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Technology Collaboration Programme on Heat Pumping Technologies (HPT)

Annex 56

Digitalization and IoT for Heat Pumps

Task 1: State of the Art

Task Report

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Preface

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

The IEA

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

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

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

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.
The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

Disclaimer

The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organised under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries. This report has been produced within HPT Annex 56. Views and findings in this report do not necessarily represent the views or policies of the HPT TCP and its individual member countries.

The Heat Pump Centre

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

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

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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The Annex is operated from 01/2020 to 12/2022. Further information is available on the Annex website https://heatpumpingtechnologies.org/annex56/

Participating countries

The following countries participate in Annex 56:

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

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

Participants and contributors to this report

This task report is the result of a collaborative effort with contributions from various authors that are listed in the table below. The report was coordinated by the Task leader Davide Rolando (KTH), davide.rolando@kth.se

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Foreword

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

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

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

Task 1 – State of the Art:

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

Task 2 – Interfaces:

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

Task 3 – Data analysis

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

Task 4 – Business Models

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

Task 5 – Dissemination

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

IoT for heat pumps

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1 Introduction

In recent years, the Internet of Things (IoT) has revolutionized the way we interact with technology. The concept of connecting devices and appliances to the internet and enabling them to communicate with each other has opened a world of possibilities in terms of efficiency, convenience, and automation. One area that has seen significant progress in IoT integration is the field of heat pumps. Heat pumps have become increasingly popular in recent years due to their energy efficiency and eco-friendliness. However, the integration of IoT technologies in heat pumps has taken their potential to a whole new level. IoT-enabled heat pumps can now be controlled remotely, monitored for efficiency, and even programmed to adjust to user preferences automatically.

This report aims to provide an overview of the current state of the art of IoT technologies in heat pumps. We will discuss the various types of IoT sensors and devices that are commonly used in heat pumps, the benefits of IoT integration, and the challenges that still need to be addressed. Additionally, we will review some of the latest research and development in this area, as well as the outlook for IoT technologies in heat pumps.

2 State of the art

Contributors: Goran Music, Gernot Steindl and Wolfgang Kastner (TU Wien)

2.1 Introduction to the Industrial Internet of Things

Advances in the iron production and chemical manufacturing in the mid and late eighteenth-century enabled production of first precise machine tools. Led by inventions coming predominantly from Great Britain, with James Watt perfecting the steam-powered engine, increasing usage of steam and waterpower in the production process started to take place. By the early nineteenth century, heavy-duty manual labor is slowly replaced by operating heavy machinery in what is now known as the First Industrial Revolution (statista, 2019). In the late nineteenth and the beginning of the twentieth century, supported by the invention of efficient methods for iron purification on the industrial scale, electricity was introduced from home applications into the manufacturing processes. Together with the optimization of production processes through introduction of concepts as just-in-time and lean manufacturing, it propelled the emergence of assembly lines and the paradigm of mass manufacturing (statista, 2019). This era, known as the Second Industrial Revolution, ended with the start of the First World War. The Third Industrial Revolution started with the intersection of analogous and electrical blocks, traditionally manually interconnected with wires to provide the logic necessary for process automation, with the emerging concept of a digital computer, rapidly advanced during the Second World War. The first Programmable Logic Controller (PLC), introduced in 1968, enabled the emergence of first fully automated production processes (Parr, 2003), reducing effort and increasing speed and accuracy (statista, 2019). This inevitably led to increase in competition, fueling globalization and emergence of the concept of supply chain management (statista, 2019).

As the enabler of the Third Industrial Revolution, the PLC concept dominates the world of automation to this day. It has adopted some advantage of computer technology, which evolved exponentially in the meantime with unprecedented continuous advancements in computing power and availability. However, with the ever-increasing need for flexibility of production systems, the classical approach to automation has been brought to its fundamental limits, revealing an inherent inability to deal with the increasing level of complexity of modern automation systems, brought on by the ever-rising requirements on their functionality. The awareness of the necessity and potential advantages of adopting and raising to the level of computer technologies once again, triggered global initiatives, such as Advanced Manufacturing (USA), e-Factory (JPN), Intelligent Manufacturing (CHN) and Industry 4.0 (GER), all gravitating toward a concept of an adaptive, fully connected, analytical and efficient plant, called Factory of the Future (FoF) (International Electrotechnical Commission (IEC), 2015).

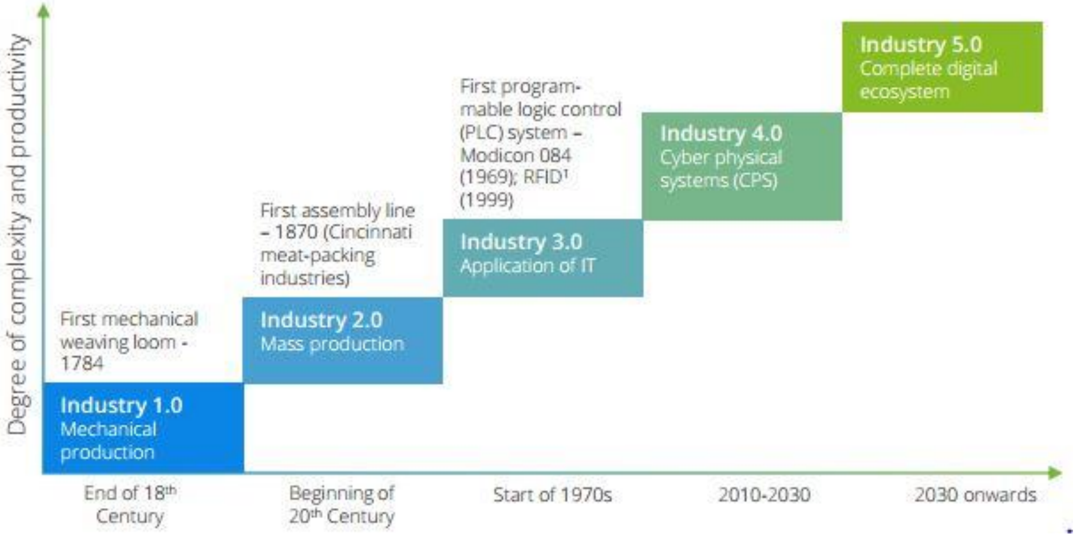


Figure 1: Industrial evolution overview. Source: (statista, 2019).

Figure 1 shows an overview of the described industrial evolution. It predicts an ultimate complete convergence of digital technologies and the analogous world, with a seamless and transparent integration into the everyday life in what is now called The Fifth Industrial Revolution. This ultimate synergy of analogous things and digital things is what is referred to as "The Internet of Things" or IoT. Currently, we are in the middle of the Fourth Industrial Revolution, characterized as a transitional era on the way toward the fulfillment of the vision of IoT, where unimpeded and transparent communication among actors, also between machines (machine-to-machine or M2M communication), enables optimization of processes across value chains, as depicted in Figure 2.

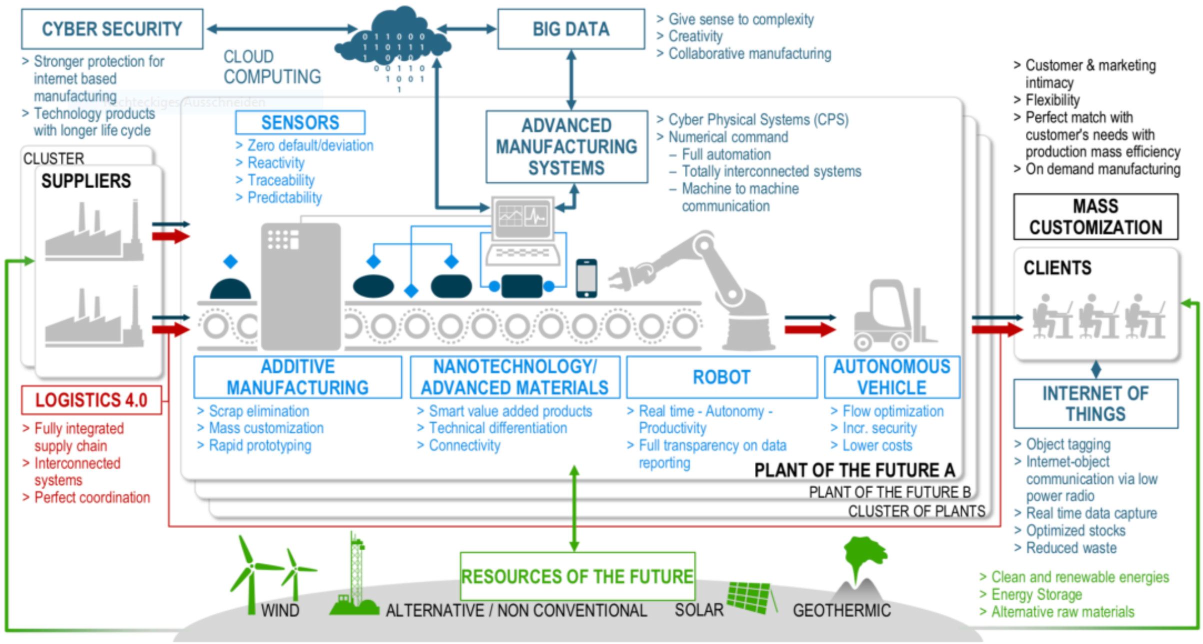


Figure 2: Trend in evolution of M2M to IoT. Source: (Blanz, 2012)

The first mention of the Internet of Things dates to a 2005 report by the International Telecommunications Union (ITU): *"Machine-to-machine communications and person-to-computer communications will be extended to things, from everyday household objects to sensors monitoring the movement of the Golden Gate Bridge or detecting earth tremors. Everything from tyres to toothbrushes will fall within communications range, heralding the dawn of a new era, one in which today's internet (of data and people) gives way to tomorrow's Internet of Things." (ITU, 2005)*

There is a number of definitions of IoT since then, diverging in focus and level of detail. In all cases, however, the IoT is spanned by uniquely identifiable, context-aware objects, able to communicate with other objects and humans and execute autonomous operations to change their own state and the state of their surroundings (Baras & Brito, 2018). These hybrid new objects, integrating physical, i.e., mechanical, properties with electrical and communicational capabilities, are known as Cyber-Physical Systems (CPSs). CPSs, prescriptive and predictive analytics will enable timely maintenance measures and the overall process optimization, with every digital device capable of providing its real-time status (the "digital shadow") to other devices, which are then able to act upon the received information, enabling prioritization of workloads, synchronization and dynamic reconfiguration, significantly reducing the need for quality inspections and surveillance and thereby expenditures in the industrial manufacturing sector (Willner, 2018). Similar or even more drastic advances are needed and can also be expected in the domain of Smart Cities and Buildings, as the modern urban areas represent approx. seventy percent of global energy-related emissions (Willner, 2018).

2.1.1 Alliances and reference architectures

The second convergence of automation technology with the computer technology is leading the way in introducing and establishing infrastructures capable of carrying the envisioned ecosystem of Things. All initiatives aim to re-introduce humans into the production lifecycle and decentralize production through the enabling of collaboration with robots to create partially hand-made products (Baras & Brito, 2018). Figure 3 depicts the envisioned free exchange of information between the different stakeholders of the production lifecycle, with one of the stakeholders being the product itself.

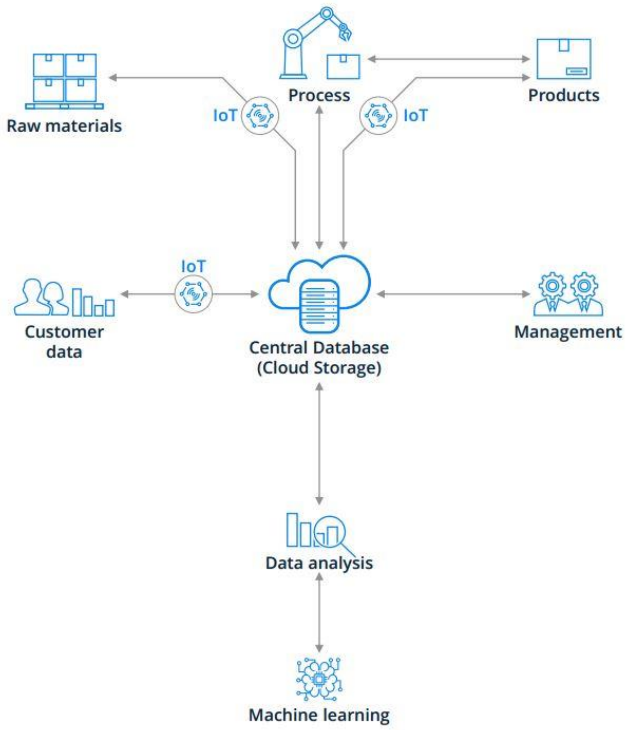


Figure 3: An IoT industrial system illustration. Source: (statista, 2019).

The global push for new technologies brought by a large number of different consortia and standards in a race for a piece of market in the new ecosystem, as can be seen in Figure 4.

Figure 4: Jungle of Consortia, Standards, OS-Projects. Source: (Blanz, 2012).

Globally most prominent movements in the industrial sector are the Industrial Internet of Things (IoT), a part of the US Advanced Manufacturing initiative managed by the Industrial Internet Consortium (IIC), and the Industry4.0 Platform, managed by a consortium of prominent German companies and standardization committees (Willner, 2018).

