IEA Heat Pumping Technologies - IoT Annex 56

Digitalization and IoT for Heat Pumps
Country Summary for Denmark

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Prepared by:

Jonas L. Poulsen, Danish Technological Institute, Energy and Climate, jlp@teknologisk.dk
José Joaquín Aguilera, Department of Civil and Mechanical Engineering, DTU, jojap@dtu.dk
Henrik Madsen, Department of Applied Mathematics and Computer Science (DTU Compute), hmad@dtu.dk
Wiebke B. Markussen, Danish Technological Institute, Energy and Climate, wbm@teknologisk.dk

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.

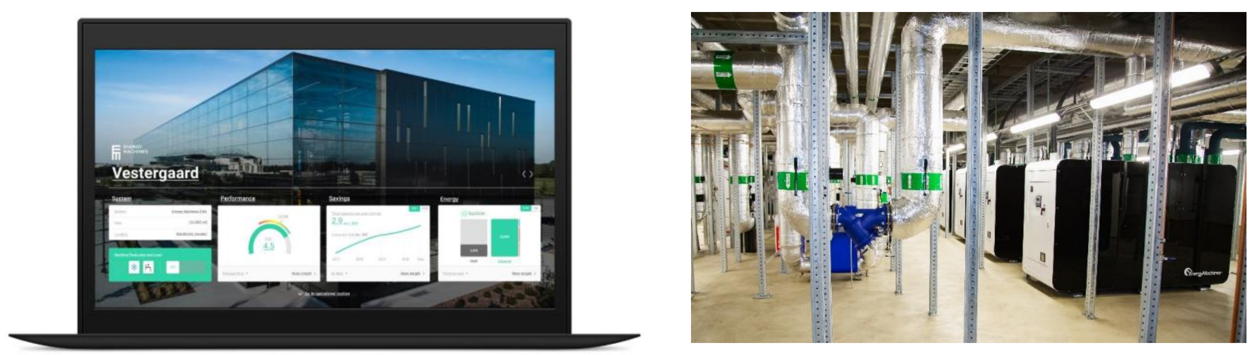

Figure 1. EMV dashboard with quick overview of current performance (left) and an Energy Machines heat pump installation with sensors placed inside the boxes (right).

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.

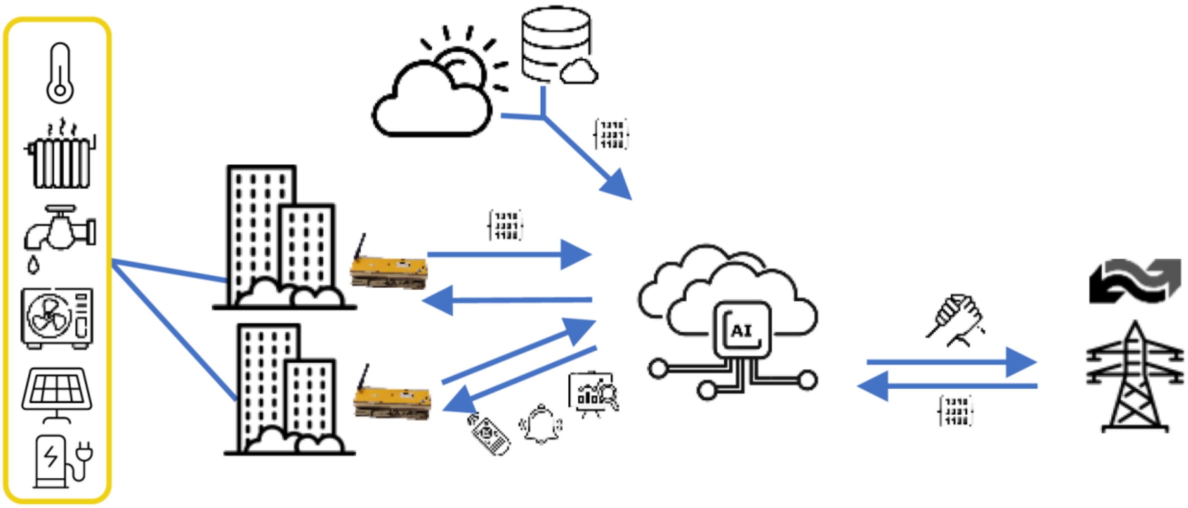

Figure 2. Neogrid PreHEAT Cloud.

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.

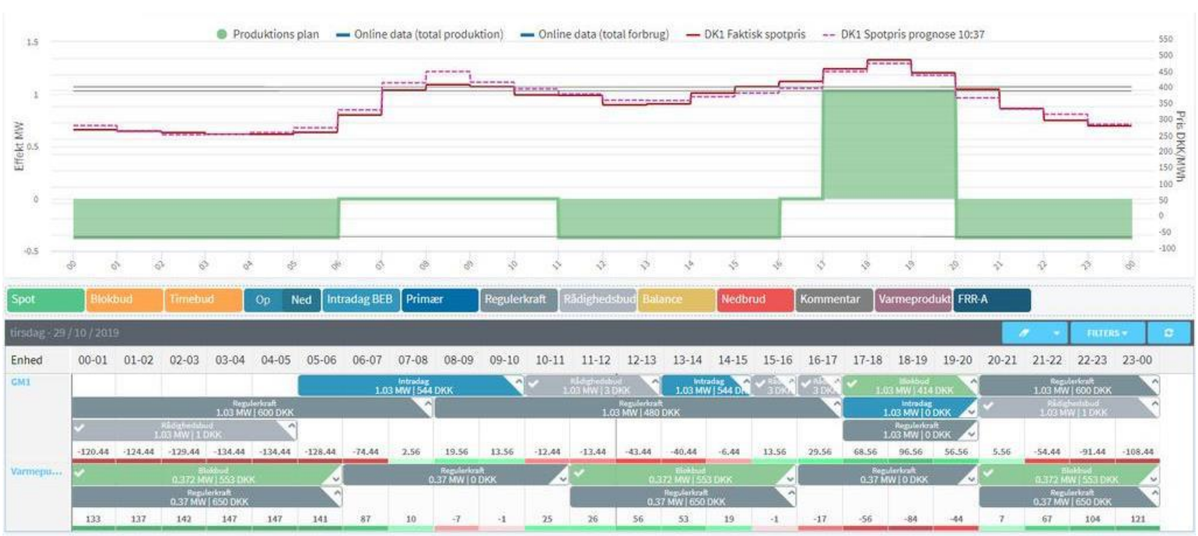

Figure 4. Interface of the energy planning and optimization platform developed by Centrica Energy Trading.

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.

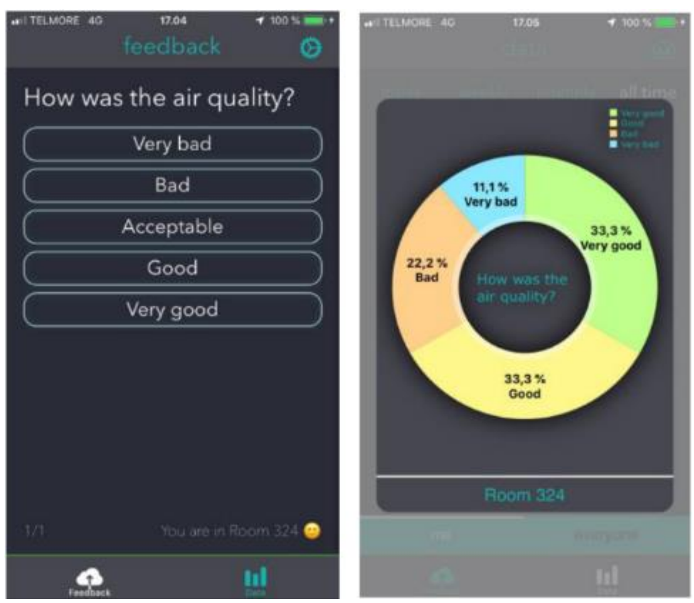

Figure 5. User feedback over Climify phone App.

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.

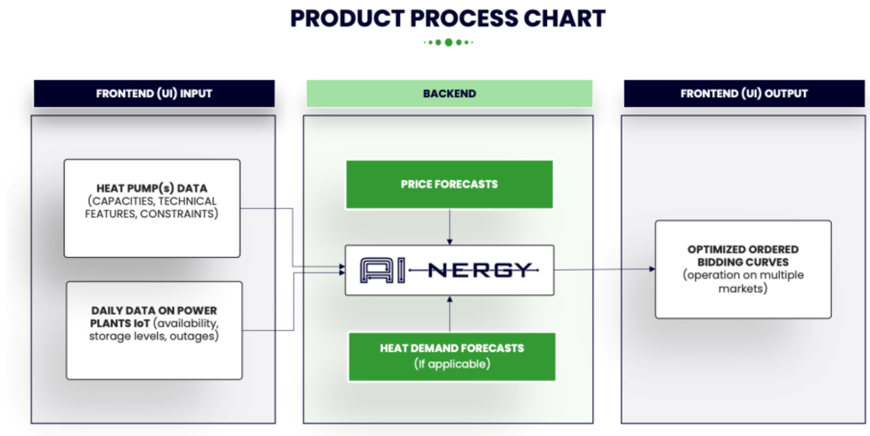

Figure 7. Scheme of the heat pump bidding product from AI-energy.

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

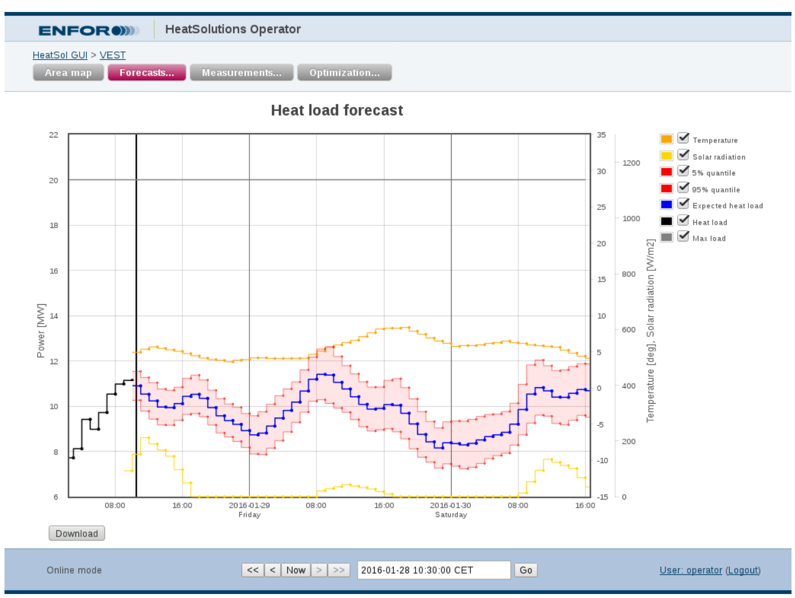

Figure 8. Example of forecast for heat load, temperature, and solar radiation.

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.

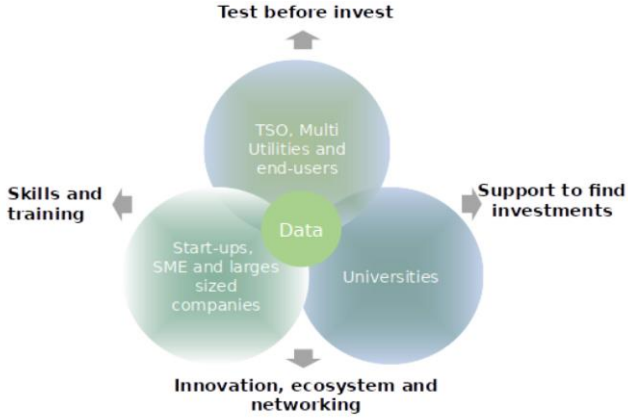

Figure 9. Data is at the core of the development, innovation and business thinking at Center Denmark.

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.

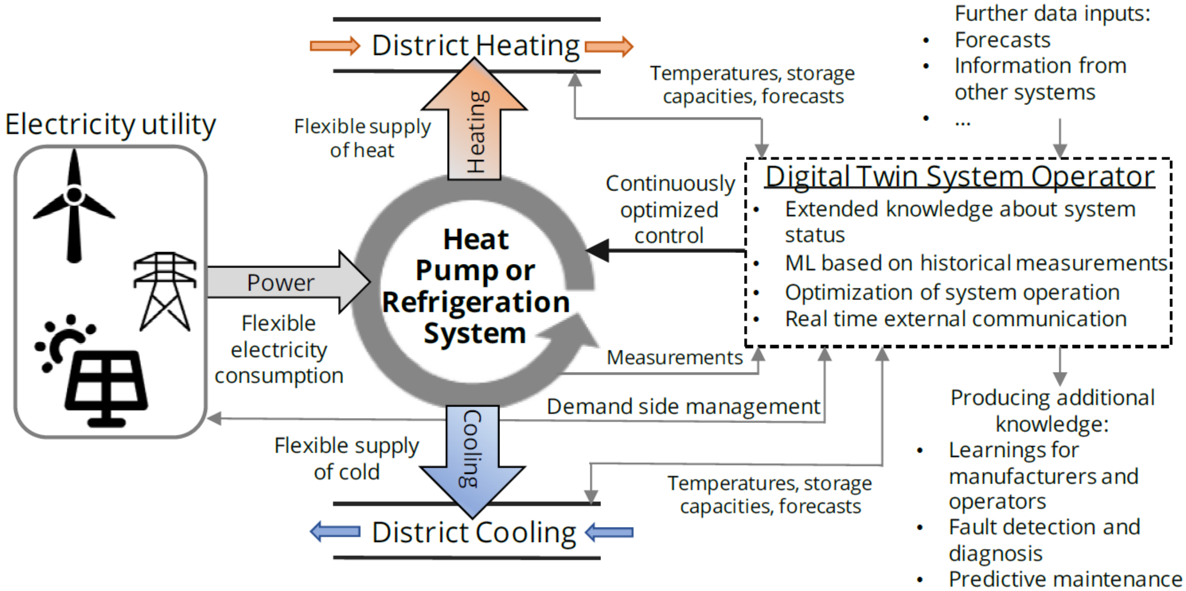

Figure 12. Diagram of the digital twin system operator.

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.

