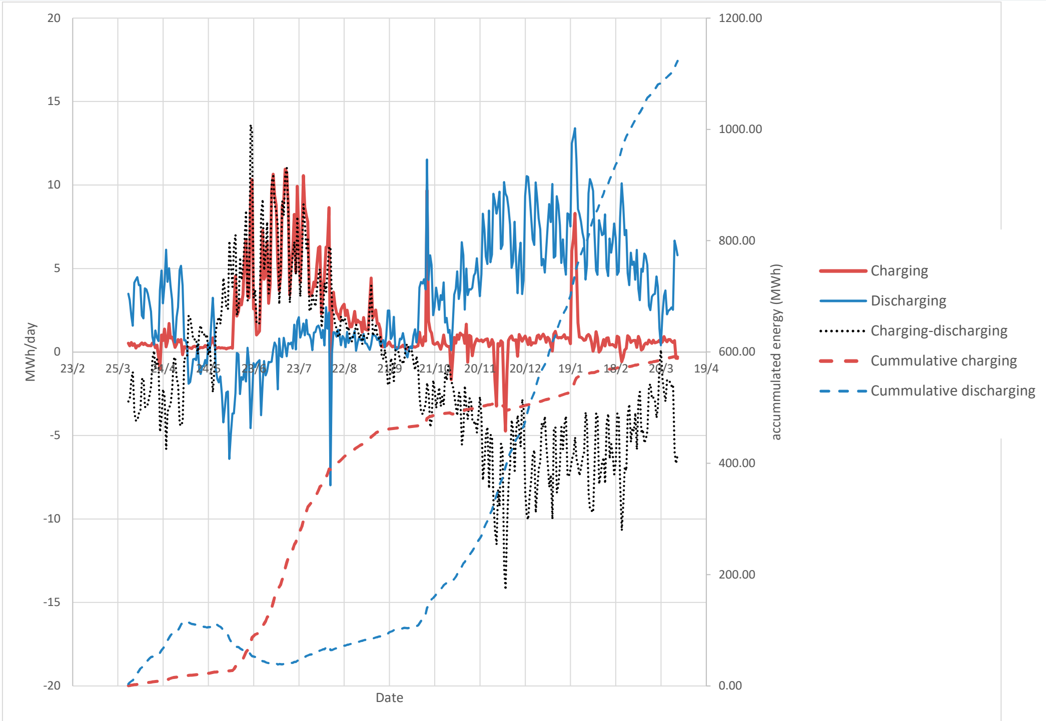

Figure 4. Borehole charging per day (left axis) from hot side (bold solid red line), discharging on the cold side (solid blue line) and the difference between the two (dotted black line) over a year of operation. In late spring, discharging is negative because of free-cooling, dumping energy back into the borehole from the cold side. During summer, charging is positive because of the active cooling demand of the building, which is when the heat pumps are mainly switched off. During autumn and winter, the borehole is discharged. Overall, the heat balance is negative, with higher discharging than charging (broken lines, right axis), not accounting for the self-charge .from the rock surrounding the borehole).

similarly in table 2 using energy-meters only. A clear distinction can be seen. First of all, the energy estimated by energy-meters is much lower, and this obviously leads to a much smaller COP. This is particularly more clear for the cooling side since the difference between cooling energy determined by EMV and energy meters is much greater. The reason for this difference is the borehole storage, as well as the fact that some output energy from HP1 and HP2 is used as input energy for HP3 (cf. Figure 2). The result illustrates the difficulty in reporting a system COP, mainly because of the borehole storage but also because of heat recycling inside the system.

To gain further insight, we will combine the EMV results with the energy-meters (thermal+electrical) and use energy-balances that can be set up from Figure 2, which are shown in eq. 1 and 2. Figure 4 shows the borehole storage charging/discharging calculated by EMV, energy-meters, and eqs. 1-2. The figure reveals how the borehole is charged by free-cooling from the cold side in early spring, then via active-cooling from the hot side during the summer, before being discharged in autumn and winter to increase system performance by increasing the evaporator temperature. Overall, the energy-balance is negative, leading to a decrease over time in borehole temperature. Nevertheless, the borehole will also "re-charge" through the surrounding rock, which requires more detailed analysis using so-called "g-functions" [2]. This analysis was not done in this study.

Conclusions

The Energy Machine Verification tool (EMV), which comes as an optional part of any Energy Machines installation, offers energy engineers, building property managers, or anyone with interest in the performance of their integrated energy system, a way to analyze results and gain insights into the "black box" of the energy system. In the case study above, the focus was on determining the system COP from the heat pumps, as well as investigating the energy flows to and from the borehole over a season of operation. Such knowledge can help the operators improve the operation and control of the integrated energy system to prevent potential future borehole freezing, as well as give them information on the current and seasonal performance of that system.

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