2.1.1.1 IIRA

The IIC considers industry to involve the areas of energy, healthcare, manufacturing, smart cities, and transportation, and aims to cover all verticals (Manufacturing, Transport, Energy, Healthcare, etc.), transforming the industry through intelligent, interconnected objects able to improve performance, lower costs and increase reliability (Willner, 2018). The IIC publishes and maintains the Industrial Internet Reference Architecture (IIRA), an architectural overview as a common basis for design of IIoT systems by different stakeholders (Willner, 2018). IIRA specifies the Industrial Internet Architecture Framework (IIAF), a standard vocabulary with a collection of viewpoints and concerns, to support system architects in systematic development, documentation, and communication of the IIoT systems and applications across industrial sectors (Industrial Internet Consortium (IIC), 2019).

IIRA viewpoints are the result of a comprehensive stakeholder requirements and use-case development and analysis, and include, as shown in Figure 5:

- the Business Viewpoint, concerned with the stakeholder identification and requirements, and the specification of the system in its business and regulatory context, together with identifying how the IIoT system achieves the stated objectives
- the Usage Viewpoint, representing how the system is supposed to be operated, typically as a sequence of activities involving human or logical users
- the Functional Viewpoint, focused on the system and component architects, developers and integrators view of the IIoT systems, and usually represented through functional components
- the Implementation Viewpoint, dealing with technologies needed to implement the functional components, their structure and interaction coordinated by activities (usage viewpoint) and supportive of the system capabilities (system viewpoint)

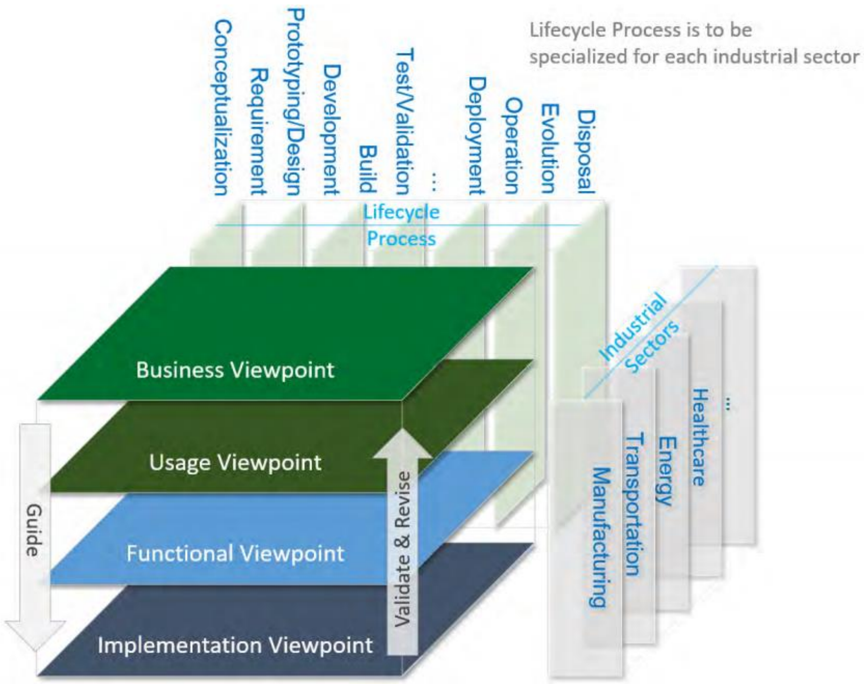


Figure 5: Relationship among IIRA Viewpoints, Application Scope, and System Lifecycle Process.

Through these viewpoints, IIRA provides an architectural framework and methodology to systems designers, including guidance from the conception to design and implementation of IIoT systems, covering important system concerns that may affect the lifecycle process, however without explicitly specifying it (Industrial Internet Consortium (IIC), 2019).

2.1.1.2 RAMI4.0

In contrast to the IIC, the Plattform Industrie 4.0 is focused mainly on the next generation manufacturing systems in the context of the added value through inter-connected cross-domain value chains (Willner, 2018). It specifies the three-dimensional Reference Architecture Model Industrie 4.0 (RAMI4.0) to systematically classify and build upon related technologies and standards of the International Electrotechnical Commission (IEC), primarily for lifecycle management in industrial measurement, control and automation (IEC 62890), enterprise control system integration (IEC 62264) and batch control (IEC 61512) (Willner, 2018). Similar to IIRA, RAMI4.0 introduces six different layers - the business, functional, information, communication, integration and asset layer and cross-sections it with the hierarchy levels and the lifecycle dimensions, as shown in Figure 6.

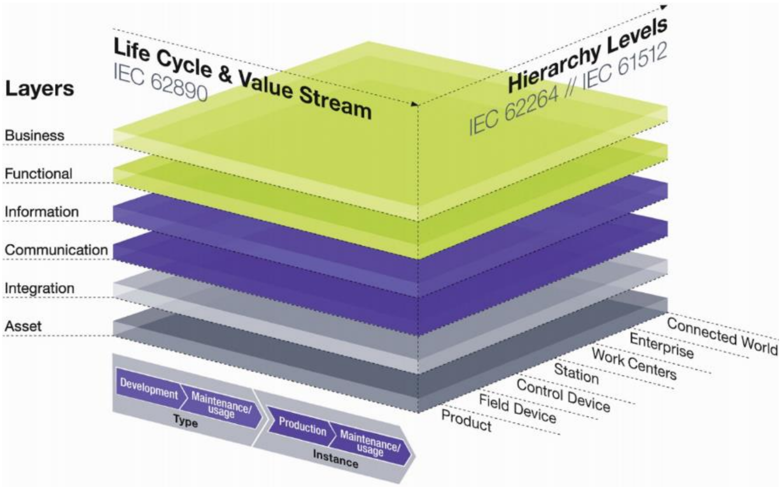


Figure 6: Reference architecture model Industry 4.0 (RAMI4.0).

The purpose of RAMI4.0 is to specify description rules for technical objects through their lifecycles, representing all relevant aspects, from development, production and use rights to their disposal, within virtual representations called components (DIN Deutsches Institut für Normung e.V., 2016). Industry 4.0 components (I4.0 components) are globally and uniquely identifiable participants capable of communication and consist of the administration shell and the asset with a digital connection within an I4.0 system and offer services there with defined quality of service (QoS) properties.

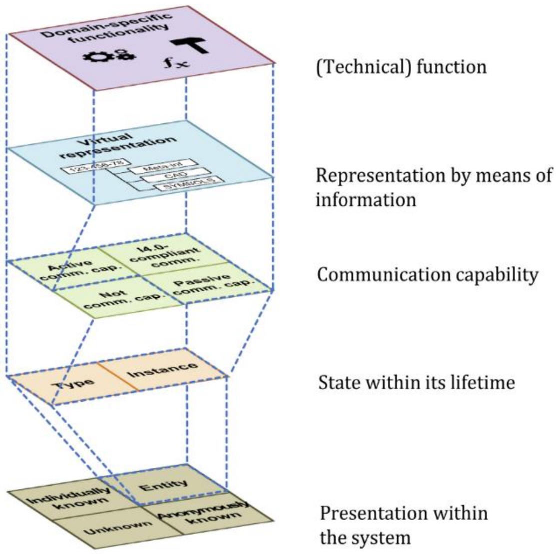


Figure 7: Concepts of an asset.

An asset is presented in a certain way, has a specific state within its life (at least a type or instance), has communication capability, is represented by means of information (data) and has technical functionality, as shown in Figure 7 (DIN Deutsches Institut für Normung e.V., 2016). Each asset has a specific lifetime, during which it serves the purpose for which it was specifically created. Assets of different types with different communication capabilities can be implemented as I4.0 components. In industrial applications, an I4.0 component can be a production system, an individual machine or unit, or a module within a machine (DIN Deutsches Institut für Normung e.V., 2016). An asset is a component only if it is an entity, has at least passive communication capability and has been equipped with an administration shell, as depicted in Figure 8 (DIN Deutsches Institut für Normung e.V., 2016). The administration shell provides the relevant information on the asset and its technical functionality, including information on how to represent it (DIN Deutsches Institut für Normung e.V., 2016).

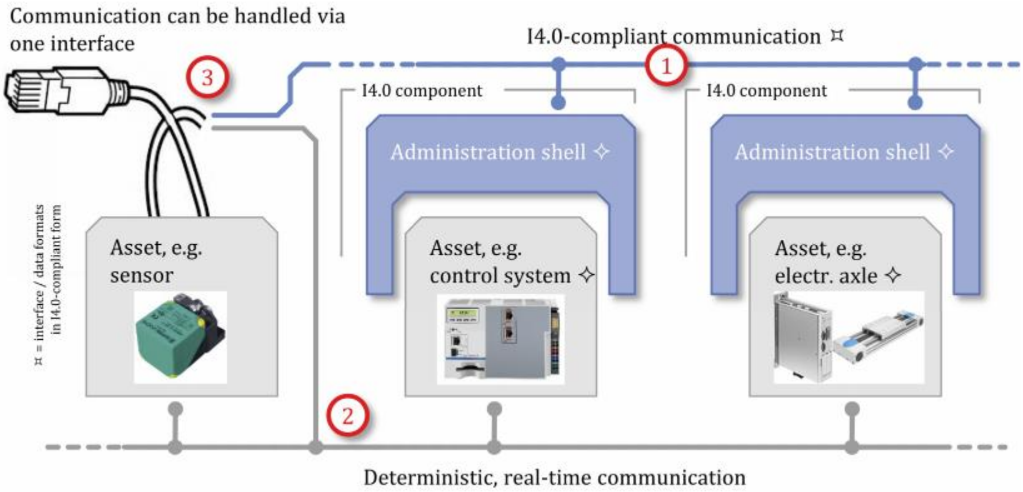


Figure 8: The concept of asset, administration shell and component. Source: (IIC and I4.0, 2017).

2.1.1.3 Alignment between IIRA and RAMI4.0

The key finding of the collaboration between the IIC and Platform Industry 4.0 is the compatibility between the approaches and technologies, as the IIoT focuses on cross-industry commonality and interoperability, while the Industry 4.0 focuses primarily on the manufacturing and includes many aspects of its value chain throughout the full product lifecycle (IIC and I4.0, 2017). A further conclusion was that both IIRA and RAMI4.0 can benefit from providing interoperability between systems based on both architectures (IIC and I4.0, 2017).

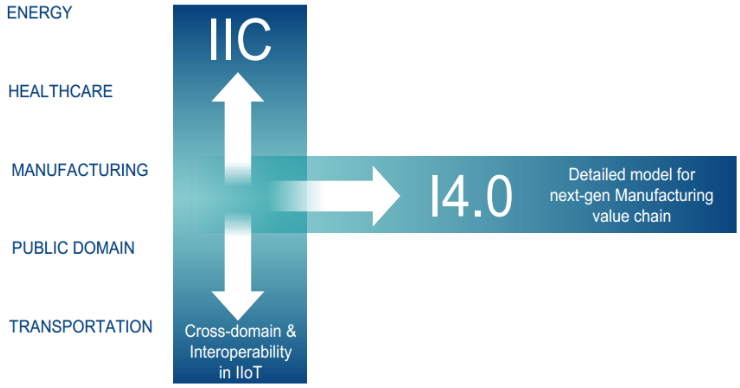


Figure 9: IIC addresses concerns about IIoT across industries broadly; Plattform Industrie 4.0 is concerned specifically and in detail with the domain of manufacturing. Source: (IIC and I4.0, 2017).

IIRA and RAMI4.0 are compatible because they both envision a world where the traditional operational technology (OT), focused on efficiency, utilization, consistency, continuity and safety, meets the Information Technology (IT), concerned with agility and speed, flexibility, cost reduction, business insight and security (IIC and I4.0, 2017). The IIoT is focused on connectivity, data, analytics, optimization, and intelligent operations, driving the convergence between IT and OT, as depicted in Figure 10. The two reference architectures are expected to play an important role in this transformation.

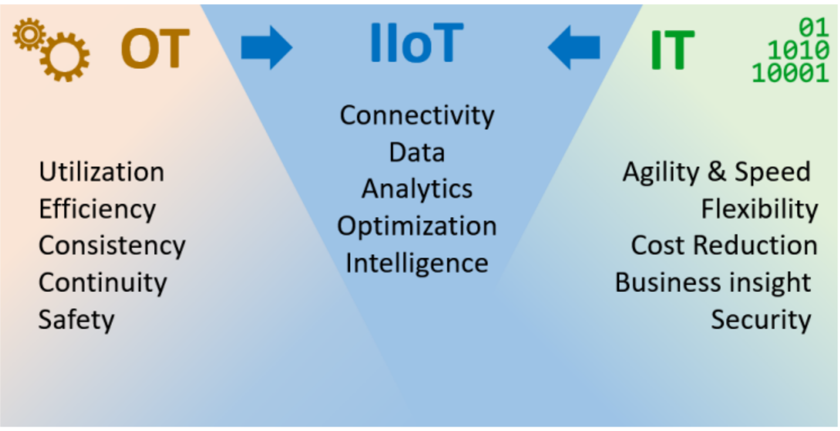


Figure 10: IIoT as a transformational force driving the convergence of OT and IT. Source: (IIC and I4.0, 2017).

IIRA and RAMI 4.0 define concepts and methods for developing concrete architectures, however they are not concrete architectures themselves. The core characteristics of the two reference architectures are juxtaposed against one another in Figure 11.