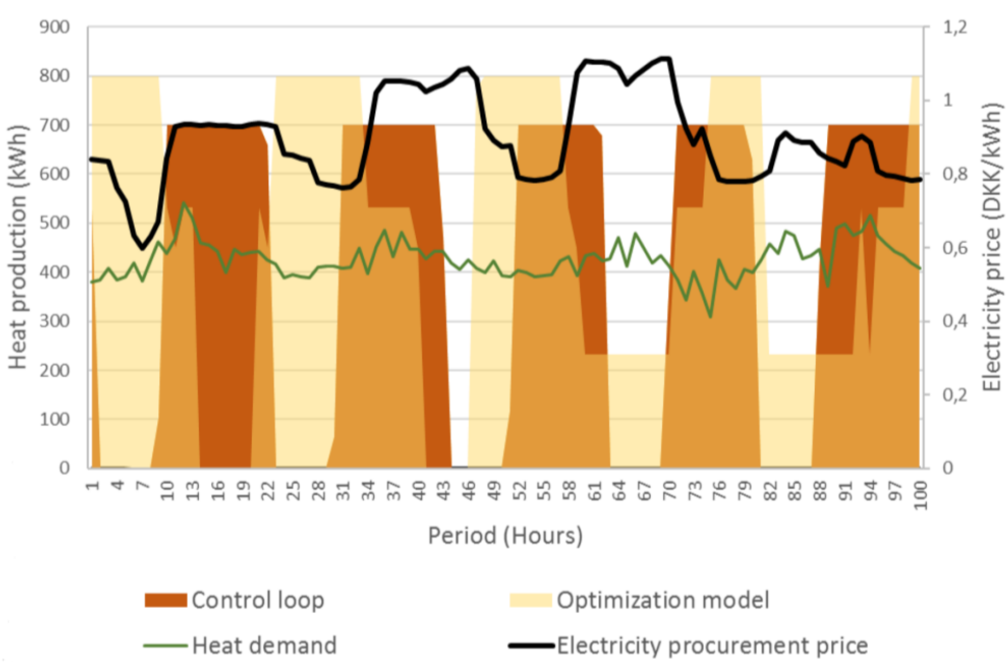

Figure 14. Flexible heat production during 100 hours period. "Control loop" with dark orange columns: Periods with heat production primarily from heat storage, and "Optimization model" with bright orange: Cost optimized heat production from heat pump (800 kW max. production). "Heat demand" is the heat 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.

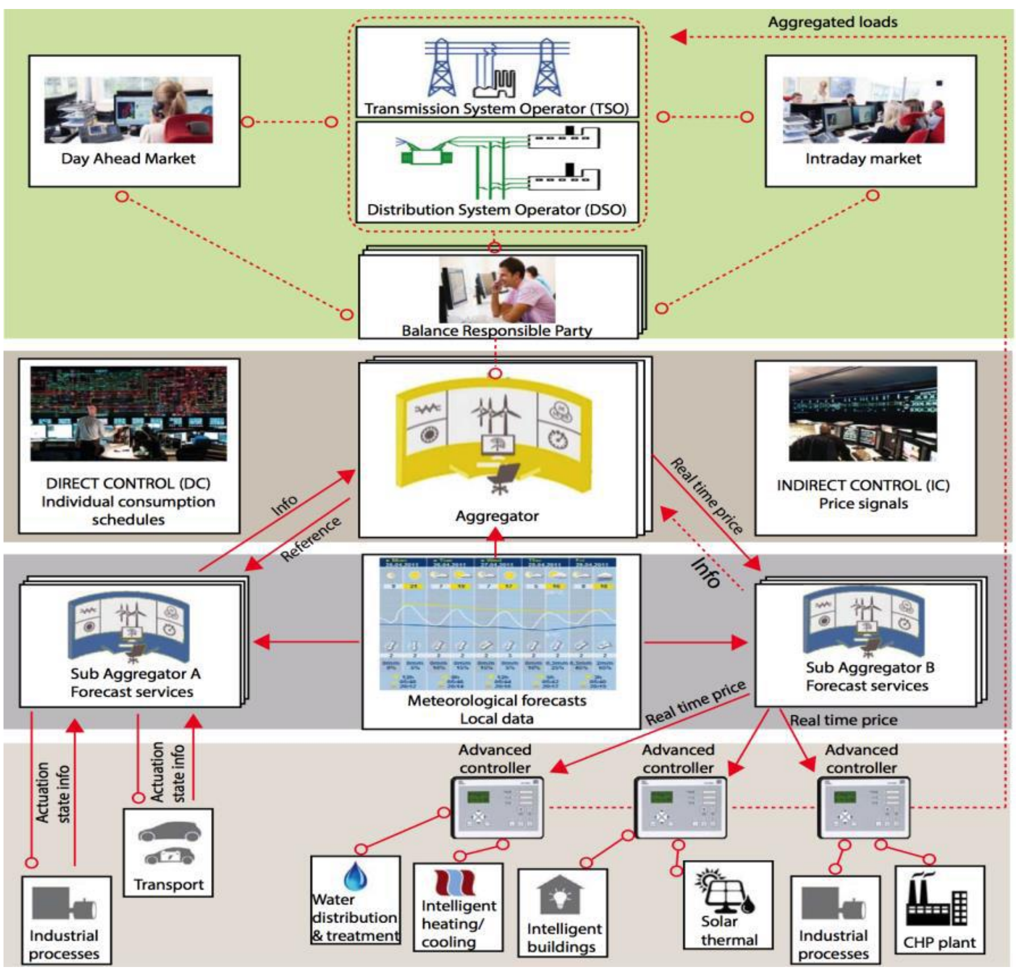

Figure 15. The Smart-Energy Operating-System (SE-OS) for digitalization of integrated energy systems.

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.

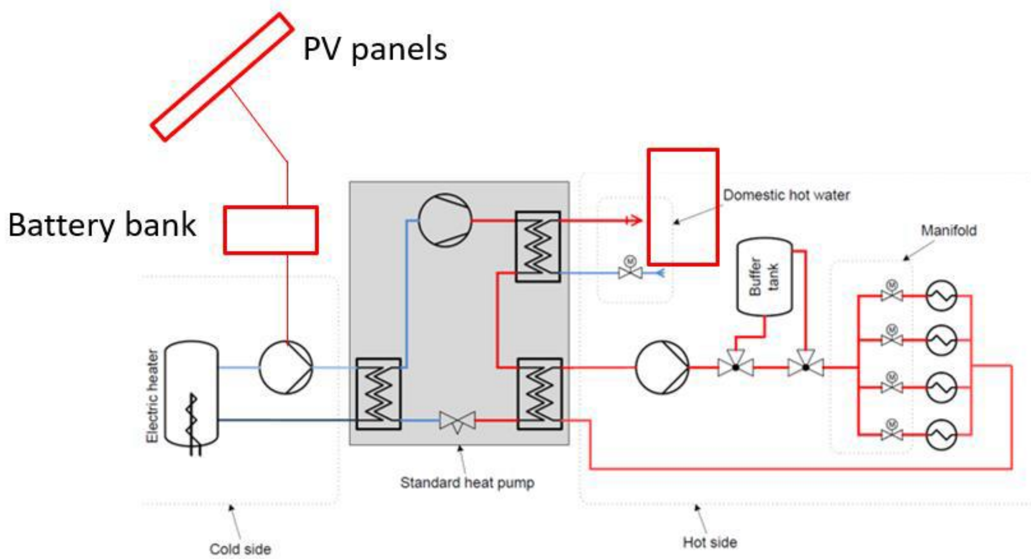

Figure 16. Principle sketch of experimental setup (on the test rig PV and battery are virtual).

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.

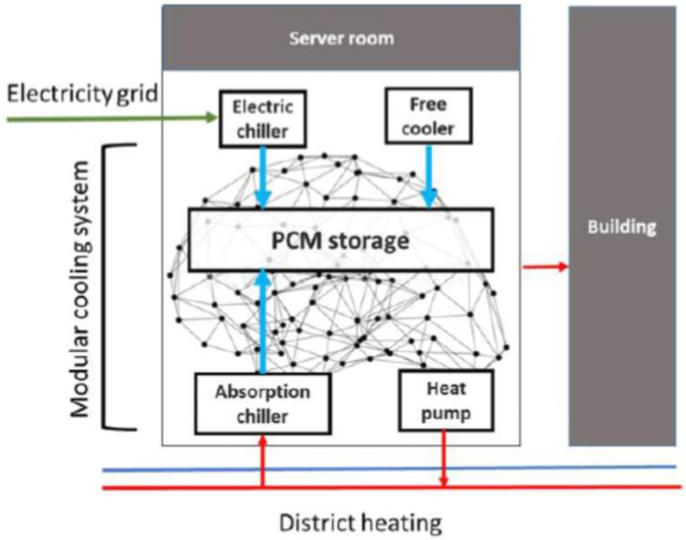

Figure 17. Overview of Cool-Data application.

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.

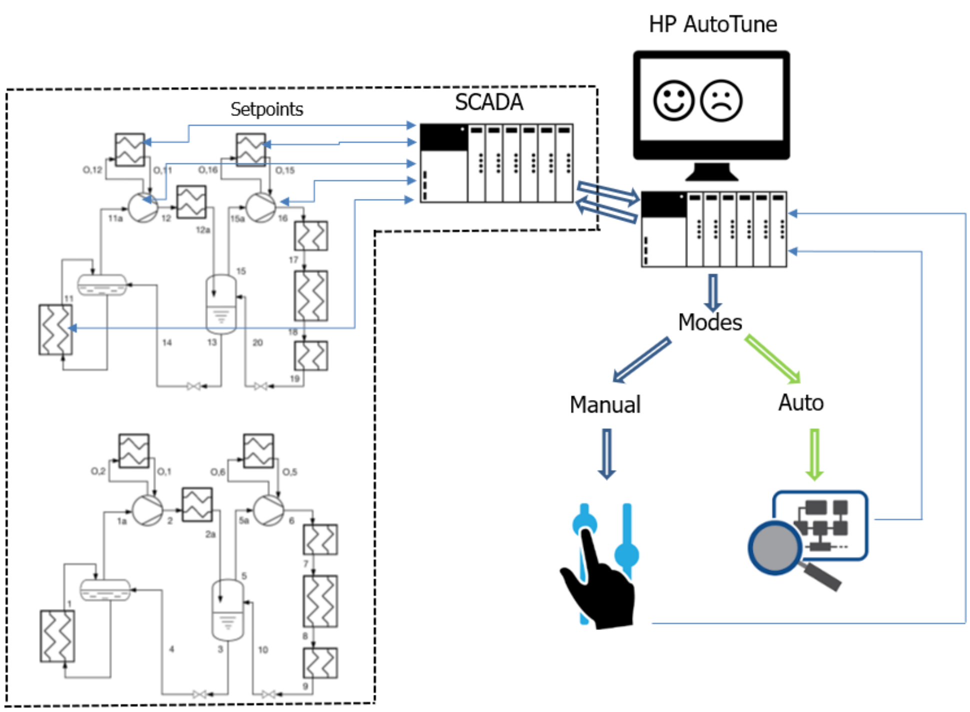

Figure 18. Concept for HP AutoTune.

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.

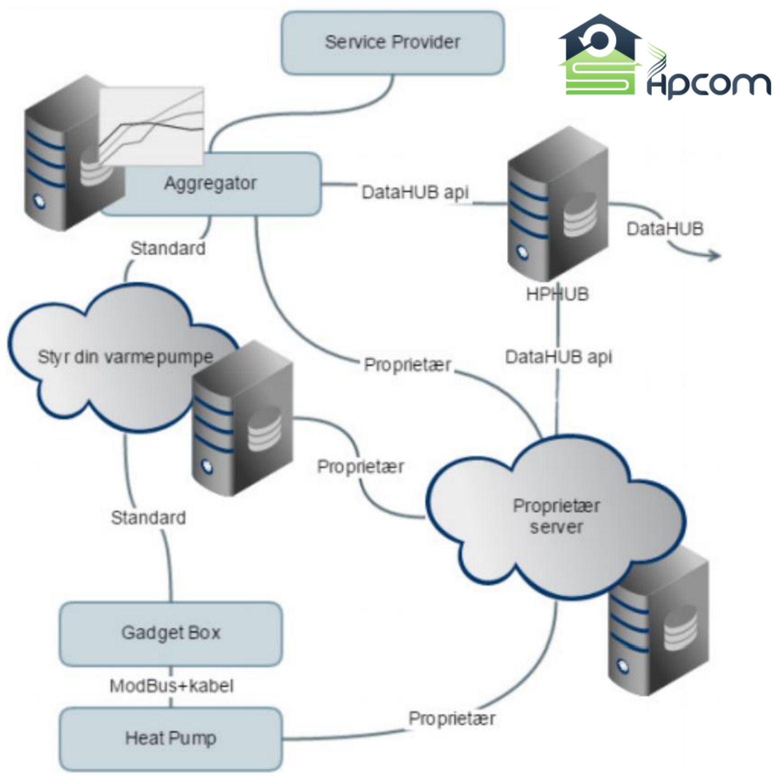

Figure 19. Principle for heat pump datahub (high level) developed in the HPCOM project.

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.

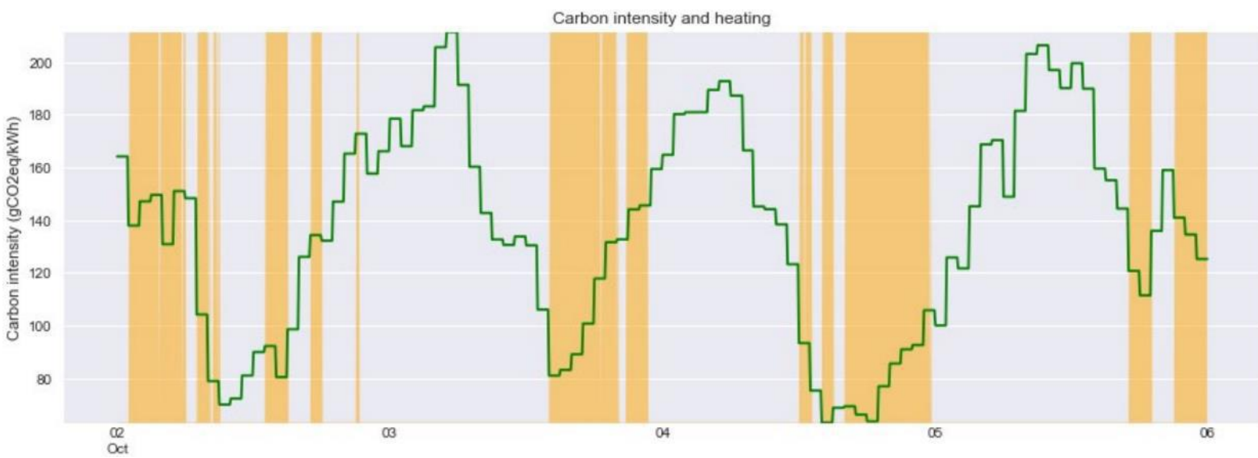

Figure 20. Predicted carbon intensity (green) and periods at which the heat pump is turned on (orange).