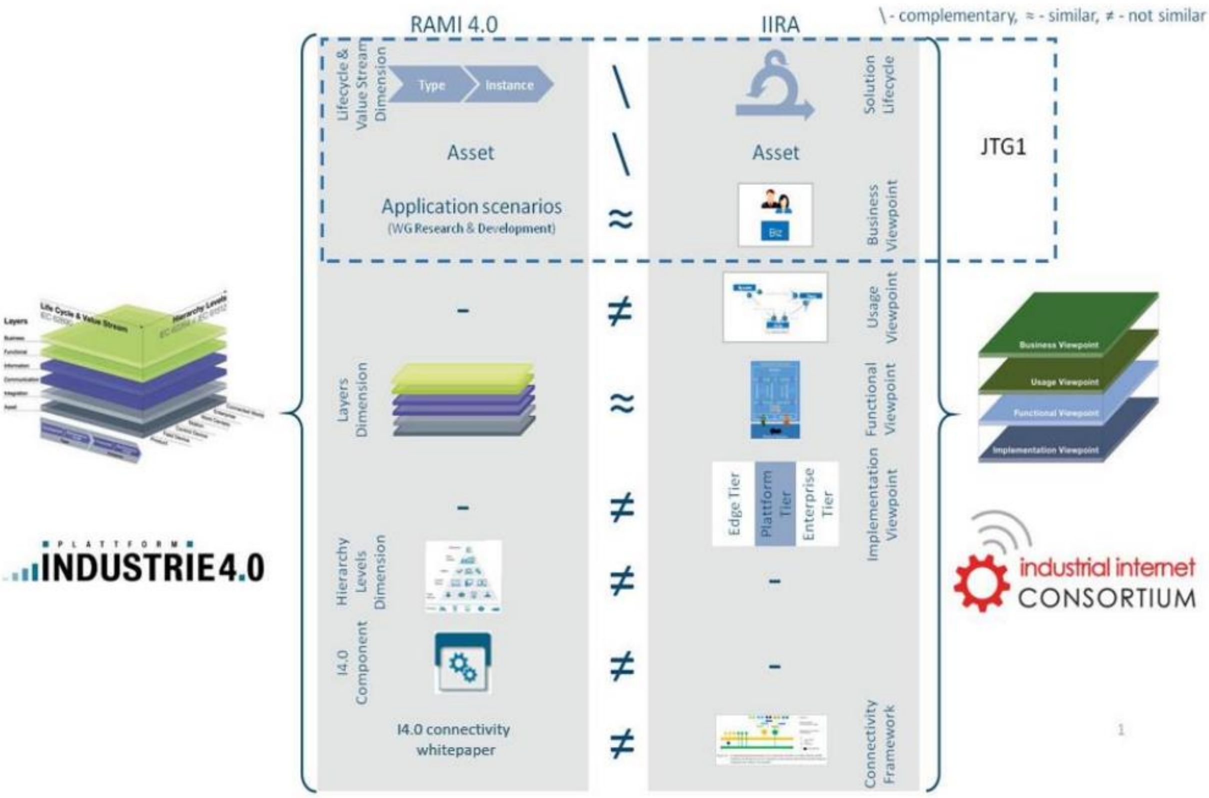


Figure 11: Fundamental concepts of the IIRA and RAMI 4.0, their similarities, and differences. Source: (IIC and I4.0, 2017).

2.2 Communication technologies in automation

The Open Systems Interconnection (OSI) standard and the corresponding Reference Model (RM) for OSI defined in ISO 7498 are the result of decade-long efforts by standardization organizations to fulfill the universal need for interconnecting systems from different manufacturers (Zimmermann, 1980). The RM OSI requires conformance of only the external behavior of participating systems, with their internal organization and functioning left out of scope of the norm (Zimmermann, 1980). The communication between two applications according to OSI takes place across seven intermediary layers (physical, data link, network, transport, session, presentation and application), each providing services to the layer above and using services provided from the layer below, with some of the layers implemented in physical devices, some in the operating system and some in the applications themselves (Kuhn, 1994). OSI provides an abstract specification of the concept of a layer but does not specify the visibility of the boundaries between layers, which is covered by other standards defining application program interfaces (APIs) often corresponding to OSI layer boundaries (Kuhn, 1994).

The RM OSI and the concept of open architecture networking were instrumental in the design of interactions between different networks and are thus key concepts behind the emergence of the Internet. It is to this day one of the most widely used and universally applicable methods for the systematic specification of communication between different systems. In practice, for most Internet applications, the seven-layer architecture of OSI has been replaced by the five-layer IP stack typically referred to as TCP/IP stack (Cirani, Ferrari, Picone, & Veltri, 2019), as shown in Figure 12.

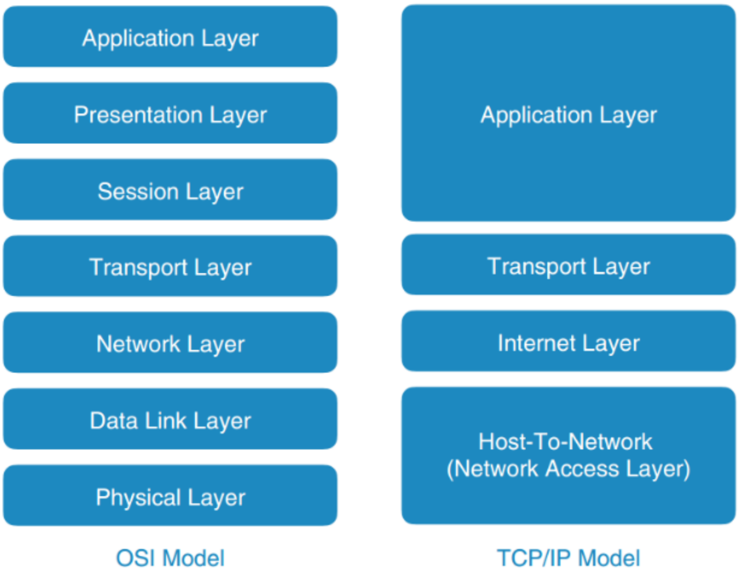


Figure 12: Communication protocol stacks: traditional seven-layer ISO-OSI stack (left) versus four-layer TCP/IP stack (right). Source: (Cirani, Ferrari, Picone, & Veltri, 2019).

The physical/link (Network Access) layer commonly addresses the actual physical interfaces and point-to-point communications with no concept of routing, the most prominent examples being the IEEE 802.3 (Ethernet) and the IEEE 802.11 (family of Wi-Fi standards) (Cirani, Ferrari, Picone, & Veltri, 2019). Currently, a wide adoption of a new version of Ethernet, standardized in IEEE 802.1 and IEEE 802.3 specifications, known as Time Sensitive Networking (TSN) is being expected, which would allow a standardized, open-architecture based time-sensitive communication, enabling utilization of the Ethernet infrastructure flexibility and scalability down to the device level.

The key protocol for inter-networking, enabling efficient and robust routing of datagrams (addressing and forwarding of individual packets) across the Internet in a scalable manner, is the network (Internet) layer Internet-Protocol (IP), defined as a combination of heterogenous networks (Cirani, Ferrari, Picone, & Veltri, 2019).

The primary task of transport layer protocols is to provide transparent host-to-host communication services towards the Application layer, masking the complexity of the underlying networking and link-by-link communication strategies (Cirani, Ferrari, Picone, & Veltri, 2019). The most used transport layer protocols are the TCP/IP protocol suite and the UDP. The transport control protocol (TCP) is used for connection-oriented transmissions, providing guarantees and features such as reliability, flow control, congestion avoidance and multiplexing (Cirani, Ferrari, Picone, & Veltri, 2019). In cases where complex supporting services are not needed, the best-effort-based user datagram protocol (UDP) provides access to IP services (Cirani, Ferrari, Picone, & Veltri, 2019) without unnecessary overhead. The TCP/IP is predominantly used in applications requiring high reliability, but with less stringent temporal requirements, and is an essential part of the infrastructure of the Internet (Cirani, Ferrari, Picone, & Veltri, 2019). UDP supports fast exchange of small amounts of data and, together with its comparatively simple implementation, is the primary candidate for the implementation of IIoT scenarios (Cirani, Ferrari, Picone, & Veltri, 2019).

The Application Layer of the five-layer TCP/IP stack envelops the three upper layers of the ISO-OSI protocol. Application layer protocols are the reason for the widespread adoption of the Internet (Cirani, Ferrari, Picone, & Veltri, 2019), as they have been used by developers to create large-scale distributed applications without having to develop own proprietary communication protocols (Cirani, Ferrari, Picone, & Veltri, 2019). Within the Internet domain, the Hypertext Transfer Protocol (HTTP) is the most important application layer protocol, enabling a stateless text-based request/response communication between clients and a server over a TCP connection (Cirani, Ferrari, Picone, & Veltri, 2019).

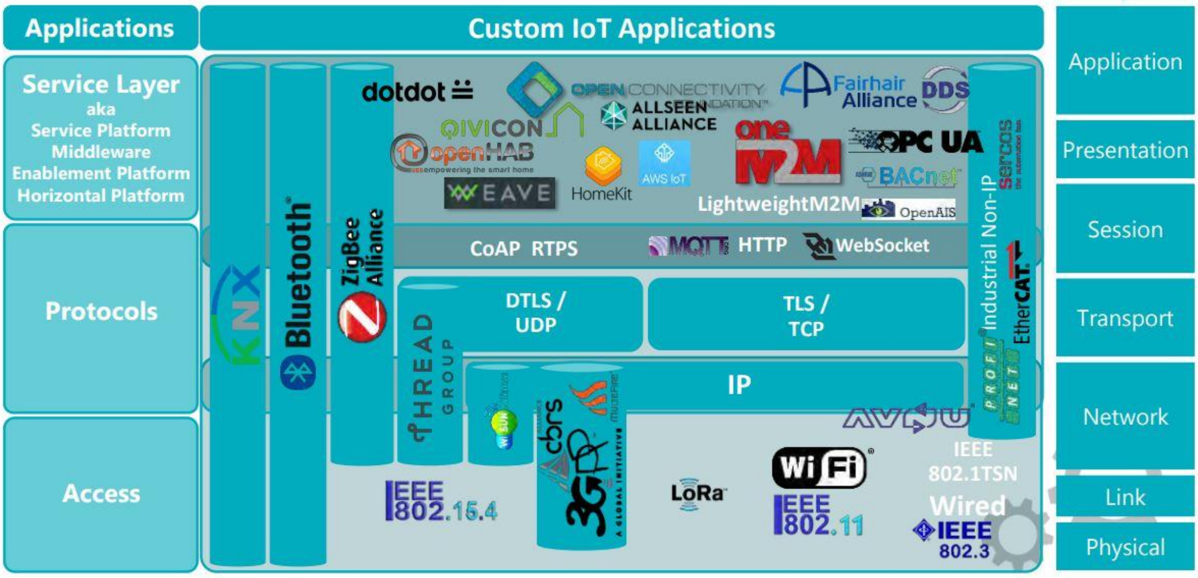


Figure 13: Technologies in IoT Stack. Source: (Blanz, 2012).

Figure 13 shows the most used communication technologies in automation and the most prominent examples of modern IIoT communication systems, in the context of RM OSI and a further simplified version of the TCP/IP stack (Transport and Internet combined into the Protocol layer). The physical/link layer is dominated by the Ethernet (TSN) and Wi-Fi standards, ensuring physical interoperability between the upper protocols. The network, transport and session layers contain the typical Internet protocols (IP, TCP, UDP, HTTP, WebSocket), together with more modern protocols developed especially for constrained Internet communication (MQTT, CoAP, RTPS). However, as is the case with the traditional Internet, the main role in the further evolution and widespread adoption of IIoT concepts and principles is expected to be played by application layer protocols, with OPC UA and oneM2M being the most prominent examples.

2.2.1 Industrial communication protocols

Since the introduction of the PLC concept in the late seventies up until the late nineties, the world of automation has been dominated by monolithic system and software models with centralized intelligence. However, even in the early days, communication between devices was a necessity. Due to the nature of the controlled systems, the early communication technologies were primarily focused on determinism and delivering the necessary timing characteristics. With time, from the first prototype communication technologies, robust bus systems were developed, named fieldbuses and capable of rapid exchange of small amounts of data with guaranteed time of delivery. Some of the most prominent examples are the Profibus or Modbus.RTU, only recently being replaced on the leading position in industrial communication by more modern, Ethernet-based real-time capable fieldbuses, such as PROFINET, EtherNet/IP, EtherCAT or Modbus.TCP, as can be seen from Figure 14.

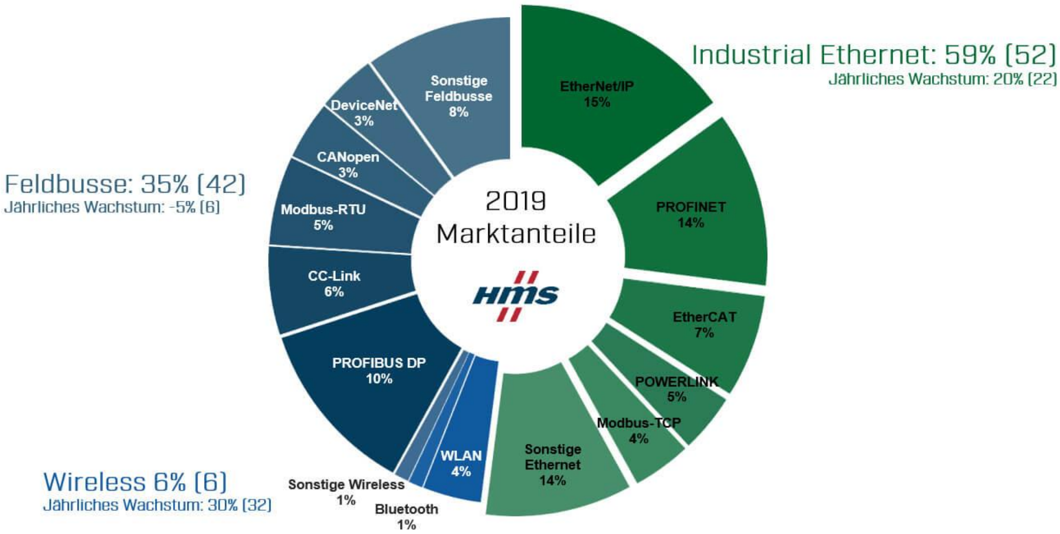


Figure 14: Market shares of industrial bus systems and networks in 2019. Source: (HMS, kein Datum).

Figure 15 shows the landscape of typical communication technologies applied in the domain of building automation. In addition to low-level protocols for specific requirements (such as DALI for lighting or ZigBee for low-power applications), Modbus TCP, BACnet and KNX are of special importance. CANopen, even though represented in building automation in a percentage of legacy applications, is prevalently used in motor control applications, in the automotive industry, robotics and medical applications.

Figure 15: Technologies in industrial and building automation bridged by OPC UA. Source: (Mätzler, Wollschläger, Fernbach, Kastner, & Huschke, 2013).

2.2.1.1 Industrial Ethernet fieldbuses

Most of the Ethernet-based fieldbuses implement only its physical layer in a standardized manner, with the datalink layer having to be extended with concepts necessary for determinism. For the same reason, as can be seen from Figure 13, Profinet, EtherCAT and Sercos implement their own network layer and above. Some, like Modbus.TCP or Ethernet/IP adopt the widely used network and transport protocols (TCP and IP) and expand them with additional constructs to ensure real-time capabilities. They can be considered the predecessors of modern communication technologies, as they organize networked devices as collections of objects, allowing heterogenous devices to exchange information using common mechanisms. However, in addition to computation overhead which reduces their scalability, the big disadvantage of most Industrial Ethernet protocols is their original model of interaction based on serial bus protocols, with simplistic data model lacking structuring capabilities or any notion of loose coupling. With the emergence of TSN as the underlying Ethernet infrastructure capable of real-time communication also for constrained devices, most of the mentioned protocols are reinventing themselves as being adherent primarily to the application layer.

The biggest competitors of Industrial Ethernet fieldbuses in recent times are upcoming standards such as OPC UA, DDS or oneM2M, native application layer protocols designed without need for the consideration of technological limitations, purely for communication and interoperability, with more capable modern interaction and data specification mechanisms. In combination with the already established session layer protocols such as WebSocket, or AMQP and MQTT which were designed for constrained devices, they build a powerful infrastructure for every kind of complex interaction envisioned by IIoT. Be that as it may, fieldbuses have been around for a long time and provide some undeniable advantages, such as reduced power consumption, which is crucial in some application areas, and is generally a desirable characteristic. However, further convergence of fieldbus technologies towards the application layer is to expected, where the know-how they embody can be utilized, i.e. in the form of semantic classification and specifications of non-functional communication requirements, such as Quality of Service (QoS), in specific domains of application.

2.2.1.2 Modbus

Originally, the Modbus was created as a simple communication protocol between control data and sensors using an RS232 port, but has since evolved to support many different interfaces and media, including RS422, RS485, radio, cellular and, most importantly for the modern IIoT communication paradigms, TCP/IP, as shown in Figure 16 (Belliardi & Neubert, 2015). Modbus is a message-based client-server protocol, where transactions take place between applications using application protocol data units (APDUs), aggregate structures containing unit identifier, code, and data fields, common for all underlying layers across transport media (Belliardi & Neubert, 2015). It provides support for different communicational capabilities offered by the currently used underlying layer (one to one, one to many, error checking, pipelining, etc.) (Belliardi & Neubert, 2015).

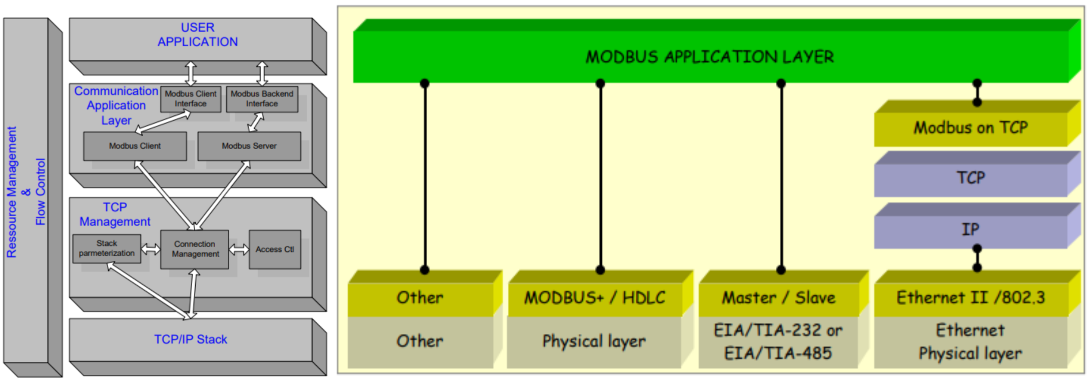


Figure 16: MODBUS Messaging Service Conceptual Architecture and communication stack. Source: (Belliardi & Neubert, 2015).

Modbus is a widely spread protocol, primarily for its commitment to simplicity, focus on basics, and recognition of advantages in delegating the handling of industrial automation diversity to applications. Some other advantages include a small footprint and capability to run on constrained systems (although this is less true for the TCP/IP variant), as well as scalability in complexity, scope, and range (Belliardi & Neubert, 2015). However, this focus on simplicity can obviously be a limiting factor as well, as some level of the data-model and inter-object communication mechanisms is a necessity in most mid- to large-scale applications, and can bring advantages to small-scale applications as well, allowing system designers and engineers to focus more on the actual problem domain, instead of worrying about system-level concerns.

2.2.1.3 KNX

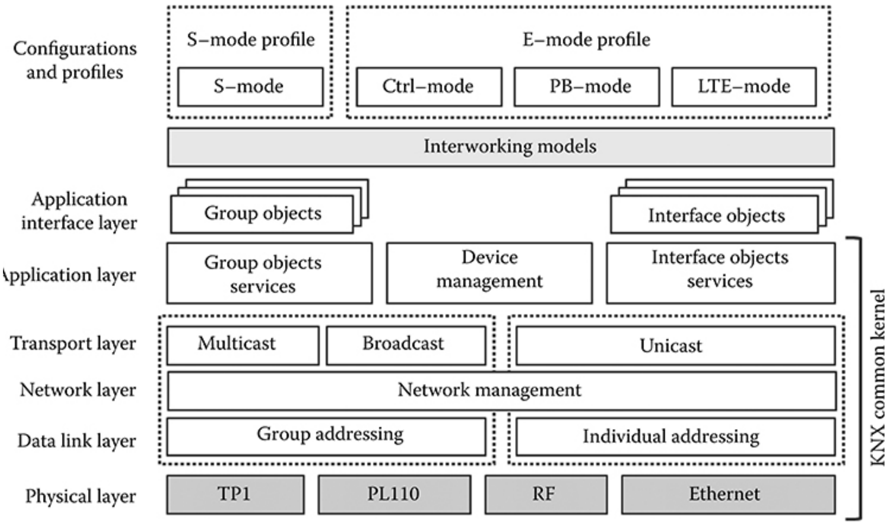


Figure 17: KNX protocol stack and reference architecture. Source: (Ruta, Scioscia, Loseto, & Di Sciascio, 2015).

KNX, standardized in ISO/IEC 14543-3 and EN 50090, is a decentralized technology developed specifically for application in home and building automation (KNX Association). The original communication medium is the KNX Twisted Pair (TP), with the standard now supporting KNX Powerline (PL), KNX Radio Frequency (KNX RF) and KNX IP for different requirements (KNX Association). Figure 17 shows the KNX communication stack in the context of OSI, together with its core architectural concepts, Group and Interface objects and services, Device management, and configurations and profiles. The KNX system provides many advantages, including exceptionally low energy consumption (especially in combination with TP and RF), decentralized bus architecture, easy and straightforward cabling (KNX Association). Additionally, it was (and still is) one of the first technologies to provide a complete domain solution with pre-defined proprietary object types, and the possibility of installing systems without programming, solely through configuration. However, its system model makes it applicable only in certain use-cases and domains such as home and building automation and is closed off for the implementation of complex and inventive scenarios, which would require additional architectural concepts.

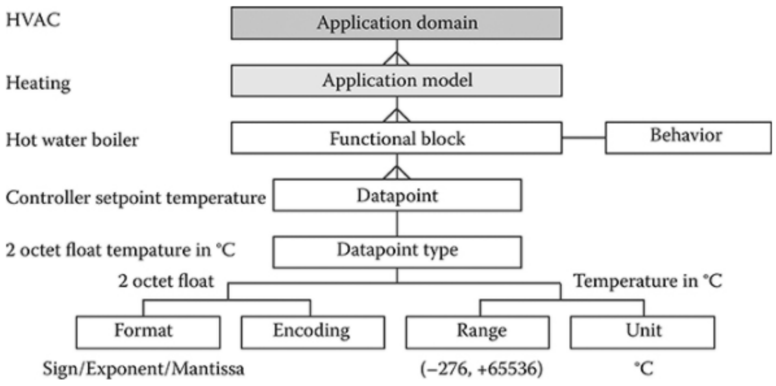


Figure 18: Example of KNX application modeling. Source: (Ruta, Scioscia, Loseto, & Di Sciascio, 2015).

Main abstraction unit in KNX, as depicted in Figure 18, are Functional Blocks (FBs) capable of communication with each other, and Data Points (DPs), which are essentially named variables of certain Data Point Type (DPT), used as main structural units in KNX communication (Ruta, Scioscia, Loseto, & Di Sciascio, 2015). Groups of FBs form applications, which form application domains.

2.2.1.4 BACnet

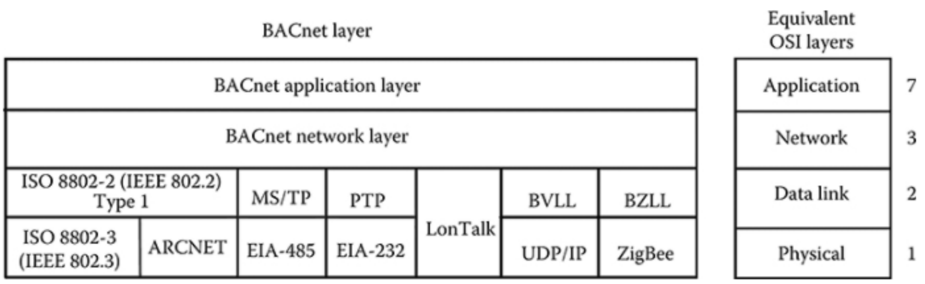


Figure 19: BACnet data-link layers in the ISO/OSI model. Source: (Schubert, 2015).

The Building Automation and Control Networking (BACnet) is the second example, in addition to KNX, of a functioning, domain-specific communication standards, which enables creation of automation application with little to no programming. BACnet is standardized within ISO 16484-5&6 and ANSI norming organization (BACnet International). Core idea behind BACnet is interoperability between systems of different vendors, however it also specifies functionality like file access, alarming, scheduling, trend logging, and remote device management (Schubert, 2015). Similar to other communication standards, it contains three major parts – the network media, objects to transport building automation data, and corresponding services for data transport (Schubert, 2015). It uses an object-oriented model for abstracting and representing information and includes a number of standardized objects for common applications, in addition to an extension mechanism which provides system architects and engineers with possibilities to create own types of objects (BACnet International). Figure 19 shows the BACnet communication stack in the context of OSI. BACnet supports several communication media, including twisted-pair and Ethernet or IP-centric infrastructures (BACnet International). However, it suffers from same disadvantages as the KNX, with a simple system and communication model capable of representing only use cases building automation.

2.2.2 Internet communication for constrained devices

The widely applied and tested Web technologies such as HTTP have been around for a long time and have an accordingly developed community and specter of products (Cirani, Ferrari, Picone, & Veltri, 2019). Together with their proven scalability, this makes Web technologies a perfect reference for the implementation of IIoT architectures and systems, where billions of devices will be interconnected (Cirani, Ferrari, Picone, & Veltri, 2019). At the same time, differences between requirements on IIoT systems and typical object systems of Web technologies, such as constrained computational or communicational capabilities, have to be taken into consideration. Currently, the most prominent HTTP-like session layer protocols for applications on (among others) constrained devices are the AMQP, MQTT and CoAP.

2.2.2.1 AMQP and MQTT

AMQP is based on queue servers, i.e., message storage facilities, and provides the possibility of direct communication, or topic-based routing of tagged messages known as exchange, with the possibility of fine-grained routing using wildcards (Cirani, Ferrari, Picone, & Veltri, 2019). Queues may be persistent (not tied to existence of consumers) or dynamically created (message deleted at user disconnection) (Cirani, Ferrari, Picone, & Veltri, 2019). AMQP supports reliable delivery and provides possibilities for different messaging scenarios (message queue, fanout or routing), including even remote procedure calls (RPCs) (Cirani, Ferrari, Picone, & Veltri, 2019).

In MQTT, the broker contains a shared hierarchical topic space, to which messages are published by the participants, filtered according to the topic, and delivered to matching subscribers (Cirani, Ferrari, Picone, & Veltri, 2019). Parts of the topic hierarchy can be used as filters, and wildcards applied to path segments for finer granularity (Cirani, Ferrari, Picone, & Veltri, 2019). A subscription in MQTT can be considered a conditional real-time receive operation, as the subscription filters are applied directly to the message stream to efficiently determine the recipients.