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.

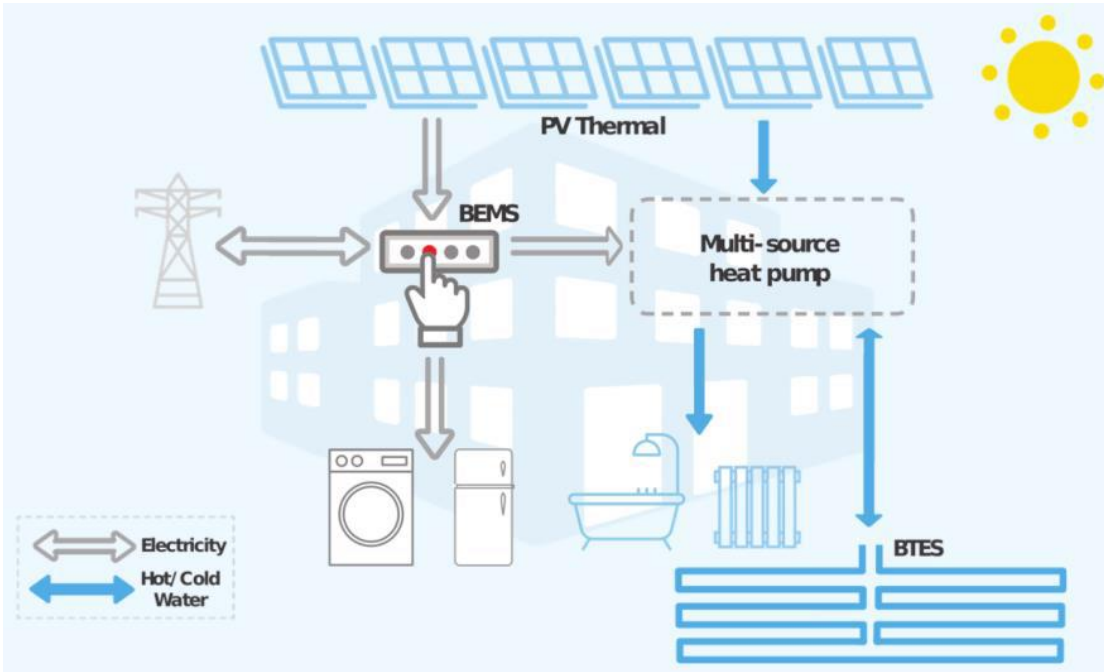

Figure 21. Concept overview for components in the RES4BUILD energy system.

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.

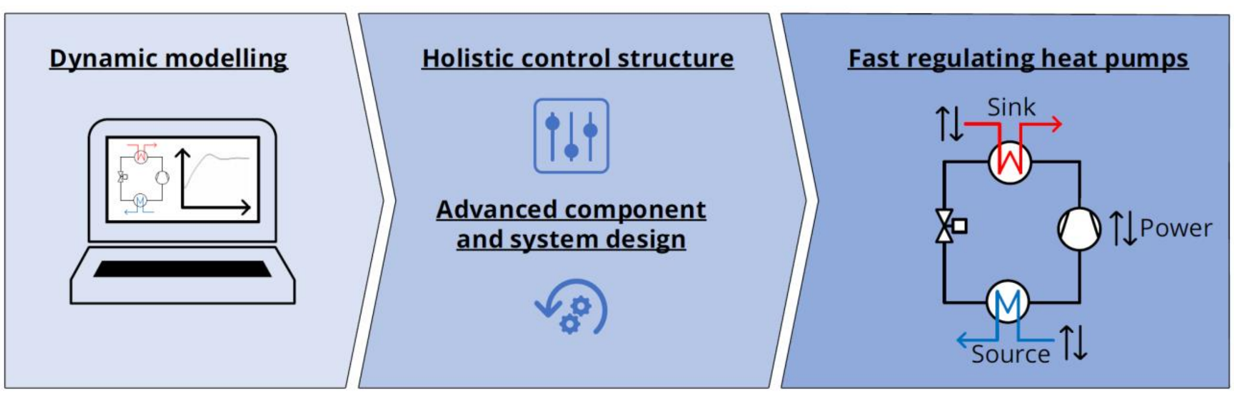

Figure 22. Concept of development of fast regulating heat pumps based on dynamic modelling.

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.

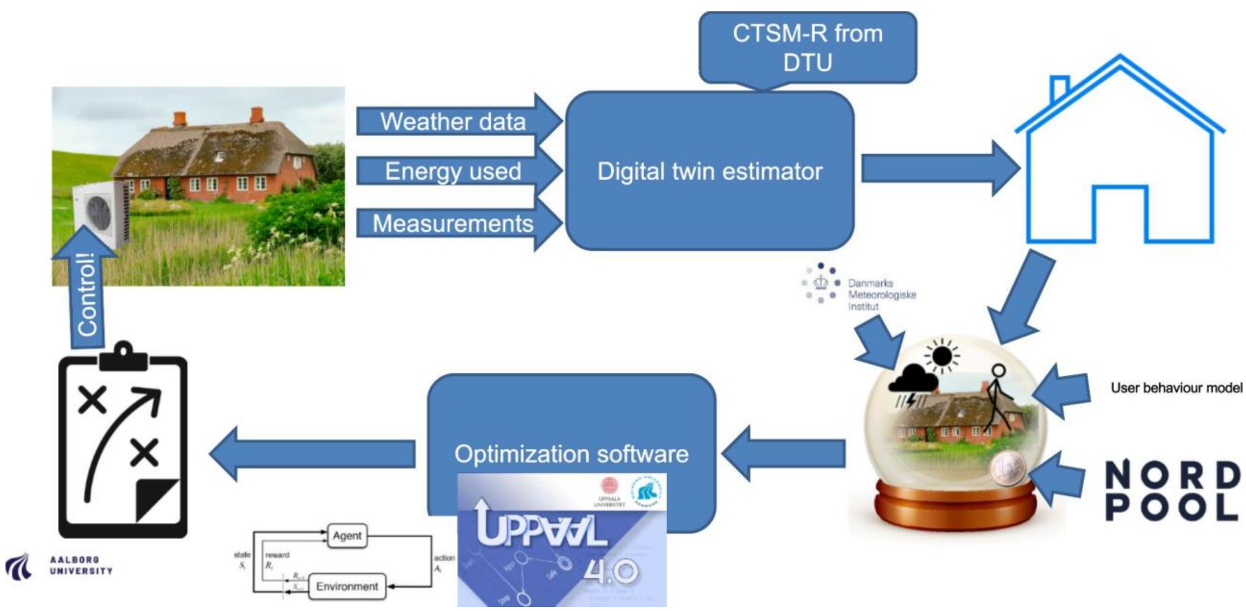

Figure 23. General flow of the approach studied in the CEDAR project.

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.

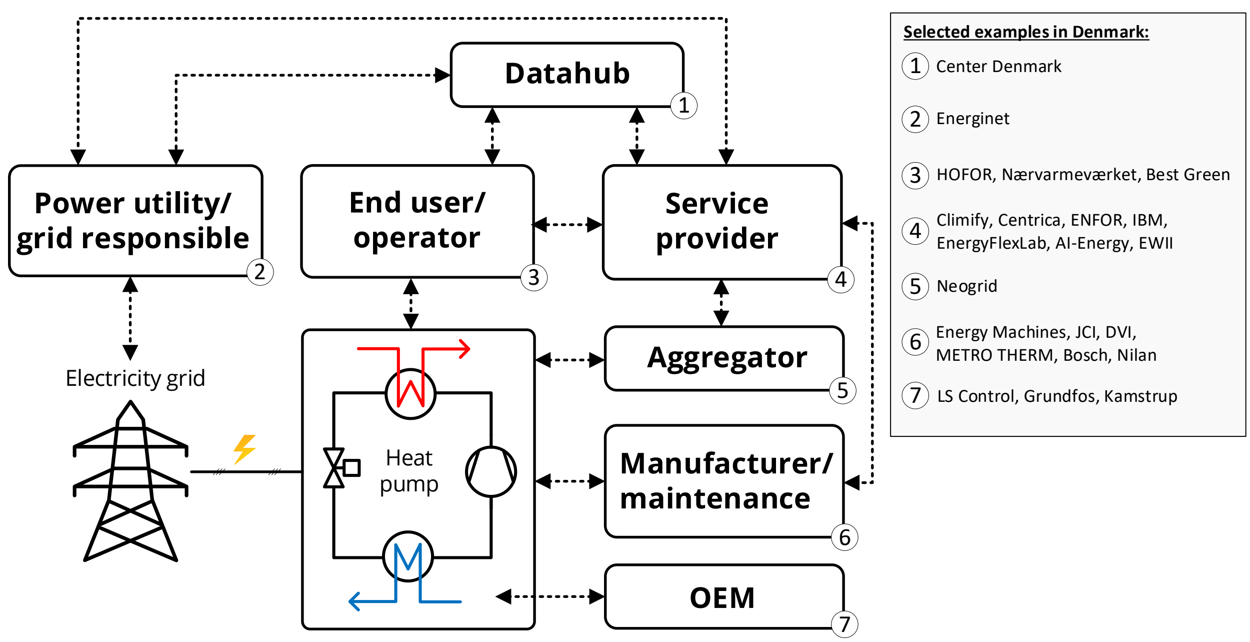

Figure 24. Visualization of supplier groups and examples of associated suppliers in an IoT-based energy system for heat pumps.

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].

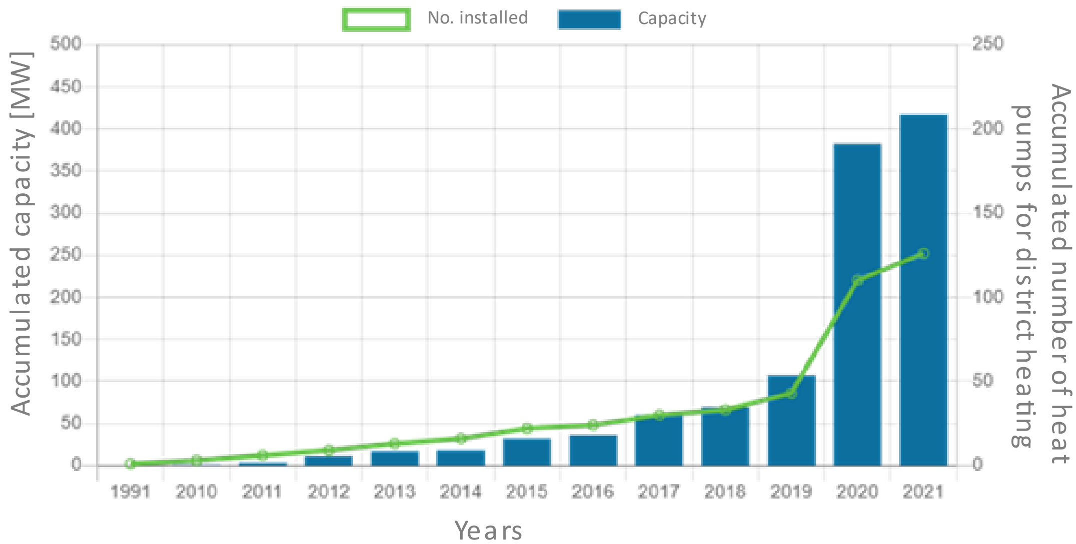

Figure 25. Overview of large-scale heat pumps for the Danish district heating network [4].

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 METRO-THERM, 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.

5. References

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[3] Energistyrelsen, "Klimastatus og -fremskrivning 2022 (KF22): El og fjernvarme (ekskl. affaldsforbrænding)," 2022. [Online]. Available: https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf22_sektornotat_8a_produktion_af_el_og_fjernvarme.pdf.

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[8] H. Lund *et al.*, *IDAs Klimasvar 2045: Sådan bliver vi klimaneutrale*. 2021.

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

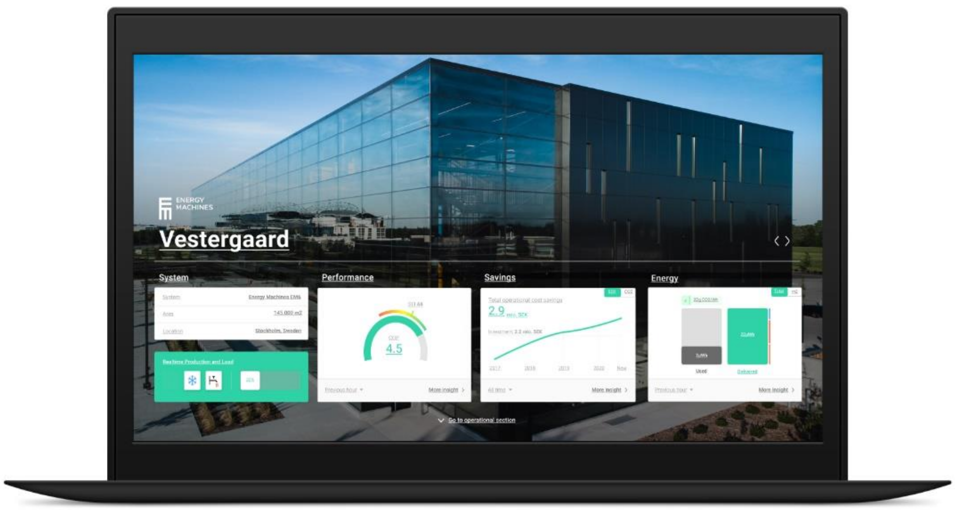


Figure 1: The energy machines dashboard including the EMV with a quick overview of current performance.

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://controlmachines.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.