The similarities of AMQP and MQTT are (Cirani, Ferrari, Picone, & Veltri, 2019):

- asynchronous, message queuing protocols
- based on TCP
- implementing an application-layer multicast
- use TLS for security at the transport layer
- widely available implementation for major platforms and programming languages.

The differences between AMQP and MQTT are (Cirani, Ferrari, Picone, & Veltri, 2019):

- MQTT is more wire-efficient and requires less effort to implement than AMQP; it is well suited to embedded devices. AMQP provides greater flexibility.
- MQTT provides hierarchical topics with no persistence (stream-oriented approach); AMQP does not provide a hierarchical topic structure but offers persistent queues as a message storage facility (buffer-oriented approach).

- In MQTT, messages are published to a single global namespace. In AMQP, messages can be sent to several queues.
- In MQTT, the broker has AMQP supports transactions, while MQTT does not.

2.2.2.2 CoAP

The CoAP protocol stack is built with HTTP as reference and supports easy mapping and full interoperability between HTTP and CoAP clients and servers, enabling legacy applications to interact with modern systems (smart objects) without any adaptations necessary (Cirani, Ferrari, Picone, & Veltri, 2019).

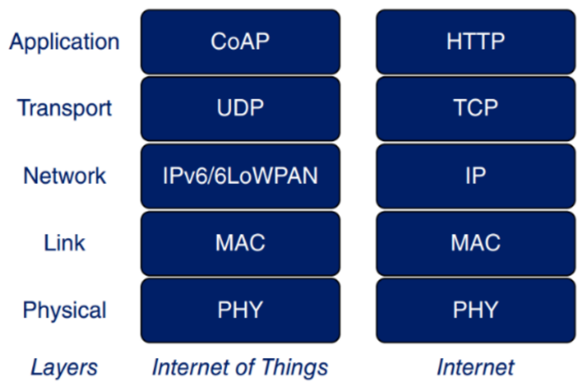


Figure 20: CoAP protocol stack vs. HTTP protocol stack.

CoAP runs on top of UDP, minimizing overhead related to establishment and maintenance of (TCP) connections, and implements a lightweight message structure, making them easy to parse, in sum drastically reducing computational requirements on implementing devices and their energy consumption (Cirani, Ferrari, Picone, & Veltri, 2019). CoAP provides support for some IoT-oriented features, e.g., asynchronous message exchange, resource observation and multicast communication.

2.2.3 Modern communication and interoperability in automation

Figure 21 shows the IIoT connectivity stack, as envisioned by the IIC. Building on top of Ethernet and TSN, the Internet infrastructure expanded with modern session layer protocols for constrained devices, powerful application layer protocols for communication modeling in any imaginable scenario are made possible. These include the conventional Web Services and the Data Distribution Service (DDS), built explicitly for rapid exchange of small amounts of data on enormous scale, with powerful QoS specification mechanisms. For the application within the IIoT, however, the oneM2M interworking middleware for horizontal interoperability across vertical markets (energy, healthcare, manufacturing, transportation) and the OPC UA connectivity standard for interoperability and information modeling within the industrial, i.e., manufacturing domain, are technologies of gravest importance. In the context of RAMI4.0, OPC UA is an open standard expressing the Communication and Information hierarchy layer.

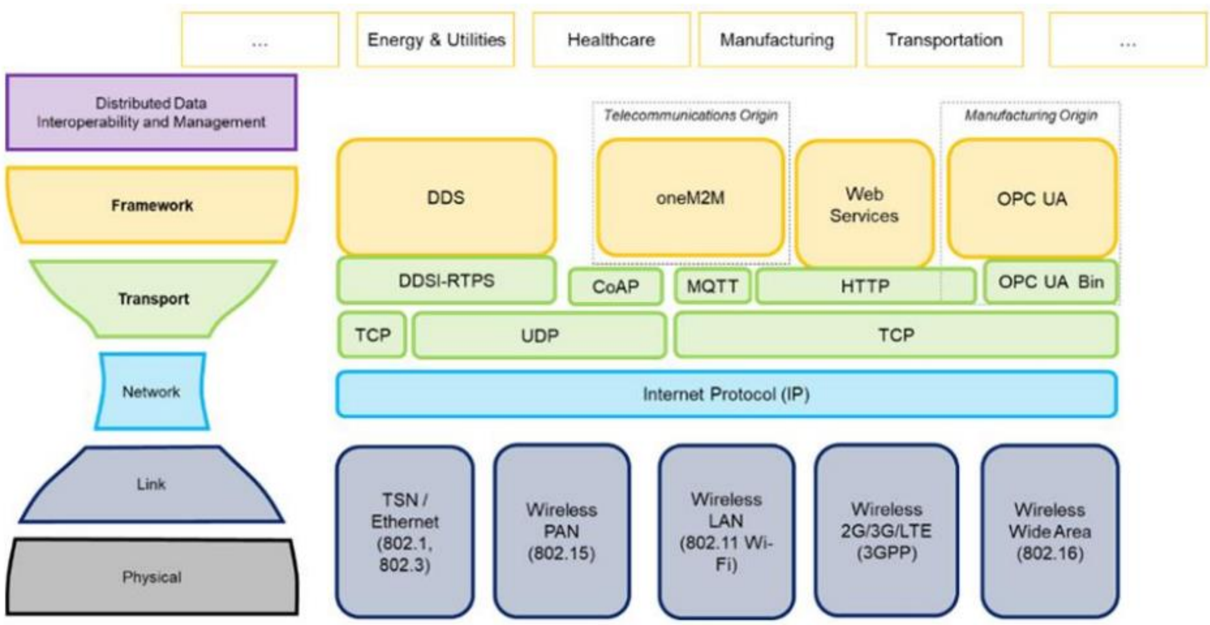


Figure 21: IIoT connectivity stack. Source: (IIC and I4.0, 2017)

2.2.3.1 oneM2M

The oneM2M standard is an M2M and IoT technology with “distal” scope, agnostic to the underlying networking technology and concerned with large scale deployments of devices in an overlay network, hiding complexity of network usage, as well as storing and sharing of distributed data (Blanz, 2012). Its focus is the horizontal layer of functions commonly needed across different market segments (energy, home, assets, manufacturing) (Blanz, 2012).

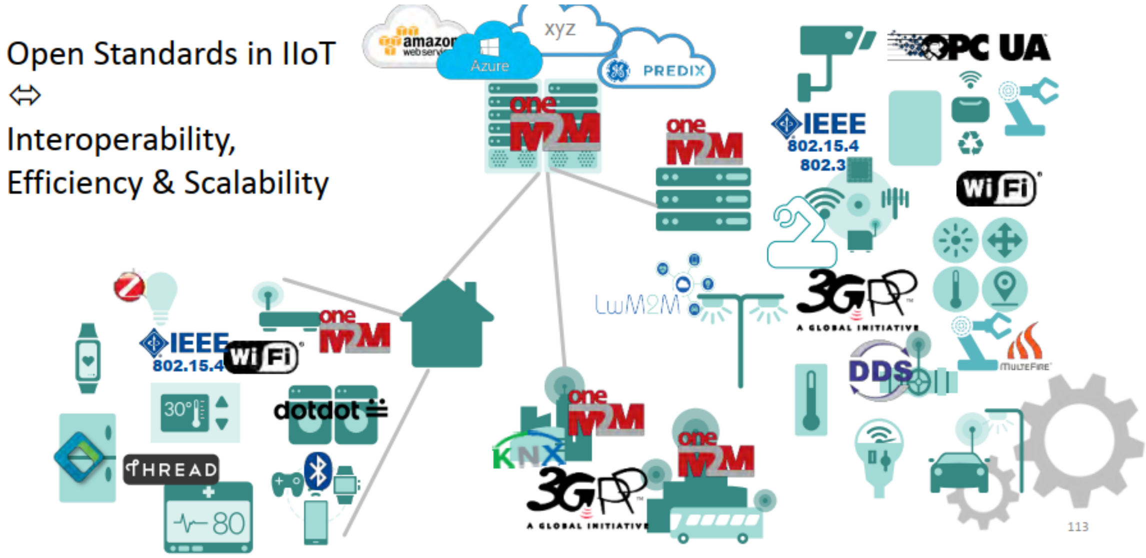


Figure 22: The oneM2M vision: Acting as interworking "glue". Source: (Blanz, 2012)

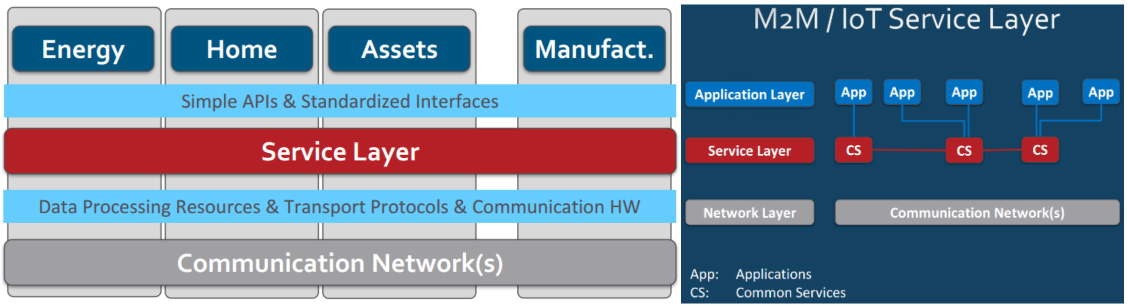


Figure 23: Functional architecture of oneM2M. Source: (Blanz, 2012).

As shown in Figure 22, the primary focus of oneM2M is on interworking, consolidation, and simplification of already existing, mainly very complementary open standards (Blanz, 2012). Figure 23 shows the generic layered functional architecture of oneM2m, consisting of the Network, Service and Applications layers. Figure 24 shows the topology of an oneM2M system and an example of use, where different devices publish their asset administration shells (AAS) through the oneM2M middleware, which makes it available to analysis and visualization applications over a conventional Internet protocol (HTTP).

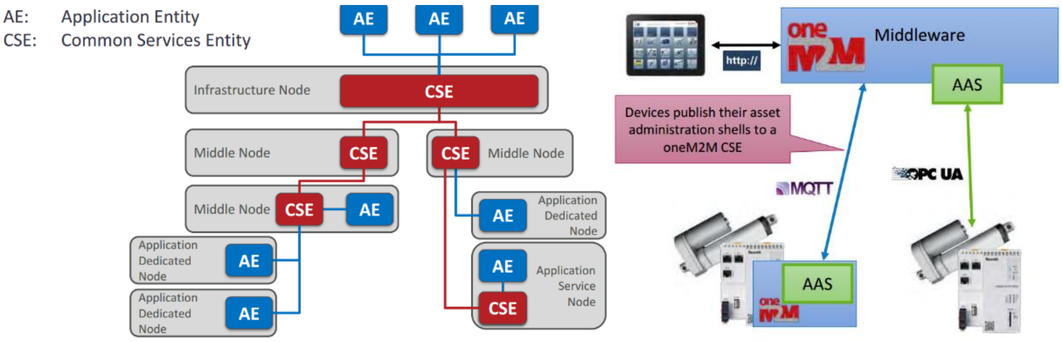


Figure 24: Topology and Infrastructure with oneM2M. Source: (Blanz, 2012).

2.2.3.2 OPC UA

The IEC 62541 norm, also known as OPC Unified Architecture (OPC UA) is the evolution of the OPC Specification, introducing the advances from the computer science world (OOP, SOA, Semantic Web, Network Model Databases) to the tested and proven capabilities of its predecessor. As can be seen from Figure 25, OPC UA is meant primarily as an interoperability norm, enabling transparent communication among heterogenous systems, and is considered one of the key technologies within the IIC and Industry 4.0 initiatives.

Figure 25: Overview of OPC Foundation collaborations. Source: (OPC Foundation, kein Datum).

Communication between distributed systems	*Modeling Data*
• Redundancy, robustness and fault tolerance	• Common model for all OPC data
• Platform-independence	• Object-oriented
• Scalability	• Extensible type system
• High performance	• Meta information
• Internet and firewalls	• Complex data and methods
• Security and access control	• Scalability from simple to complex models
• Interoperability	• Abstract base model
	• Base for other standard data models

Figure 26: Requirements and goals of OPC UA. Source: (Mahnke, Leitner, & Damm, 2009).

OPC UA is meant as much for data modeling as it is a technology for communication between distributed systems, as can be seen from the requirements and goals listed in Figure 26. OPC UA models Clients and Servers as interacting partners, multiple of which can be contained within a system, and allows for the possibility of combining both functionalities into a coherent unit (OPC Foundation, 2015). The Client initiates a request, and the Server responds, e.g., over a secure channel. The OPC UA architecture is shown in Figure 27.

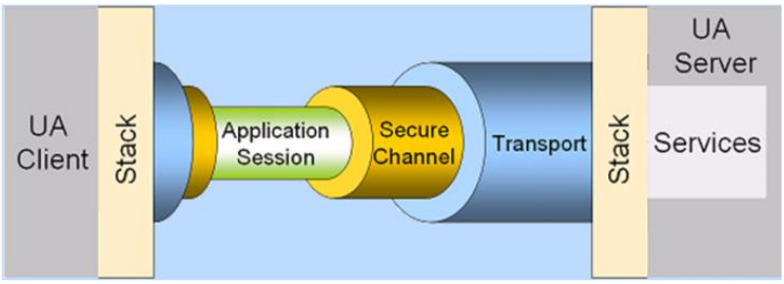


Figure 27: The client-server architecture of OPC UA. Source: OPC Foundation.

The core concepts of the OPC UA information model are Nodes and References, which span its address space (OPC Foundation, 2015). Nodes can have different base classes, the most important ones being variables, methods, and objects, all of which are a part of the integrated object model (OPC Foundation, 2015). Objects are containers which structure the address space and encompass variables and methods (OPC Foundation, 2015). A Reference is a connection between two nodes and can be accessed only indirectly, by browsing a Node and following References (Mahnke, Leitner, & Damm, 2009). To expose different semantics on how the Nodes are connected, ReferenceTypes are used, which are defined as nodes (and can thus be accessed by a client) and are organized in a separate hierarchy (Mahnke, Leitner, & Damm, 2009).

As OPC UA is applicable to systems of different scale and capabilities, from small embedded devices, where small amounts of data have to be transferred in short time intervals, to enterprise systems where efficient handling of structured data is more important, it specifies abstract OPC UA Services as interfaces between clients and servers, which can be mapped to different transport mechanisms for different requirements (Mahnke, Leitner, & Damm, 2009). In practice, OPC UA consists of implementable specifications, communication stacks, SDKs (in multiple programming languages) and higher-level third-party toolkits (OPC Foundation, 2015).

2.3 Knowledge engineering in automation

2.3.1 Information modeling

Computer technologies are used to support and optimize activities throughout a product's lifecycle, with transparent and efficient information exchange between systems being the most critical issue, and formal and unambiguous information modeling languages the major enabler of consistent large-scale, complex, networked computer environments (Lee, 1999). An information model represents a given domain or application from a specific viewpoint, using concepts as entities, attributes and relationships, as well further concepts derived from them. The concept of a viewpoint is exceptionally important, as it reflect the specificity of a certain model and helps to define and limit its scope. A further important aspect of information modeling is the choice of modeling technologies, as it has a direct impact on the complexity of the resulting model, and consequently its implementability and usability.

The most relevant modeling methodologies are the entity-relationship (ER), the functional and the object-oriented (O-O) approach (Lee, 1999), each with their own advantages and disadvantages, depending on the particular modeling subject and viewpoint. The ER approach is the generic modeling technique, most prominently used in design of databases, and is also the basis for the functional and O-O approach. The ER approach is best utilized in applications with high level and detailed static data requirements (Lee, 1999). Where data changes dynamically and functions are more complex than data, the functional approach may be more appropriate, using objects and functions over objects as basis and data-flow diagrams to depict the transformation of data as it passes through the system (Lee, 1999). Finally, the O-O approach introduces a critical paradigm shift, focusing primarily on defining objects of the domain and adding functions later in the design process (Lee, 1999).

The process of information model development is a three-step iterative process, consisting of scope definition, requirements specification, and model development, as shown in Figure 28, each of them of equal importance in creating a coherent and valid model.

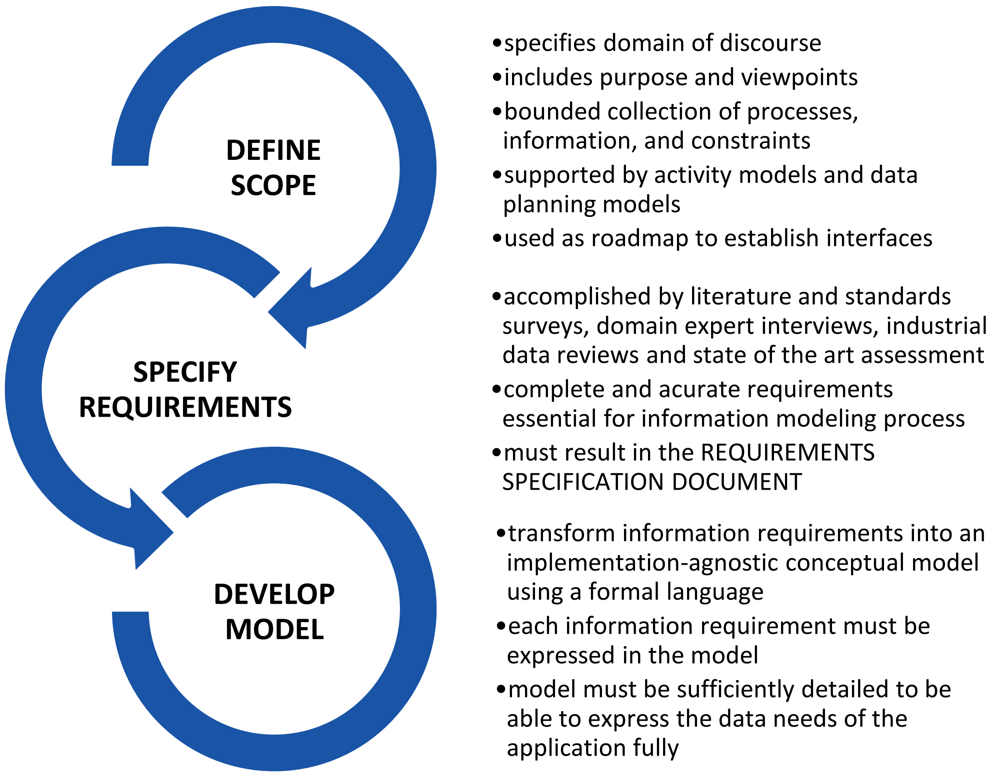


Figure 28: Information Model Development Process. Adapted from (Lee, 1999).

One of the most important decisions in the process of creating an information model is the choice of the modeling language(s). There exist many different languages for different requirements and purposes, the most prominent formal general-purpose ones being EXPRESS and UML, both providing graphical as well as textual representation. EXPRESS or ISO 10303-11 is part of the Standard for the Exchange of Product model data (STEP), is based on programming languages (Ada, Algol, C, C++, Euler, PASCAL) and the O-O paradigm, and allows unambiguous object definition and specification of data properties, constraints and operations (Lee, 1999). UML is a widely known and accepted general modeling language based on the O-O paradigm, which organizes models in a number of complementary views representing different aspects of a systems, using diagrams representing common O-O concepts such as classes, objects, messages, and relationships between them (Lee, 1999).

The following implementation methods, issues and lessons learned related to information modeling are listed in [20]:

a. Information requirements serve as the foundation of the model. A thorough requirements analysis is a necessity. Literature surveys, standard surveys, domain experts' interviews, industrial data reviews, and state- of-the-art assessments are a source of capturing knowledge. Workshops are a good way to gather requirements.

b. Modeling is an iterative process, as refinements are often necessary. As iteration continues, the information model obtained at the end of each iteration is presented to the user community to obtain further feedback. Based on the feedback, either another iteration starts, or the information model is cast in concrete.

c. It is useful to establish a set of naming conventions for a big and complex model in the beginning of the modeling effort. The naming conventions should be descriptive in nature. Advantages for using naming conventions are consistency, ease of identifying entities, and ease of collaboration.

d. Developing a glossary of terms that are used by the applications is also useful. The purpose of the glossary is to provide a unique definition for each term to eliminate improper use due to conflicting definitions.

e. There are several common problems during the implementation process. If a particular information model serves as the medium for transferring the data, the application system should be brought into some degree of compliance with this information model. Occasionally, there is no complete data mapping between the model and the system. If the data requirements are not complete, further requirements analysis should be conducted. For proprietary data, implementation-specific arrangements should be made.

f. Using different measurement units is another common error in an implementation. Under this situation, the attributes in different units should be included in the information model.

g. Conflicts in precision is another issue. The information model should specify precision for numeric data. If the application system carries a lower precision, the accuracy may be lost.

h. Sometimes the same terms may have different meanings or different terms may have the same meaning. The glossary mentioned in item d) that precisely defines all terms presented with the information model is an effective solution to this problem.

i. Having industry reviews of the information model is critical. It helps to ensure the model's necessity, correctness, and completeness.

2.3.2 Building Information Modelling and Facility Management (BIM & FM)

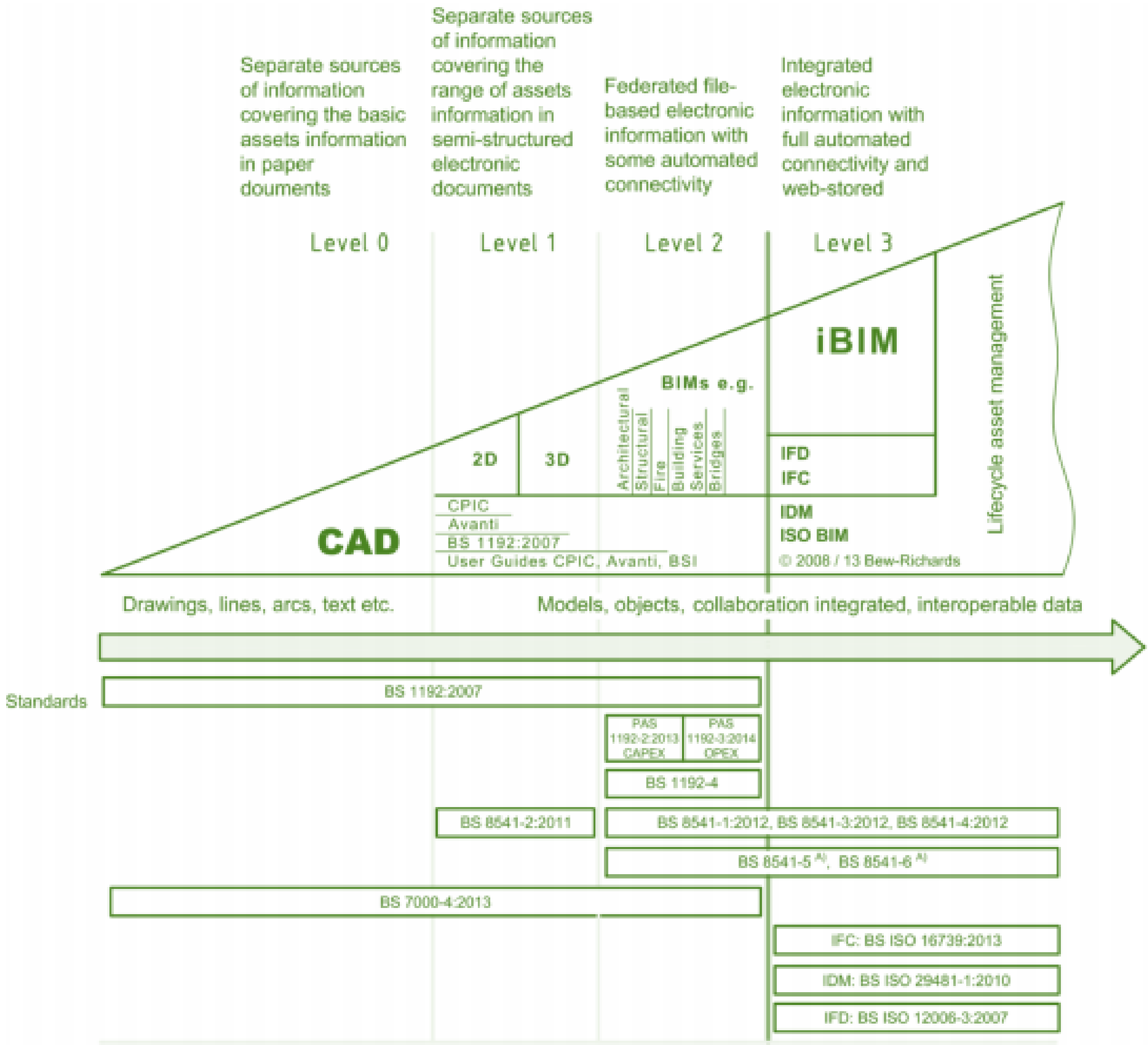


Figure 29: BIM-relevant Norms in a maturity level model (British Standards Institution).