Contact information

Tobias Dokkedal Elmøe

✉ tobias.dokkedal.elmoe@energymachines.com

PreHEAT for Heat Pumps by Neogrid Technologies ApS

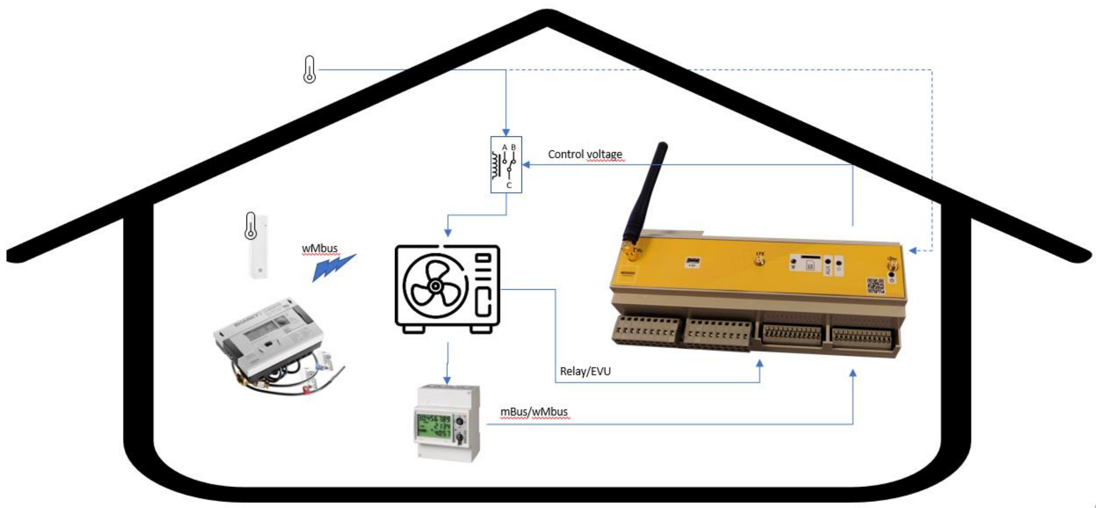


Figure 1: Hardware setup for PreHEAT Heat Pump Controller.

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.

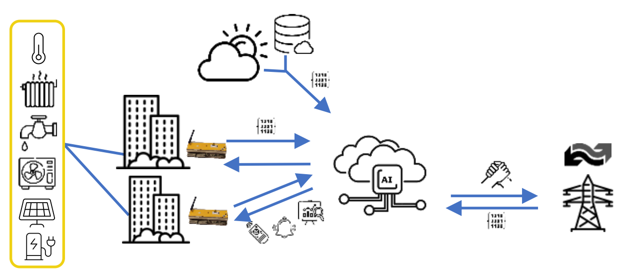


Figure 2: Neogrid PreHEAT Cloud.

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.

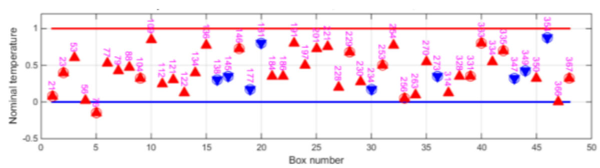


Figure 3: Swarm controller in operation.

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/

Contact information

Henrik Stærmose, Neogrid Technologies ApS
info@neogrid.dk
+45 7223 4000

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.

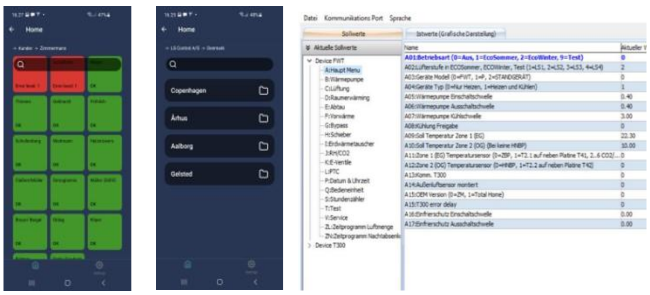


Figure 2: Swift overview of products, product groups and data view.

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

Contact information

Stig Petersen, LS Control A/S
sp@lscontrol.dk
+45 5550 5555

Energy Planning and Optimization Platform

Centrica Energy Trading

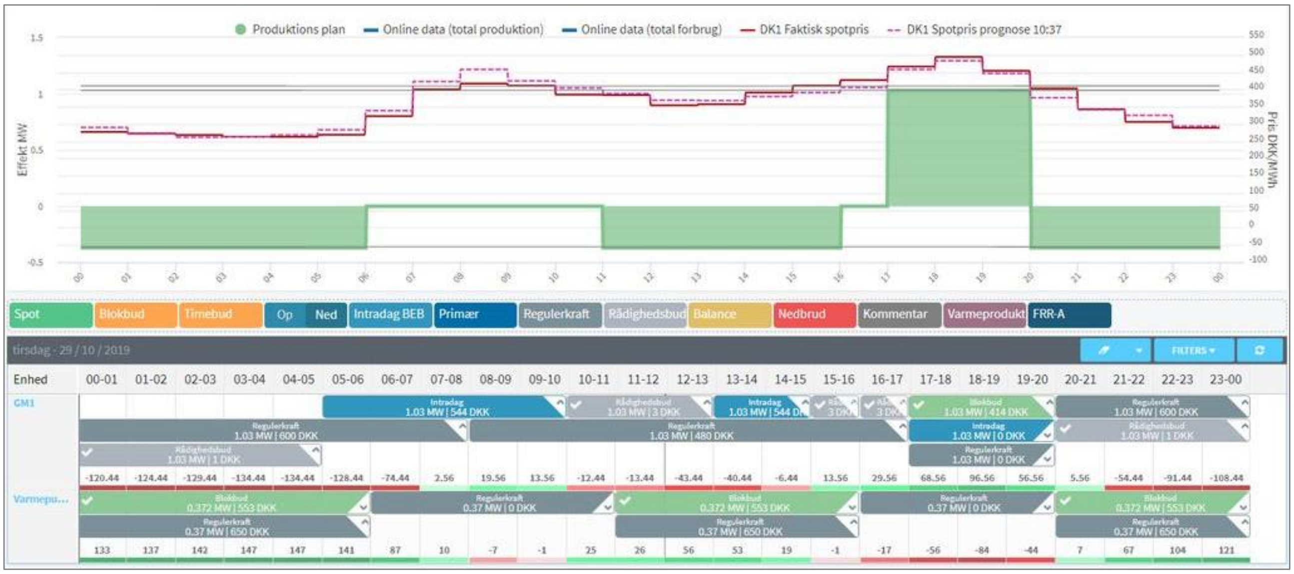


Figure 1: Interface of the energy planning and optimization platform developed by Centrica Energy Trading.

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.

Contact information

Mikkel Hesselbæk – Head of Flexible Services
Mikkel.Hesselbaek@centrica.com
+45 27 87 57 52

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

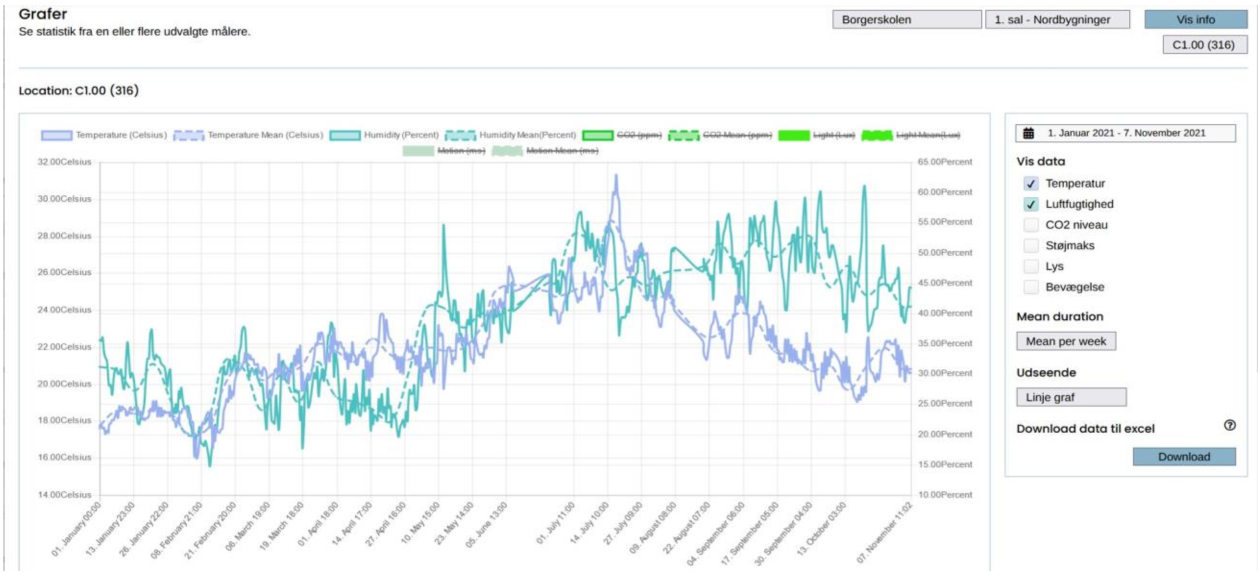


Figure 1: An example of the interface used in Climify: the user is able to zoom in and out in time and display multiple attributes,

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.

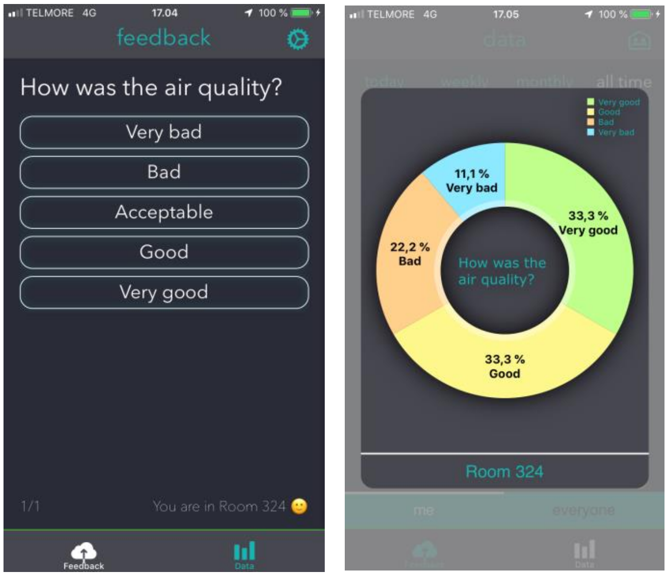


Figure 2: User feedback over phone app.

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.

Contact information

Davide Cali
dc@climify.com
+45 31 83 23 96

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/

Contact information

Kenneth Hjortshøj, TLV Forsyning / Nærvarmeværket
kmh@tlv.dk
+45 2156 4399

Artificial intelligence assisted products

AI-nergy

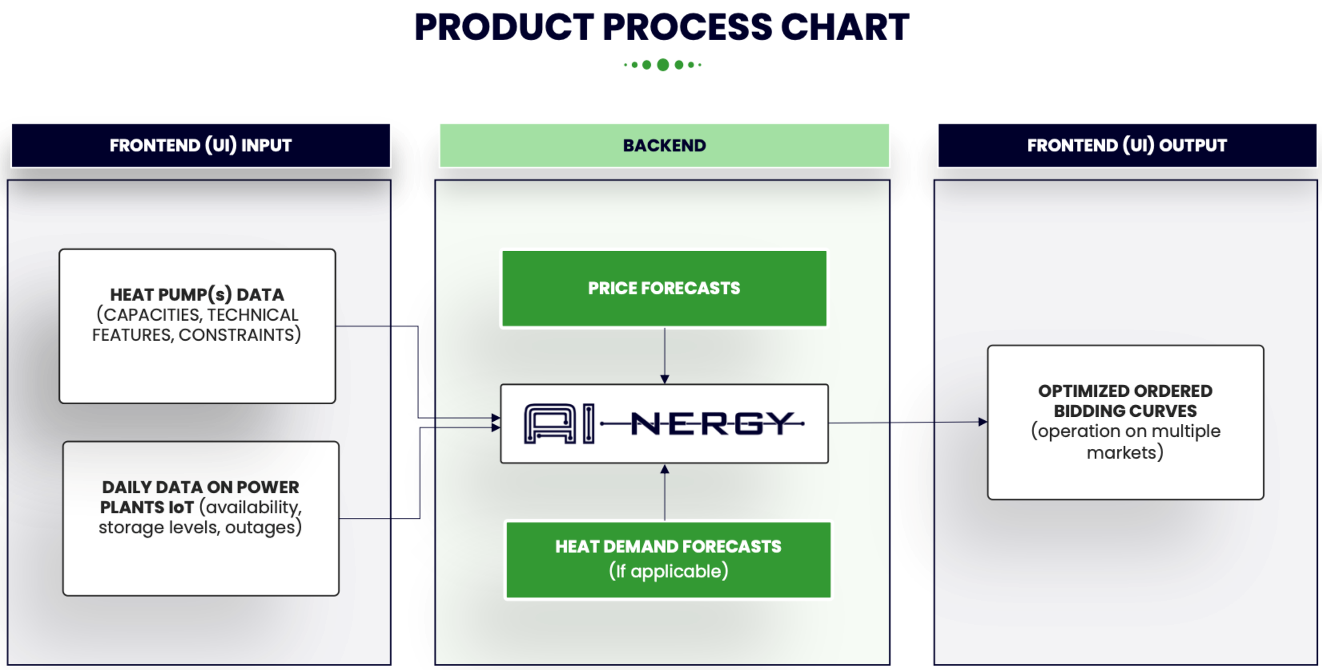


Figure 1: Scheme of the heat pump bidding product.

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.