The Building Information Management (BIM), standardized in ISO 19650, was developed in order to consolidate the large number of different information sources throughout the lifecycle of a building, and consists of one or more accurate virtual (digital) models, containing precise geometry and data needed to support the construction, fabrication, and procurement activities through which the building Is realized, operated, and maintained. BIM is a modeling technology and associated set of processes to produce, communicate, and analyze building models, characterized by (Sacks, Eastman, Lee, & Teicholz, 2018):

- Building components represented with objects, carrying computable graphic, identification data and parametric rules
- Components that include behavior descriptions
- Consistent and redundant data

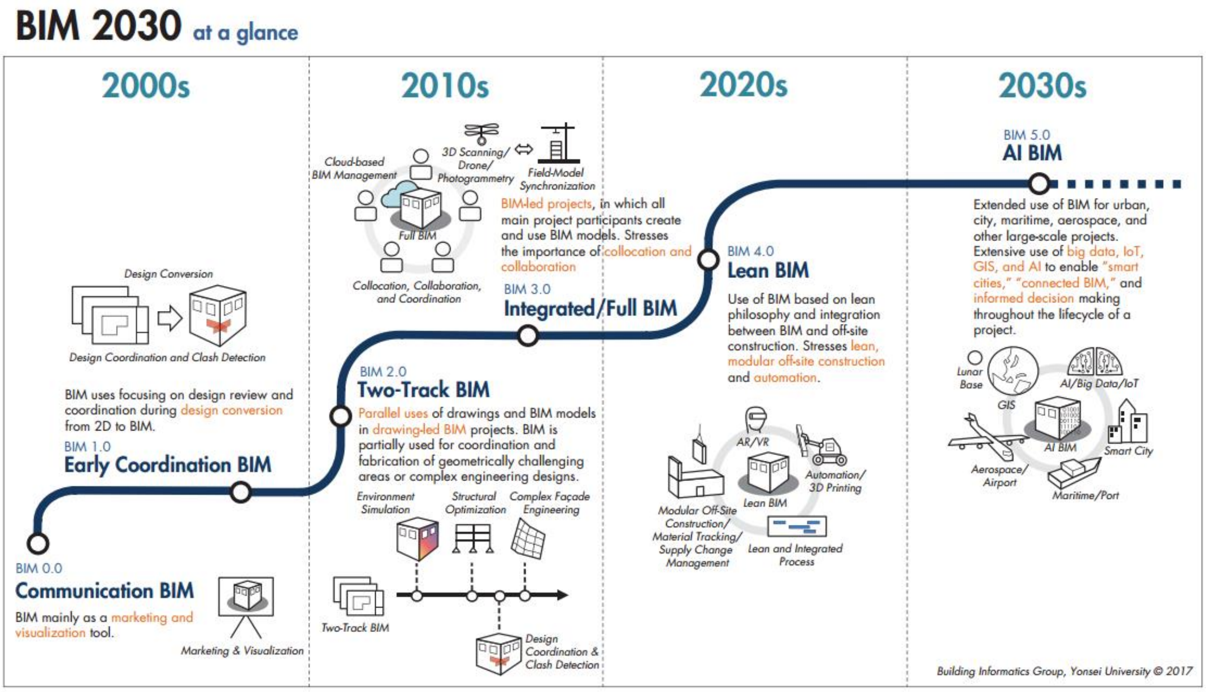


Figure 30: BIM development through the decades. Source: (Sacks, Eastman, Lee, & Teicholz, 2018).

One way of classifying BIM models is according to the level of implementation of information technology, i.e., maturity. Figure 30 depicts the development of the BIM standard through the decades, together with prediction for the future evolution towards completely automatized processes with utilization of artificial intelligence.

Due to the generic nature of BIM, it can be utilized in different scenarios and improve many business practices, reducing variation and cycle times, enabling visualizations, simulations and analysis of construction products and processes, as well as improving information flows in general (Sacks, Eastman, Lee, & Teicholz, 2018). The biggest challenge for BIM is the paradigm shift it introduces to all participants of the process (collaboration and teaming, legal changes to document ownership and production, changes in practice and use of information) and implementation issues connected to variety and complexity of handled data (Sacks, Eastman, Lee, & Teicholz, 2018).

Essential for reaching the next threshold in construction and building information management are interoperability technologies enabling collaborative work processes with smooth information exchange (Sacks, Eastman, Lee, & Teicholz, 2018). The most important interoperability standard in connection with BIM is the Industry Foundation Classes (IFC) or ISO 16739 international standard for building product data models, a *logical schema* based on the ISO STEP EXPRESS language with a few minor restrictions (Sacks, Eastman, Lee, & Teicholz, 2018). IFC is designed as an extensible framework to address all building information over the entire lifecycle (Sacks, Eastman, Lee, & Teicholz, 2018). In addition to IFC which is responsible for data modeling, additional dimensions of specification are necessary in order to enable a seamless data exchange – some of the most prominent in the BIM ecosystem are the buildingSMART Data Dictionary (bSDD) and Information Delivery Manual (IDM) (Sacks, Eastman, Lee, & Teicholz, 2018). In simple terms, the IFC represents the format, the IDM the process and bSDD the meaning (Jaritz, 2018). Figure 31 shows the central role of the IFC in information exchange between elements of a BIM ecosystem.

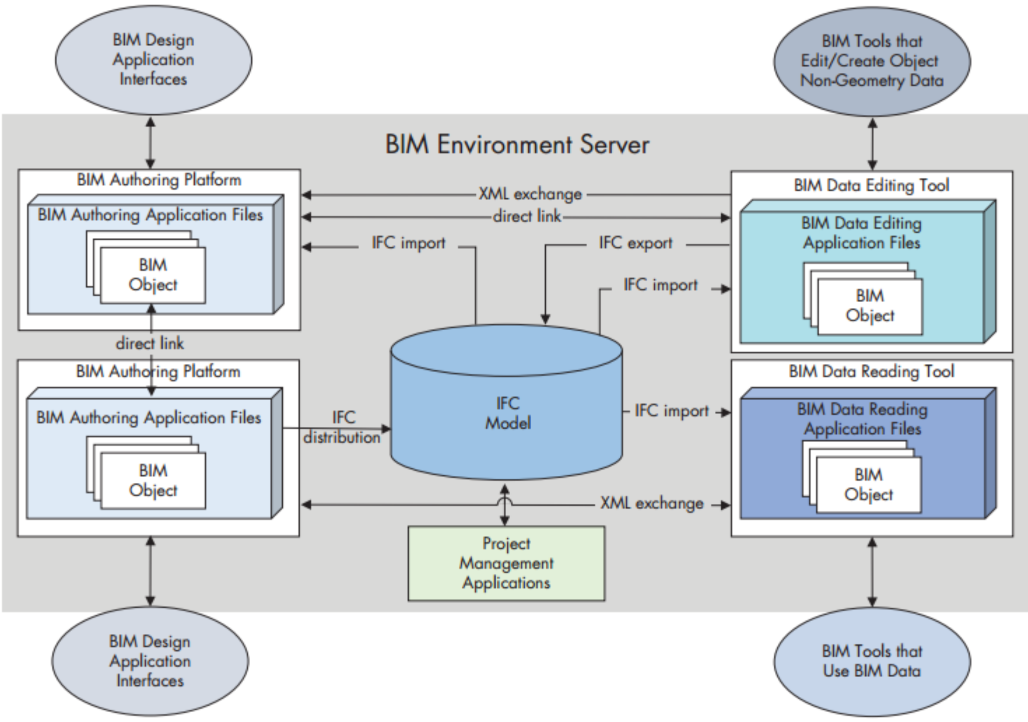


Figure 31: Example of IFC role in a BIM environment. Source: (Sacks, Eastman, Lee, & Teicholz, 2018).

As shown in Figure 33, by applying open standards, it is possible to transfer data from the Project Information Model (PIM), which contains the geometrical and semantical data as well as documentation, to the Asset Information Model (AIM) relevant in the facility operations phase (Jaritz, 2018). It is useful to include Facility Management (FM) in the early phases of planning and design, in order to include the FM strategy of the owner from the beginning of the project and facilitate the data transfer from BIM to FIM (Jaritz, 2018).

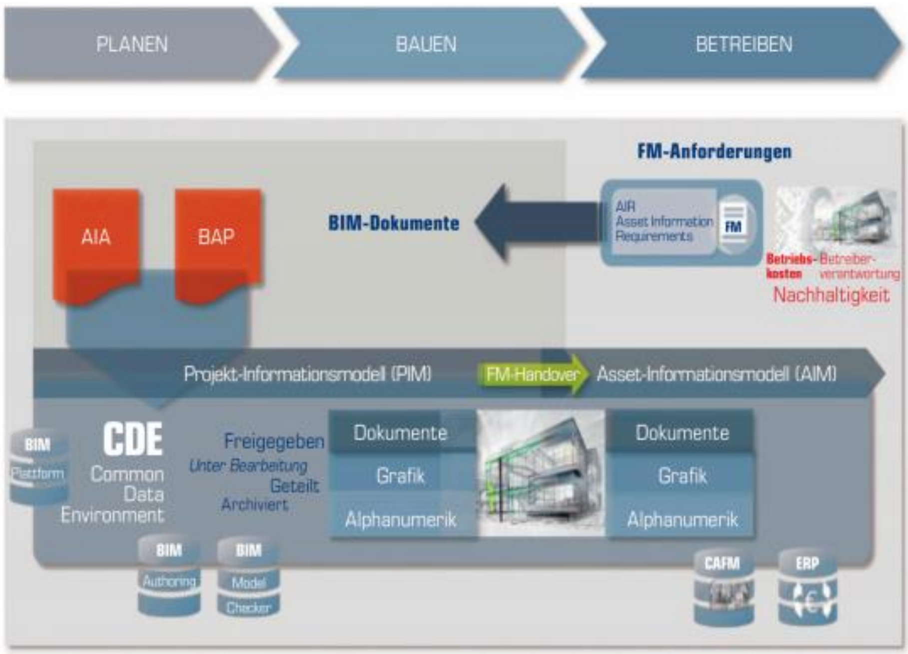
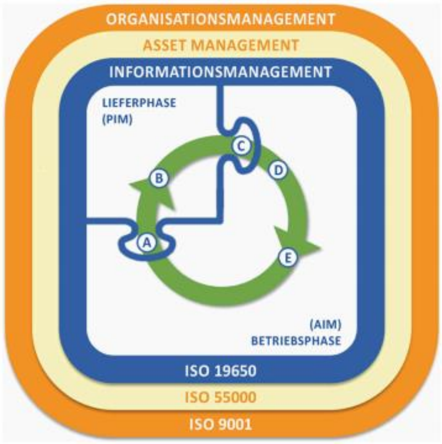


Figure 32: FM-Requirements in a BIM process (GEFMA 2017).



Legende (aus ISO 19650-1:2017):

AIM	*Asset-Informationsmodell*
PIM	*Projektinformationsmodell*
A	*Übergabe der relevanten Informationen vom AIM zum PIM*
B	*Übergang von der Konstrukteursabsicht zu einem Informationsmodell zur Beschreibung des physischen Asset*
C	*Rückgabe der relevanten Informationen vom PIM zum AIM*
D	*Verifizierung der Konstrukteursabsicht durch Beurteilung der Asset-Leistung*
E	*Fortlaufende Asset-Management-Tätigkeiten und deren Reflexion im AIM*

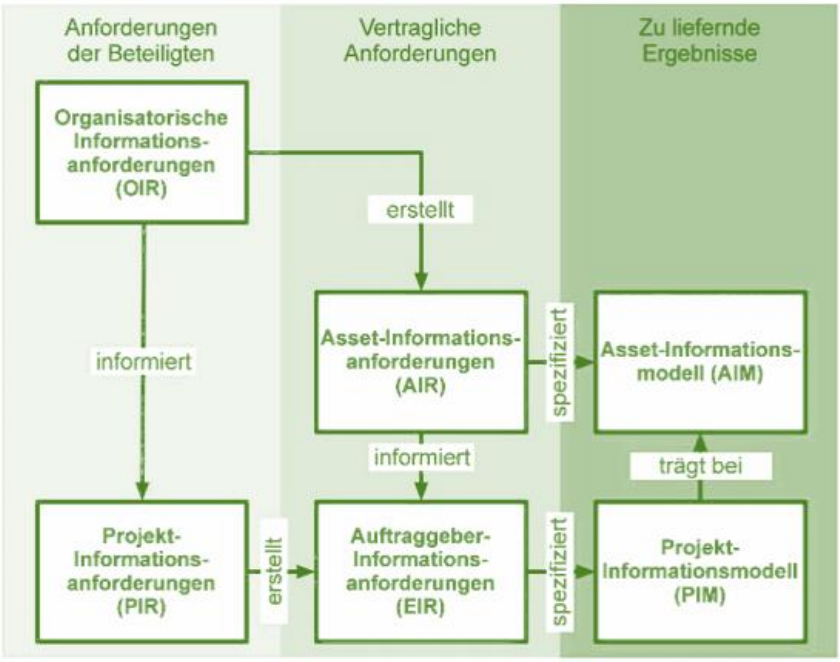


Figure 33: The generic Project and Asset Information Management Lifecycle, and the Hierarchy of Information Requirements (ISO19650:2017). Source: (Jaritz, 2018).

FM utilizes an additional set of different data from Computer Aided Facility Management (CAFM), Computerized Maintenance Management Systems (CMMS), Electronic Document Management Systems (EDMS) or Building Automation Systems (BAS), all usually functioning as separate silos applications, even though partly working on the same data and processes (Jaritz, 2018). Ensuring proper transfer of all necessary data to Facility (Information) Management ideally leads to a complete overview of the building state, which is why it is important to provide data in a form acceptable to all involved parties – builders, owners, and facility managers (Jaritz, 2018). In addition to IFC, the Construction Operations Building information exchange (COBie) addresses the handover of information dealing with operations and maintenance as well as more general facility management information (shown in Figure 34), outlines a standard method for collecting the needed information throughout the design and construction process, and categorizes and structures the information in an easy-to-implement manner (Sacks, Eastman, Lee, & Teicholz, 2018).