Contact information

Dominik Dominkovic
dominik@ai-nergy.net
+45 93 51 15 30

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

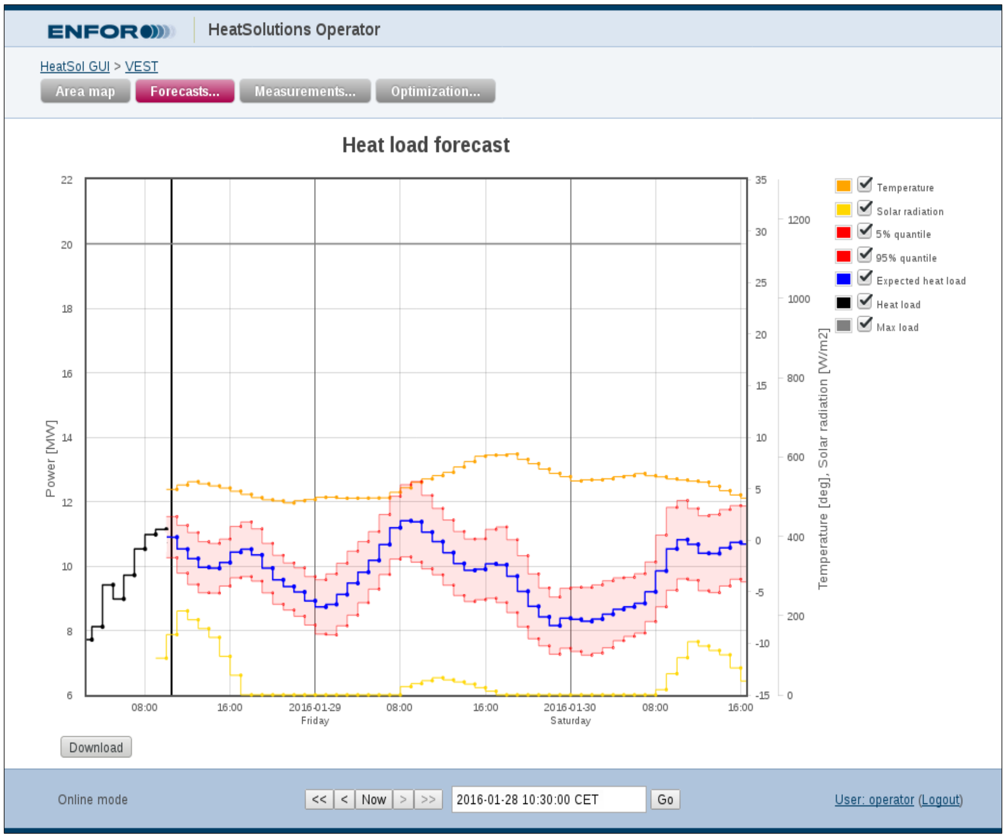


Figure 1 – Example of forecast for heat load, temperature, and solar radiation.

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.

Contact information

Mikkel Westenholz – CEO
miw@enfor.dk
+45 27 77 27 83

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/

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.

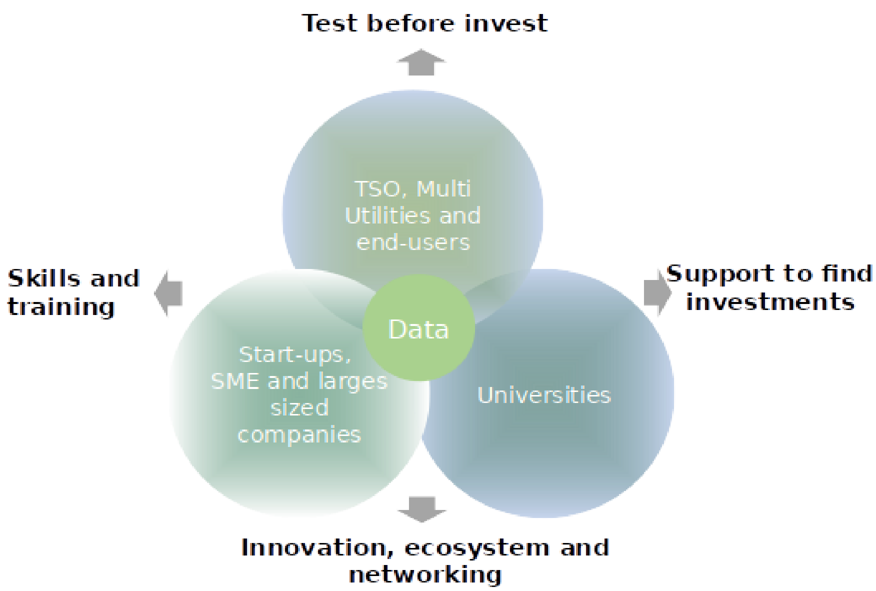


Figure 2: Data is at the core of the development, innovation and business thinking at Center Denmark.

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.

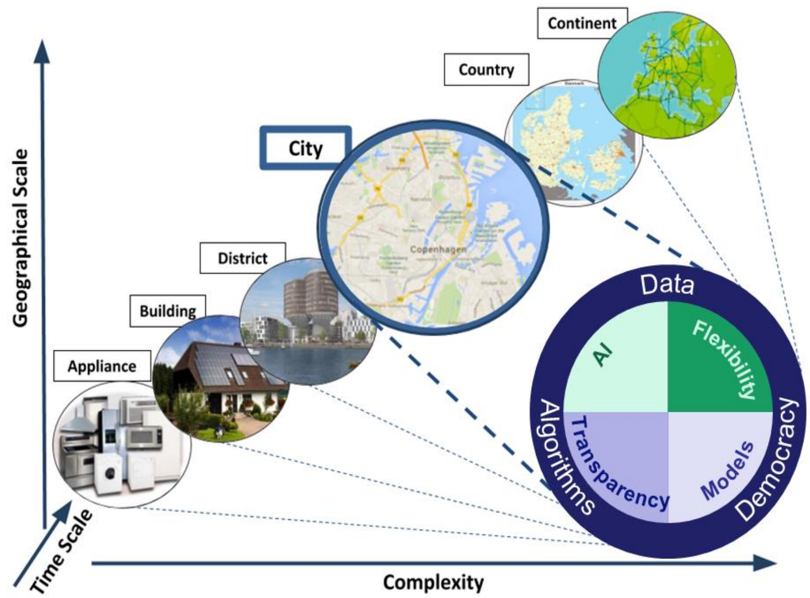


Figure 3: A spatio-temporal hierarchy is the core of the Smart-Energy Operating-System.

Contact information

Søren Skov Bording
soren@centerdenmark.dk
+45 2340 8612
Link: https://www.centerdenmark.com/

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

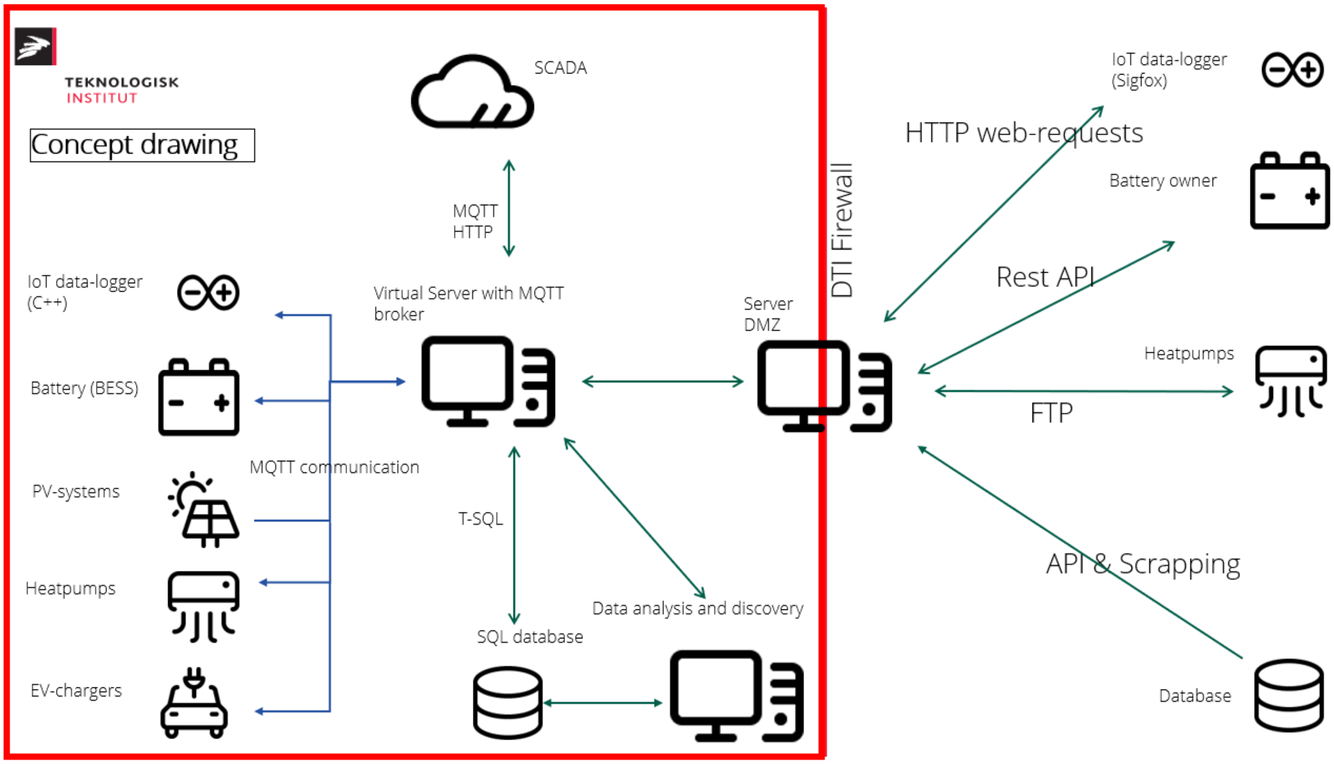
A key-feature of the EnergyFlexLab digital infrastructure is a modular setup that enables easy installation of new components and/or digital services "on-the-fly". Adding a new component and/or digital services does therefore not interrupt currently running tests at the EnergyFlexLab platform.

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

Contact information

Lars Overgaard
Danish Technological Institute
✉ lod@teknologisk.dk

MyUpway™ – Online heat pump control

METRO THERM A/S

METRO THERM

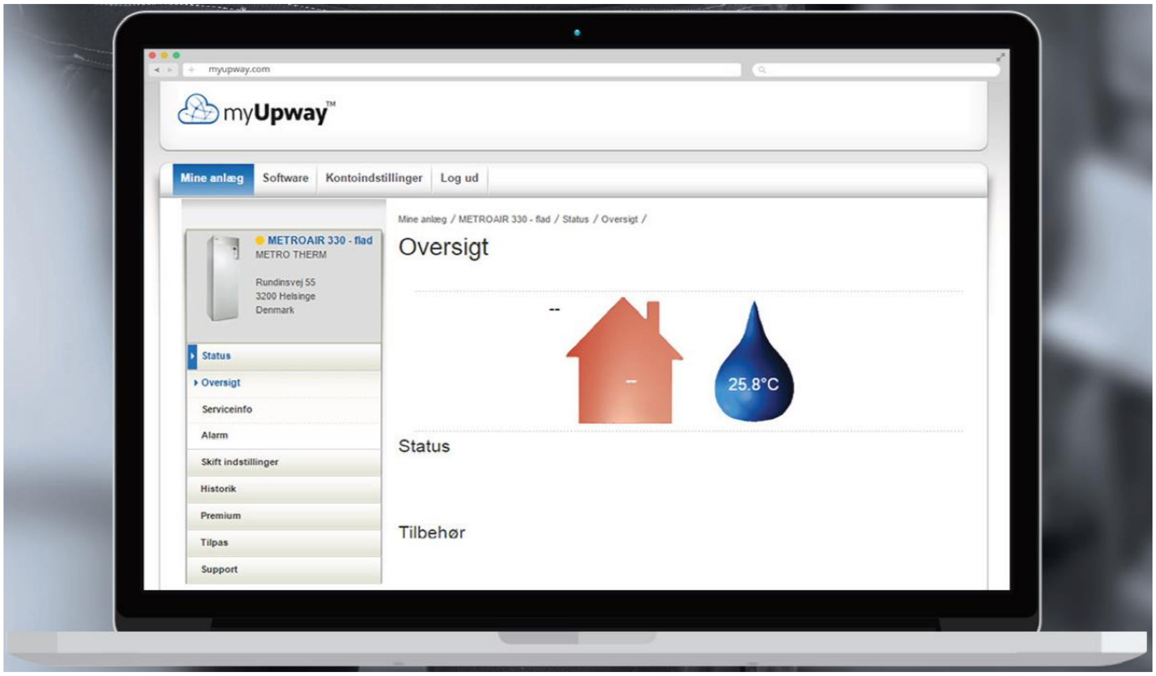


Figure 1: Homepage of the online-service myUpway™ where overall heat pump information is displayed.

Summary of IoT case

The platform myUpway™ 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™ 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™ includes a feature called Smart Price Adaption, which enables the automatic adjustment of heat pump operational periods to minimize electricity consumption costs.

MyUpway™ 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™ represents METRO THERM's version of the online service platform from its parent company NIBE named NIBE Uplink™. 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.

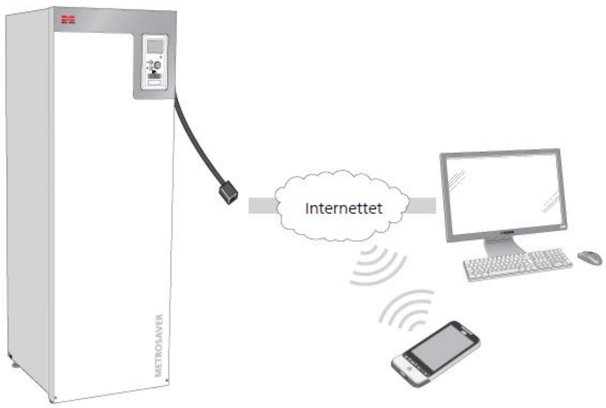


Figure 2: Representation of the interconnection between METRO THERM heat pumps and desktop through myUpway™.

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

Contact information

Lykke Strange Olsen
✉ lso@metrotherm.dk
📞 48 77 00 00

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

EUDP
The Energy Technology Development and Demonstration Programme

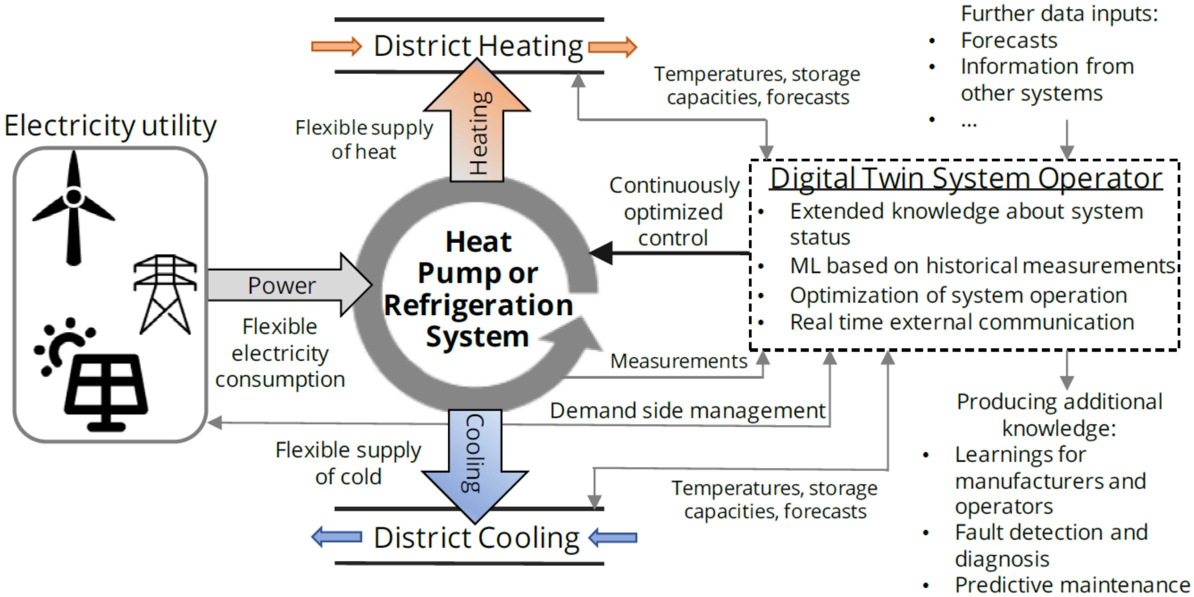


Figure 1: Diagram of the digital twin system operator.

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/

Contact information

Benjamin Zühlsdorf, Project Manager,
Danish Technological Institute
bez@teknologisk.dk

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.

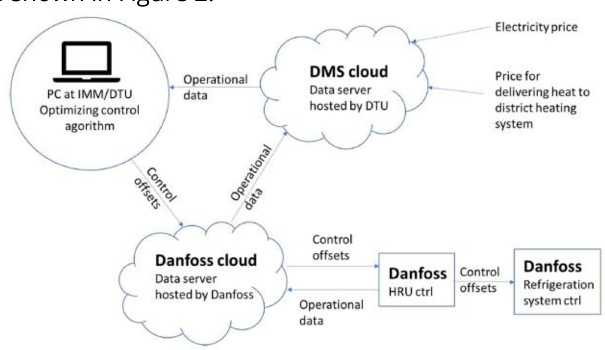


Figure 2: Sketch of the communication framework used for demonstration of the control of the heat recovery unit according to dynamic price signals.

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.

Contact information

Jan Eric Thorsen, Danfoss AS, Nordborg, Denmark
jet@Danfoss.com

Lars Finn Sloth Larsen, Danfoss AS, Nordborg, Denmark.
lars.larsen@danfoss.com

Yi Zong, DTU Wind and Energy Systems, Risø, Denmark. yizo@dtu.dk

Brian Elmegaard, Wiebke Meesenburg, DTU Construct, Kongens Lyngby, Denmark.
be@dtu.dk, wmeese@dtu.dk

FlexHeat – Intelligent and Fast-regulating Control

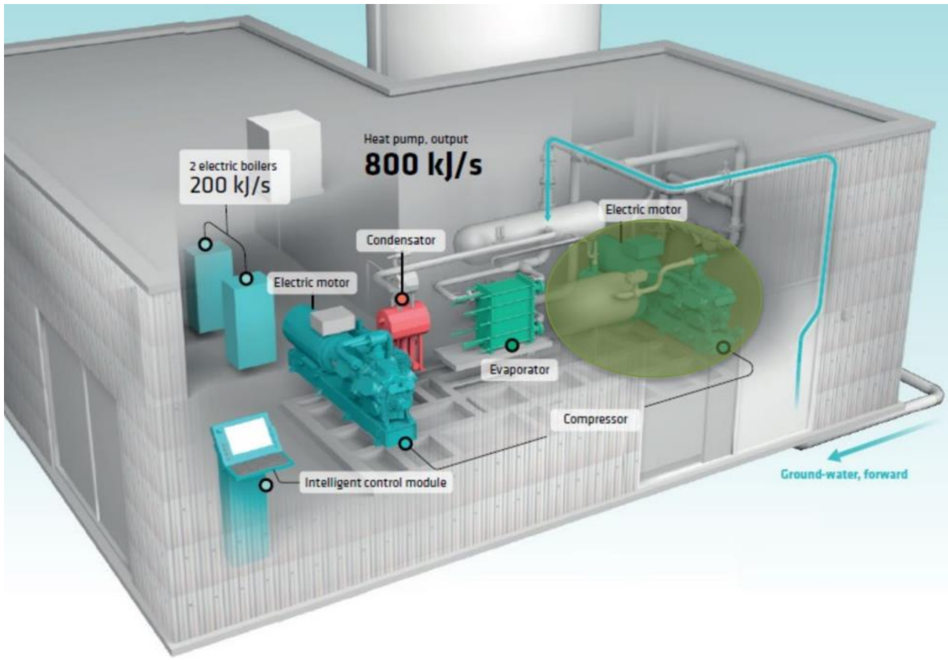


Figure 1: 3D drawing of the energy system with the most important [HOFOR, communication department, 2021]

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.

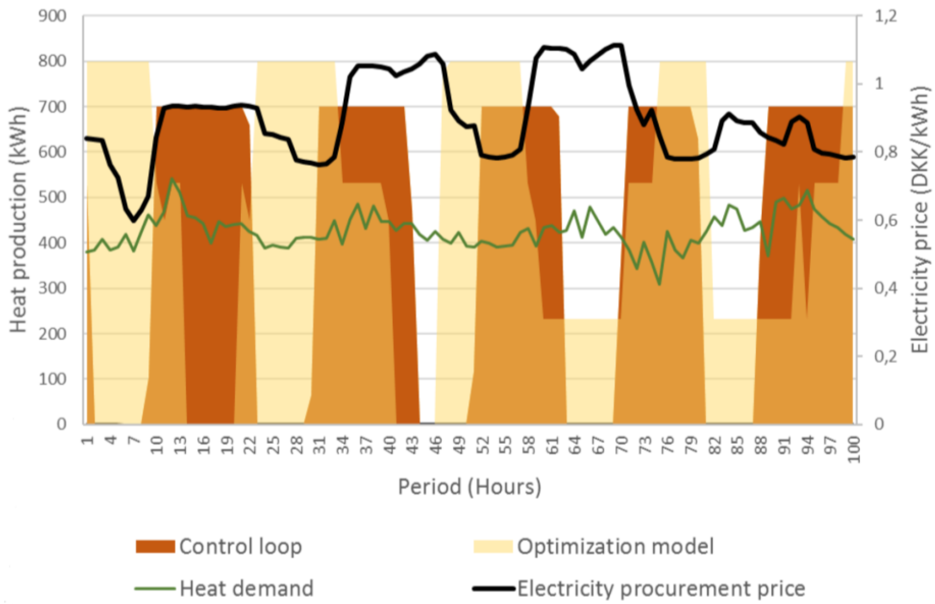


Figure 2: Flexible heat production during winter [HOFOR, 2021]

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.

Contact information

Tore Friis Gas Kjeld
tgkj@hofor.dk
+45 27 95 43 41

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

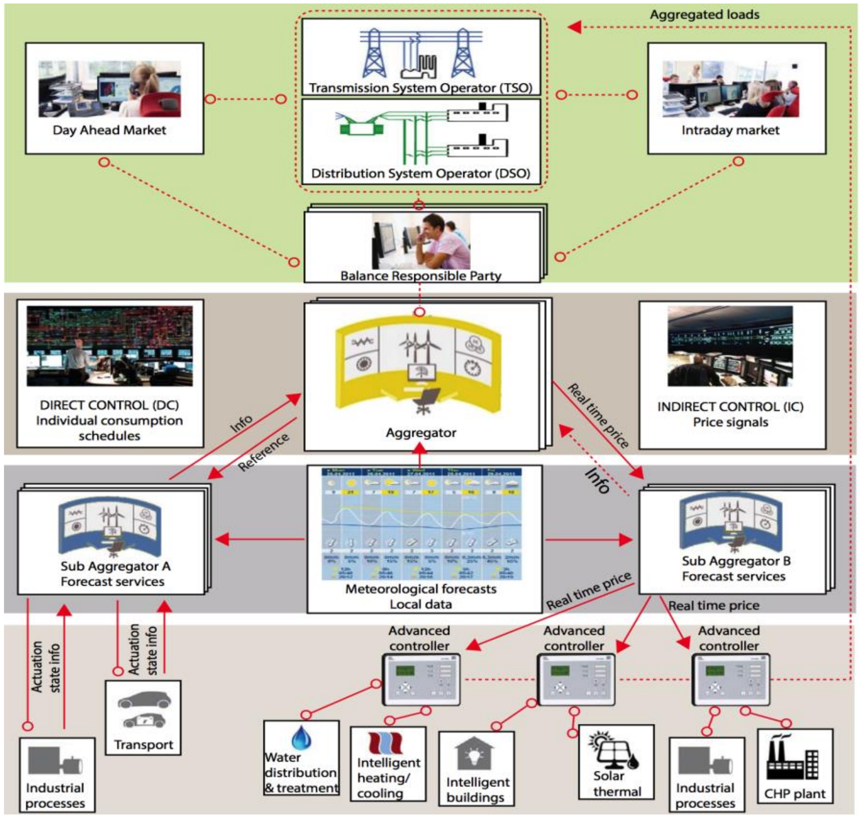


Figure 1: The Smart-Energy Operating-System (SE-OS) for digitalization of integrated energy systems.

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.

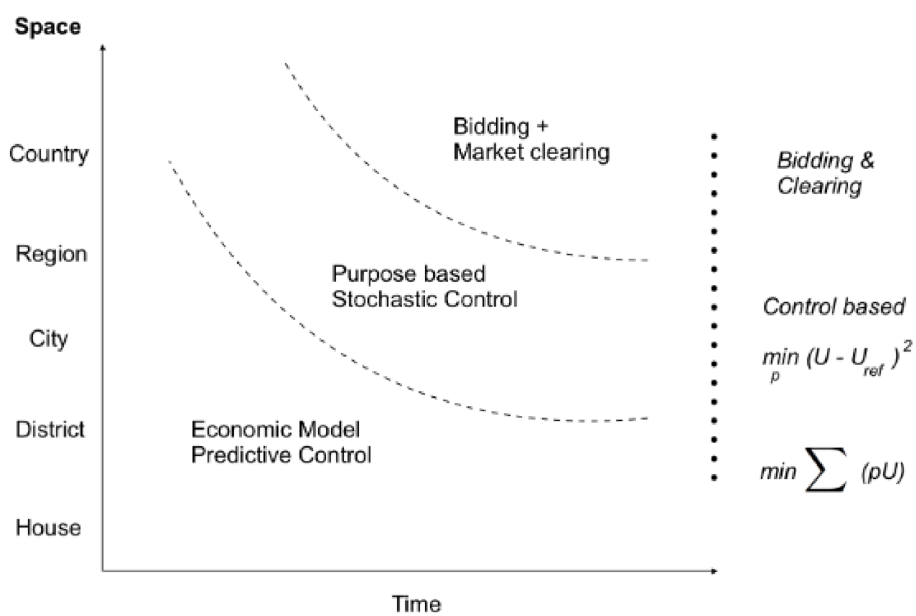


Figure 2: Hierarchical control and markets.

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.

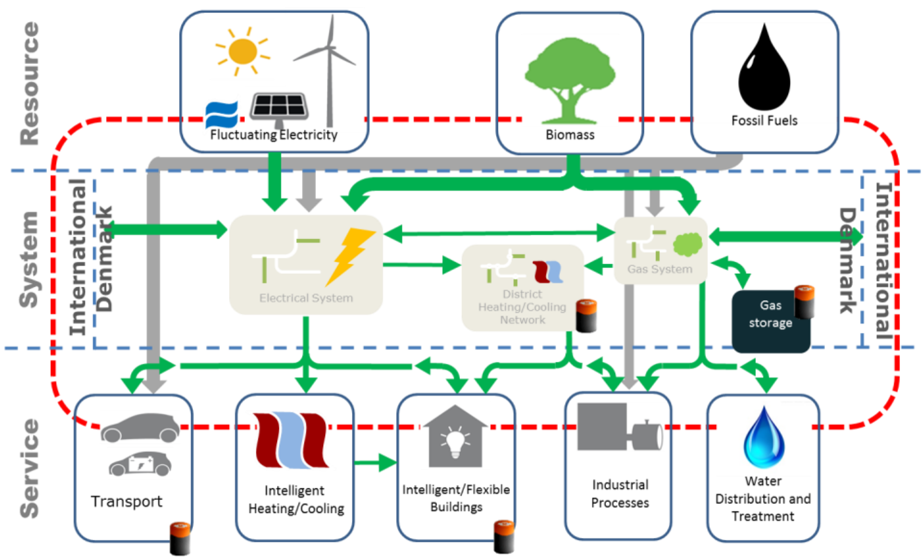


Figure 3: Grey-box models and data-driven Digital Twins.

Contact information

Henrik Madsen
Professor, Head of section, Department of Applied Mathematics and Computer Science,
Technical University of Denmark
hmad@dtu.dk
+45 2083 4304

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

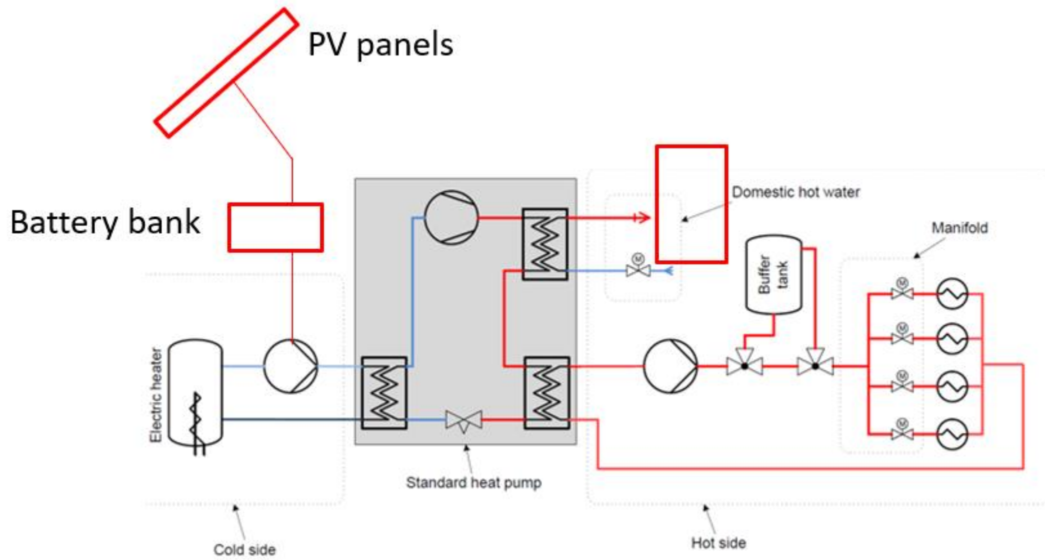

Figure 1: Principle sketch of experimental setup (on the test rig PV and battery are virtual).

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

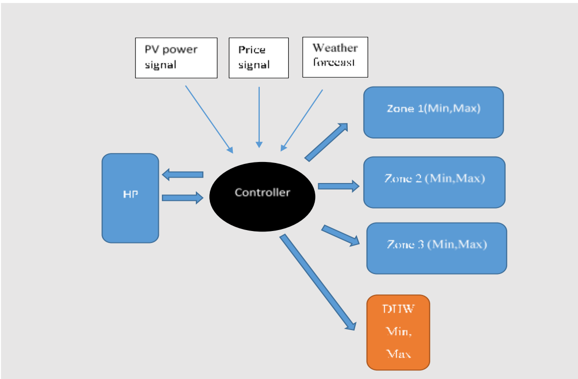

Figure 2: Simple representation of the controller.

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.

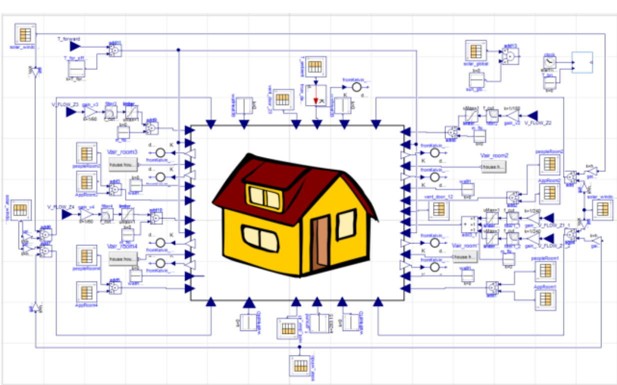

Figure 3: House model in Dymola.

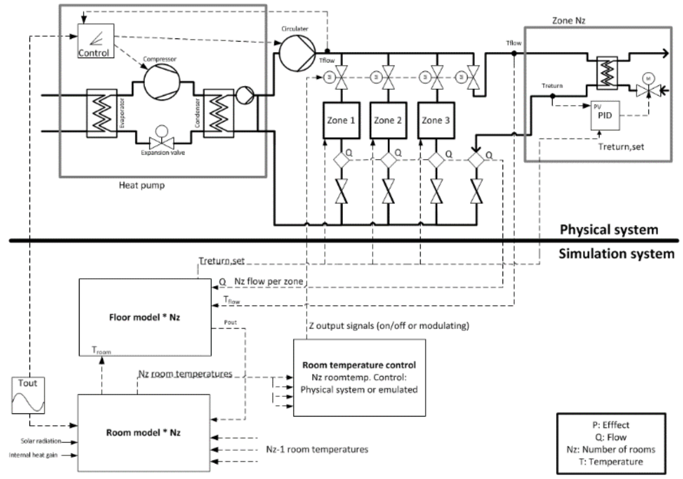

Figure 4: Physical and simulation system.

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

Ivan Katic
Danish Technological Institute
ik@teknologisk.dk

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

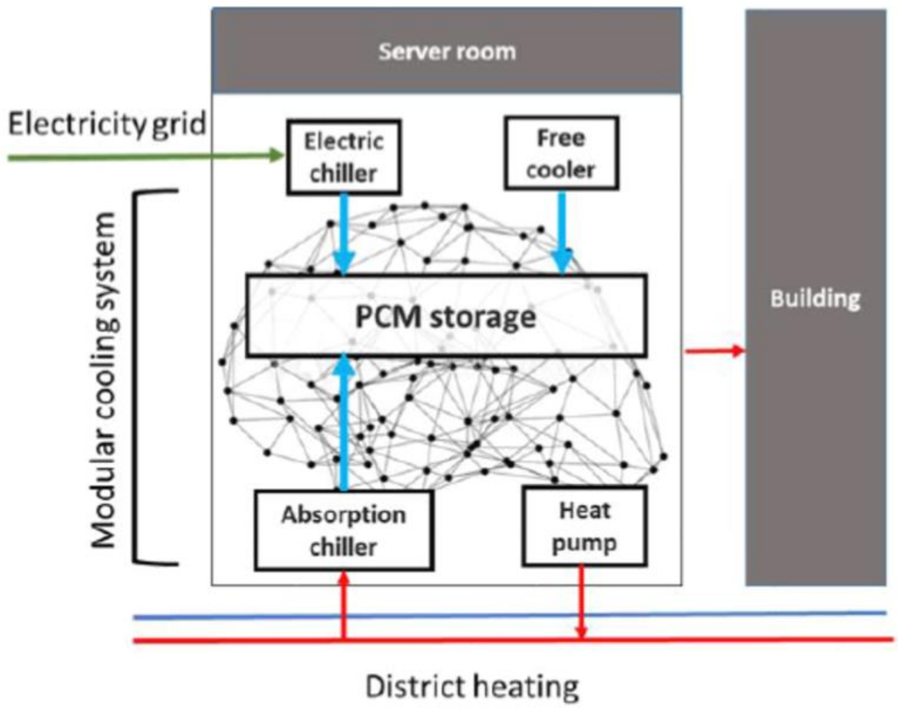

Figure 1: Cool-Data Overview

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.

Contact information

Dominik Dominkovic, Cool-Data DTU
✉ dodo@dtu.dk
✆ +45 93511530

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).

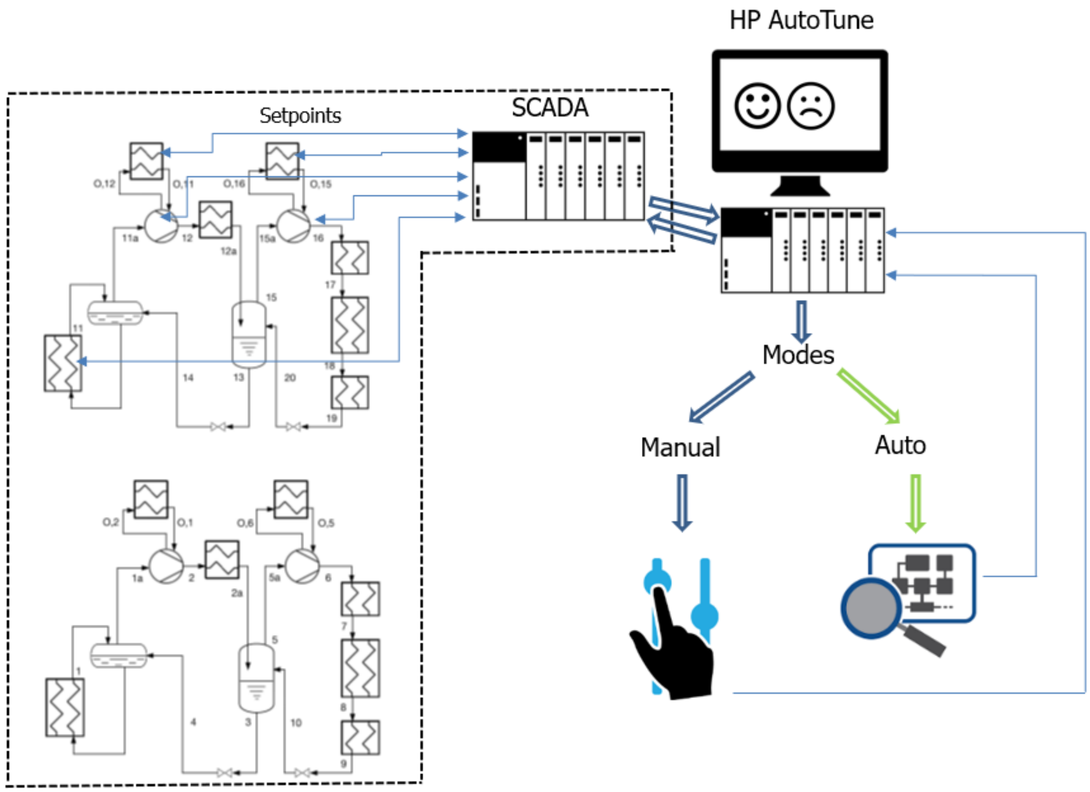

Figure 2 – Concept for HP AutoTune.

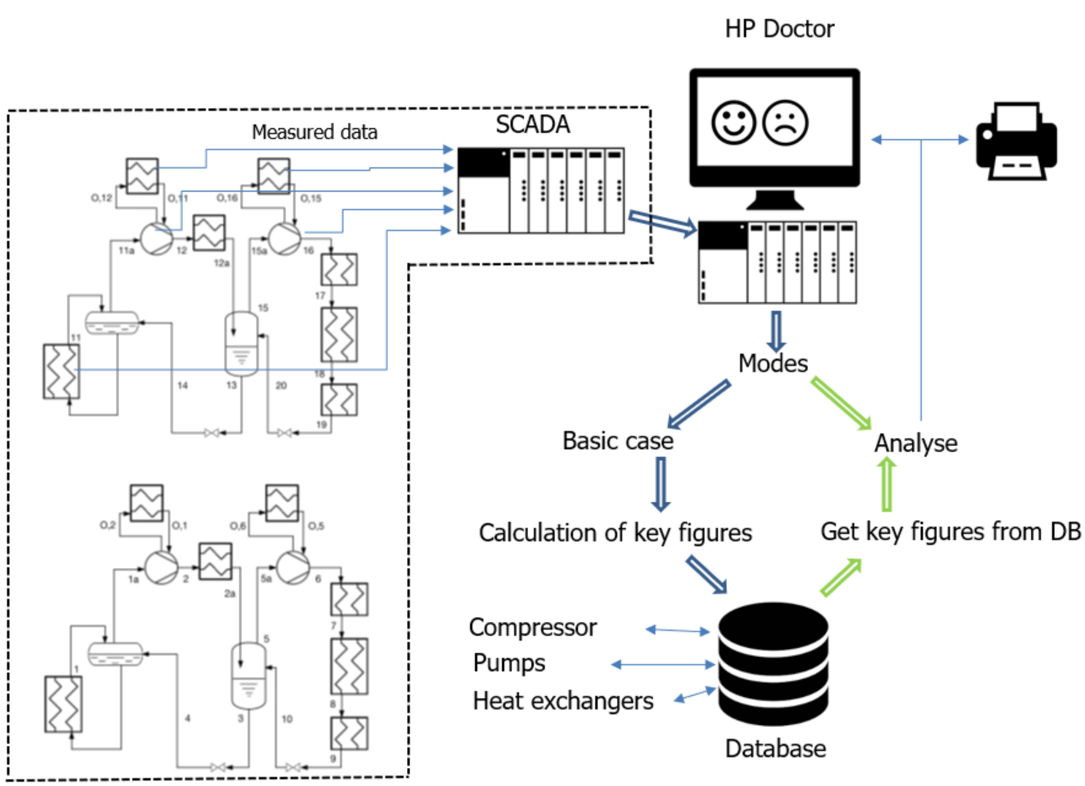

Figure 3 - Concept for HP Doctor.

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).

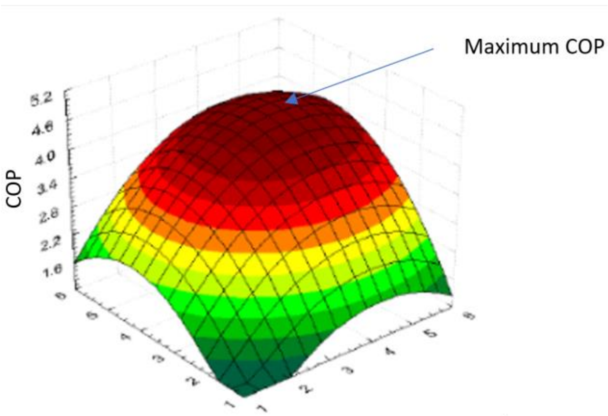

Figure 4 - Concept for optimum COP based on IWO.

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.

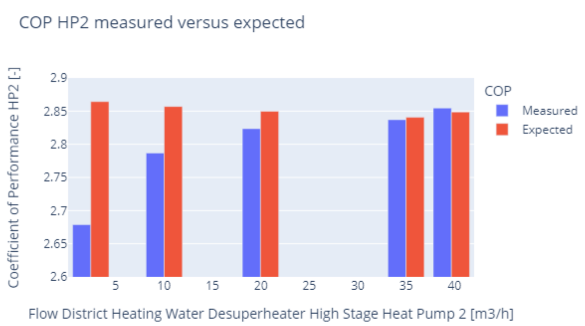

Figure 5 - Use of the regression to evaluate influence of water flow through desuperheater

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.

Contact information

Jóhannes Kristófersson,
Danish Technological Institute
jkri@teknologisk.dk

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

<u>WP1:</u>

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.

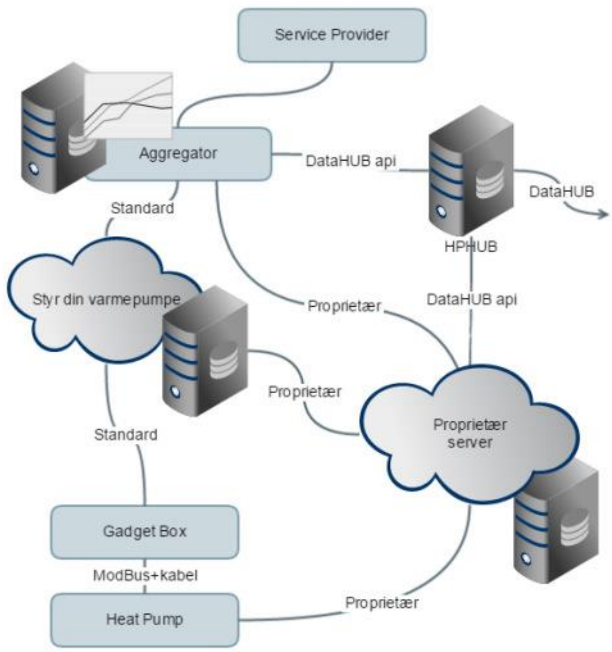

Figure 2: Principle for heat pump datahub (high level).

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.

Contact information

Claus S. Poulsen, Danish Technological Institute
✉ csp@teknologisk.dk
📞 +45 72 20 25 14

Project: Flexible Energy Denmark (FED)

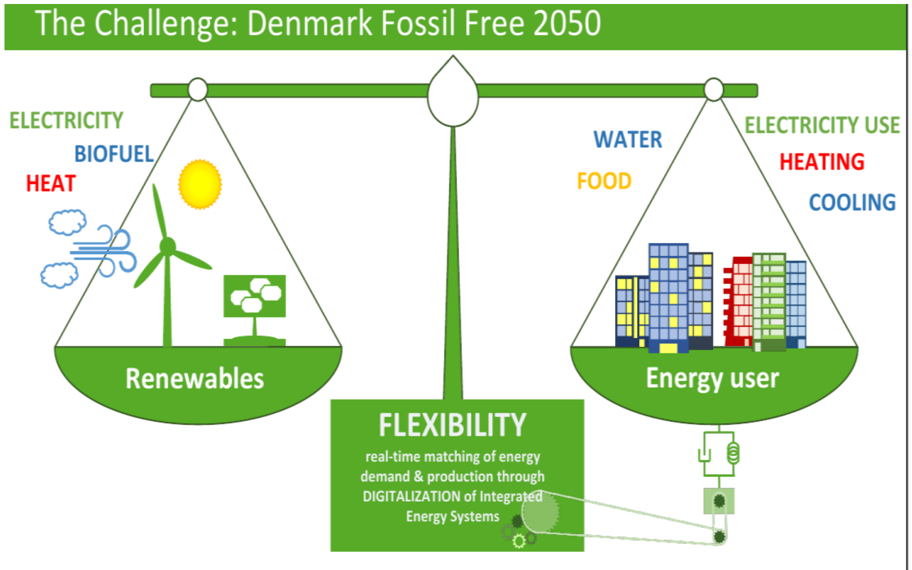

Figure 1: Flexible Energy Denmark establish the tools and solutions for enabling the end-user flexibility for large-scale integration of wind and solar energy.

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.

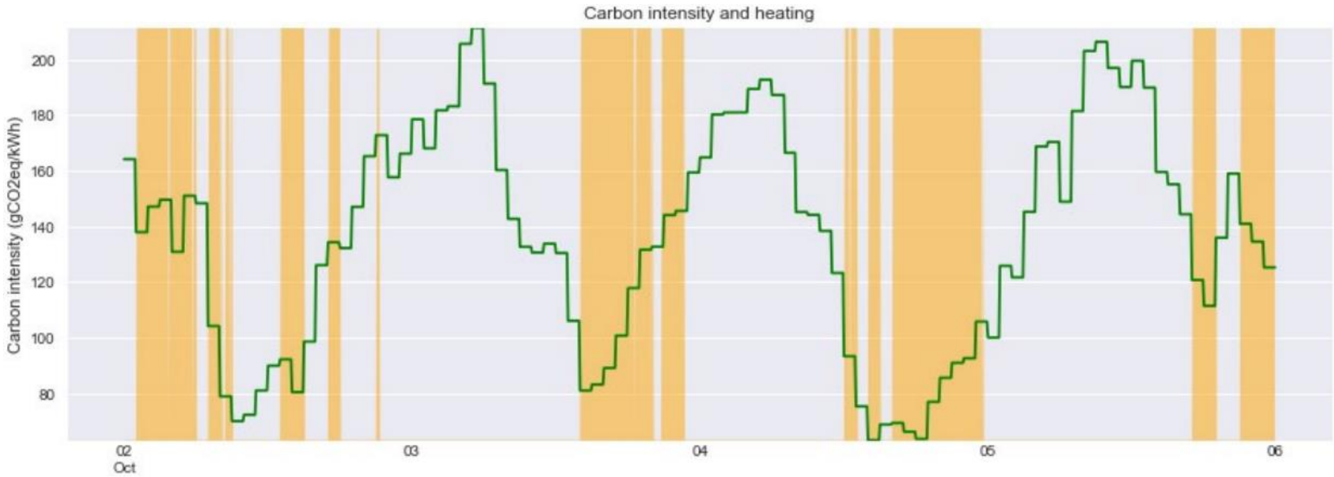

Figure 2: Predicted carbon intensity (green) and periods at which the heat pump is turned on (orange). The installation is located in Denmark.

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/

Contact information

Henrik Madsen
hmad@dtu.dk
+45 20 83 43 04

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

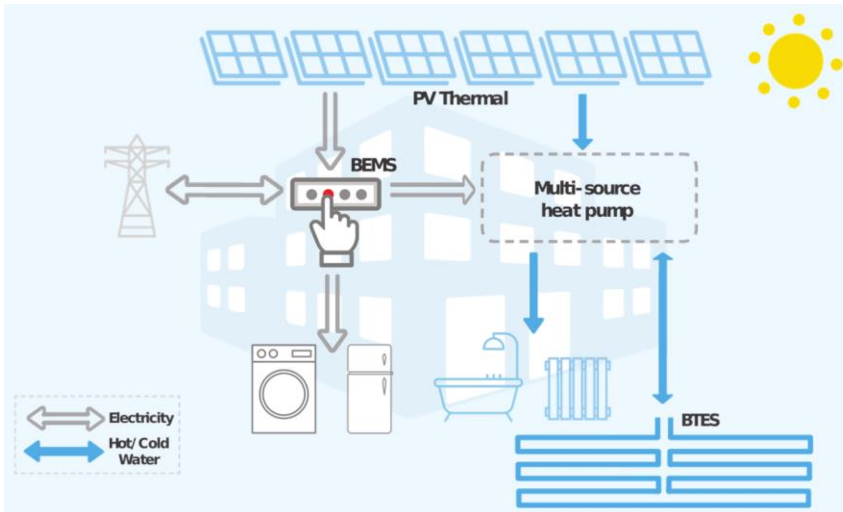

Figure 1: Concept overview for components in the RES4BUILD energy system.

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

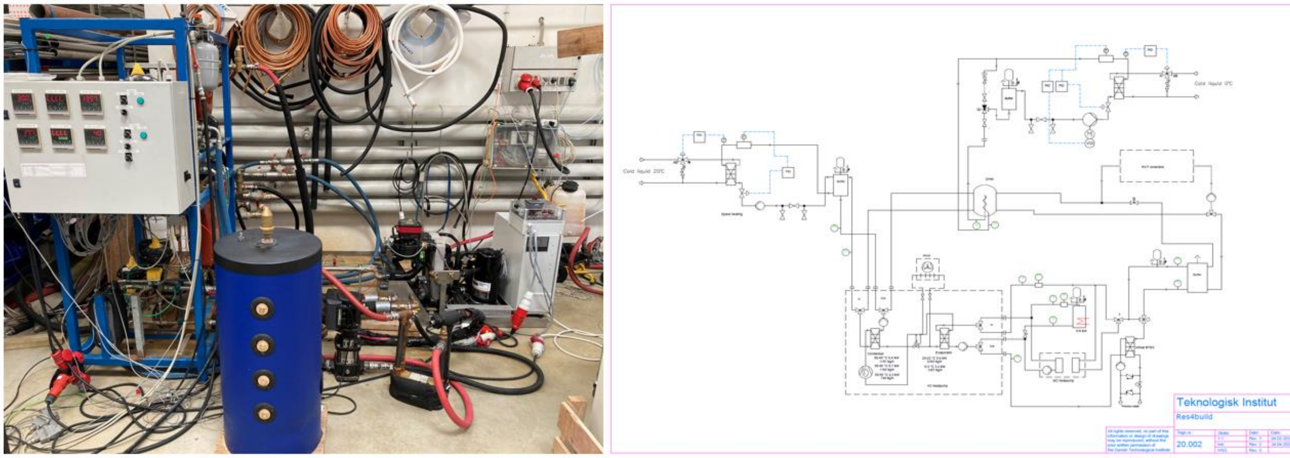

Figure 2: Preliminary test setup with the multi-source heat pump at Danish Technological institute.

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/

Contact information

Michael Papapetrou, WIP
michael.papapetrou@wip-munich.de

Project: Development of fast regulating heat pumps using dynamic models

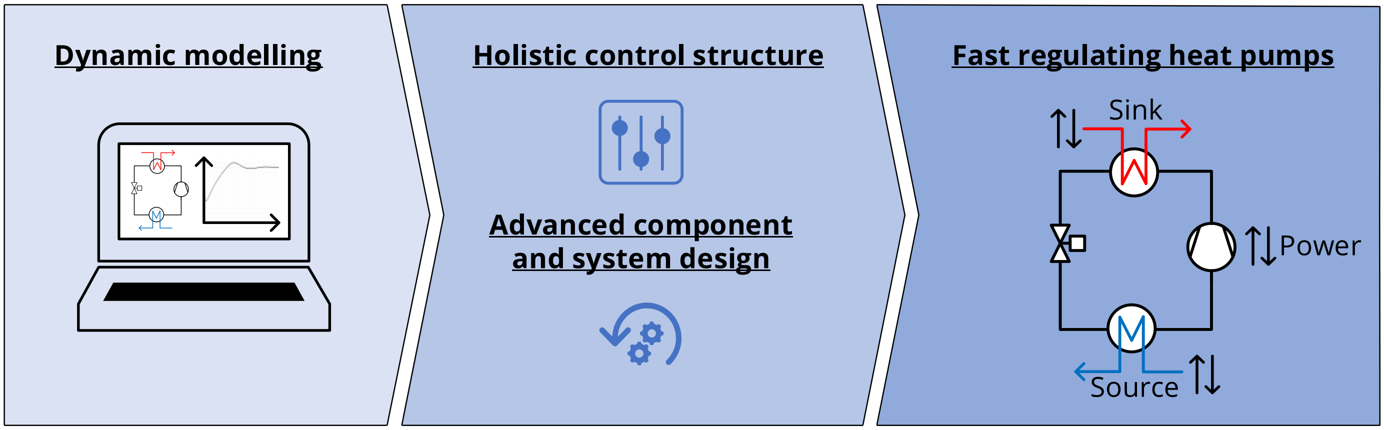

Figure 1: Concept of development of fast regulating heat pumps based on dynamic modelling.

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

Contact information

Klaus Vinther, Johnson Controls
✉ klaus.niels.vinther@jci.com

Kenneth Kramer, Danish Technological Institute
✉ kkra@teknologisk.dk

Wiebke Meesenburg, DTU Construct
✉ wmeese@mek.dtu.dk

CEDAR

Cost Efficient heat pumps using DigitAl twins and Reinforcement learning

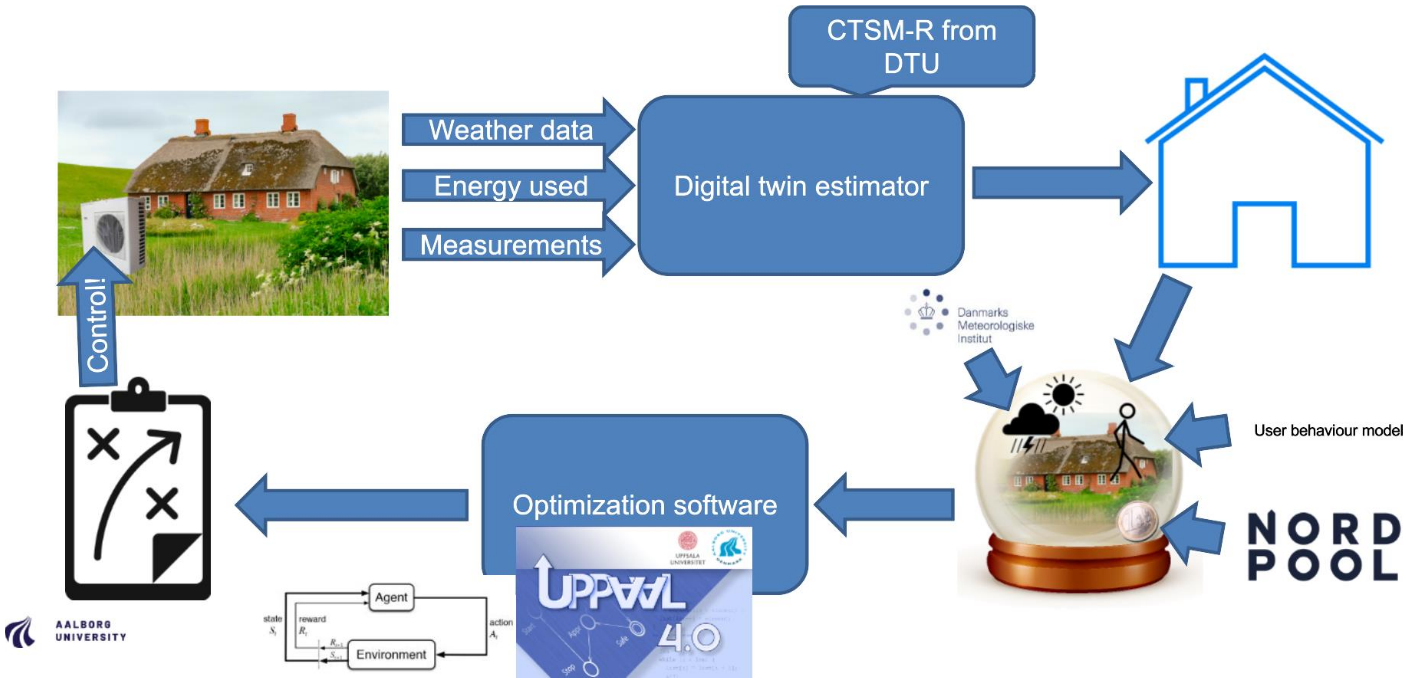

Figure 1: General flow of the approach studied in the CEDAR project.

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.

Contact information

Peter Gjøl Jensen
✉ pgj@cs.aau.dk