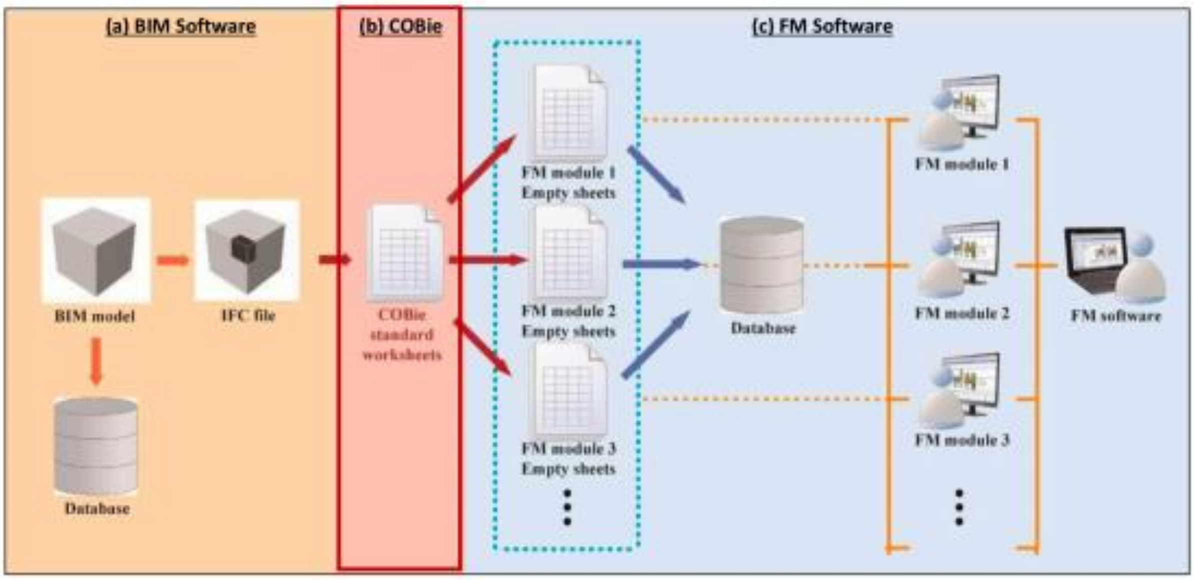


Figure 34: Transfer of building data between BIM and FM software by COBie Standard (Tu and Chang 2017).

2.3.3 Engineering data modeling and AutomationML

AutomationML is currently standardized within the IEC standard series IEC 62714. It is a standard for production systems engineering and commissioning, providing a common data format for representation of different aspects of automation systems (topology data, mechanical data, electrical, pneumatic, and hydraulic data, function describing data, process control data, generic data) through all system lifecycle phases (Lüder, 2015). All these information sets, as depicted in Figure 35, can be represented with AutomationML.

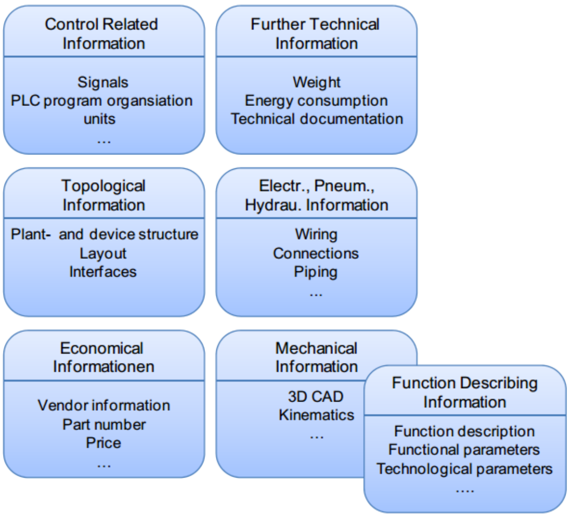


Figure 35: Information sets represented by AutomationML. Source: (Mahnke, Leitner, & Damm, 2009).

AutomationML reuses existing open technologies for the specification of concrete system aspects, in their original form and not branched for AutomationML needs, as depicted in Figure 36.

- Description of the component topology and networking information including object properties expressed as a hierarchy of AutomationML objects and described by means of CAEX following IEC 62424,

- Description of geometry and kinematics of the different AutomationML objects represented by means of COLLADA 1.4.1 and 1.5.0 (ISO/PAS 17506:2012),
- Description of control related logic data of the different AutomationML objects represented by means of PLCopen XML 2.0 and 2.0.1,
- AutomationML does not define semantics of production system components itself, but instead integrates the eCl@ss classification standard, and
- Description of relations among AutomationML objects and references to information that is stored in documents outside of the top-level format using CAEX means.

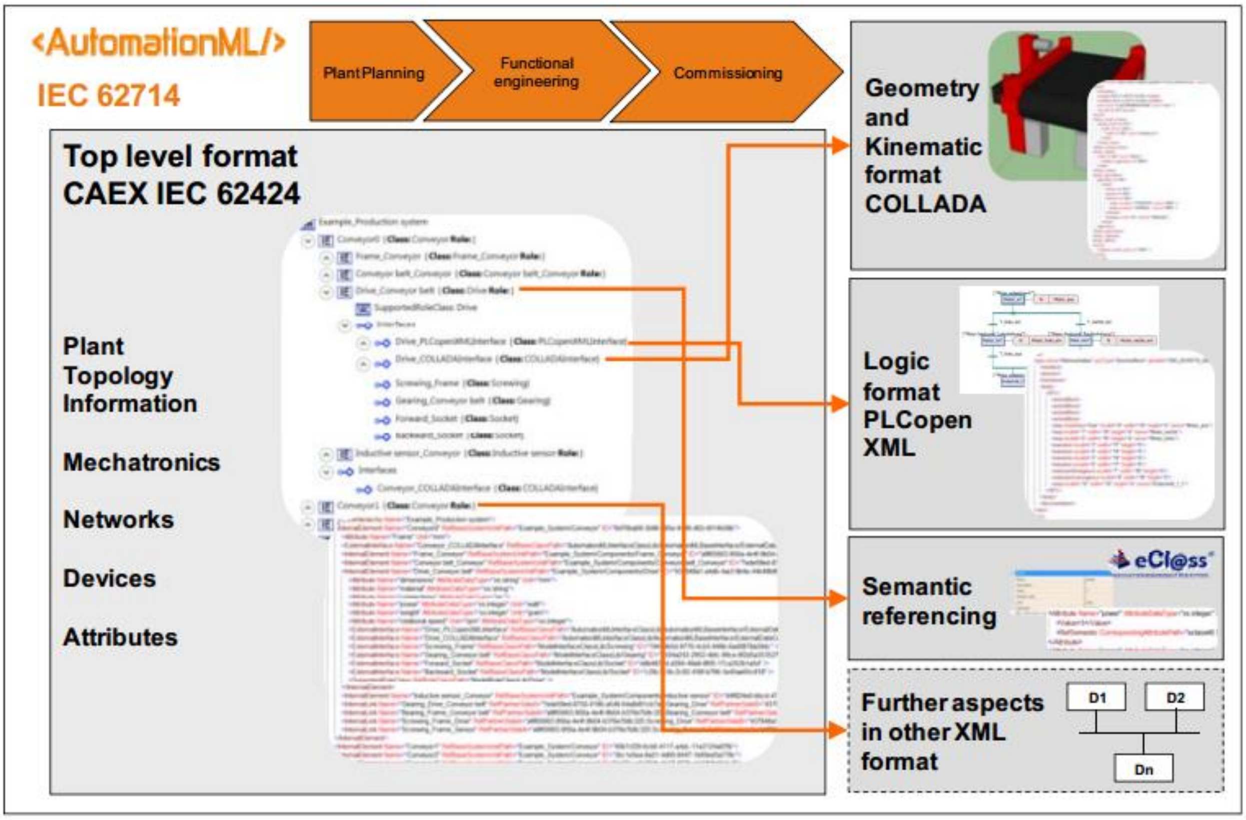


Figure 36: Structure of AutomationML Projects. Source: (Lüder, 2015).

AutomationML integrates only a part of the IEC 61131-3 standard (Sequential Function Chart (SFC) and Function Block Diagram (FBD)), and uses additional modeling mechanisms for behavior specification, as depicted in Figure 37.

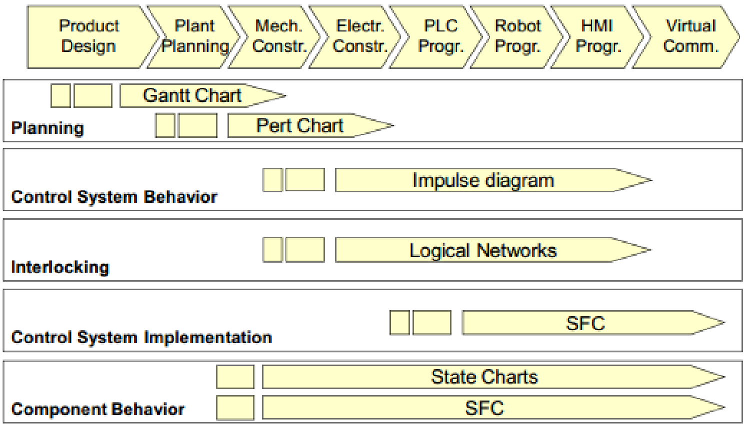


Figure 37: Model Types Reflected by AutomationML Logic Description. Source: (Lüder, 2015).

3 Security and Data Protection by Design and by Default

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3.1 Introduction

As the connectivity of heat pump systems increases, new applications and business models build around heat pump systems are developed. As many of these applications center around data processing, it is important to consider information security and data protection while designing these systems.

The importance of information security is well known in this field. Whether in private homes or industrial settings, users are typically depended on their heat pumps to keep their homes warm or the industrial process going. However, the long technological lifecycle of heat pumps paired with the shorter lifetime of consumer electronics necessitated specific considerations for this field.

For example, technological standards widespread in the consumer market today may not remain available during the heat pump lifecycle. The world of consumer electronics and household automation today is very different than it was 20 years ago. As technological and security standards evolve, it will be necessary to provide secure update mechanisms to swiftly update the systems while at the same time remaining easy to operate for users. This does also include planned deprecations of i.e. server infrastructure, so that users remain in control of their heat pump systems during the whole product lifecycle.

It is also important to consider that heat pump usage data reveal a lot about the environment it is used in. For example, in the residential setting, building occupancy can usually be derived by heating patters. This is valuable information worth protecting, as malicious actors like burglars or stalkers may abuse this information. Even if the systems use technical identifiers only meant to identify the heat pump, in the residential setting it is usually possible to identify the users behind the heat pump. Privacy is therefore an important topic for these systems. As privacy is a property of the overall system and not a feature of individual components, OEMs and suppliers need to work together with manufactures to achieve user privacy.

One important strategy to achieve this goal is privacy by design and by default, where privacy aspects are considered from the system design onset and without further user intervention and the most privacy friendly settings are chosen.

To assess the current practice of the industry, a survey among heat pump manufactures was performed during this project. The results show that privacy by design and by default are considered important topics by manufactures when developing IoT heat pump systems. Despite their importance, manufactures only reported limited familiarity with these topics.

This document shall therefore provide guidance and recommendations specific to heat pump systems. After a brief overview of the essential concepts of information security and data protection, the focus of these document is on questions of particular relevance for IoT heat pump systems.

3.2 Information Security

Information security deals with the protection of information in systems. Its purpose is the "preservation of confidentiality, integrity and availability of information".[1] Confidentiality means that only authorized parties have access to the information and information is not disclosed to unauthorized parties. Integrity means that the information has not been modified. And lastly availability implies that the information can be accessed by authorized parties when needed.

3.2.1 Available materials

Many recommendations and guidelines for security of IoT devices are available from different organizations, i.e., the baseline security recommendations for IoT[2] by ENISA or the Cyber Security for IoT: Baseline Requirements[3] from ETSI. There are also guidelines which combine security and privacy like ISO/IEC 27400:2022 IoT security and privacy guideline.[4] They are mostly focused on general advice applicable to a wide range of IoT devices. The focus of this document shall therefore be on topics arising from the specific characteristics of IoT heat pump systems.

3.2.2 Current developments

Many data protection norms also contain provisions for information security. However, if data protection norms are not applicable for a specific system, there currently is little regulation on information security from a legal perspective. Note that this may change in the future with the current proposal for the e-privacy directive, where machine to machine communications only

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[1] ISO/IEC 27000:2009

[2] https://web.archive.org/web/20230312044622/https://www.enisa.europa.eu/publications/baseline-security-recommendations-for-iot/

[3] https://web.archive.org/web/20220829150324/https://www.etsi.org/deliver/etsi_ts/103600_103699/103645/02.01.02_60/ts_103645v020102p.pdf

[4] https://web.archive.org/web/20230313072008/https://www.iso.org/standard/44373.html

concerning legal persons may be regulated as well.[5] However, the discussion process on the e-privacy regulation has long been ongoing and it is currently[6] unclear when and with what provisions the regulation will be finalized. Similarly, the proposed European Cyber Resilience Act directly targets the security of IoT products but is still under discussion.[7]

Note however that for consumer products additional stipulation for security already exist as part of the product warranty requirements.[8] This also includes the requirement to make security updates available.[9]

3.3 Data Protection

In contrast to information security, the purpose of data protection is to guard fundamental rights and freedoms of natural persons with regards to their privacy.[10] Many provisions of data protection revolve around the concept of personal data. The General Data Protection Regulation[11] (GDPR) defines personal data as “any information relating to an identified or identifiable natural person (‘data subject’) […]”.[12] The GDPR is only applicable if personal data is processed.

3.3.1 Personal data

One key question for IoT systems is therefore if personal data is being processed. It is important to note that it the concrete identity of the natural person does not need to be known, it is sufficient that the person can be identified. This implies that identifiers which can be reconnected to a natural person (i.e. pseudonymous data) are considered personal data for the purpose of the GDPR. The GDPR does not protect the privacy of legal persons (i.e. companies).

There is an important distinction between domestic and industrial installations. While information security principles should always be applied, the applicability of data protection is

[5] Proposal for a Regulation of the European Parliament and the Council concerning the respect for private life and the protection of personal data in electronic communications and repealing Directive 2002/58/EC (Regulation on Privacy and Electronic Communications)

[6] As of march 2023

[7] Proposal for a Regulation of the European Parliament and the Council on horizontal cybersecurity requirements for products with digital elements and amending Regulation (EU) 2019/1020

[8] Directive (EU) 2019/771 of the European Parliament and of the Council of 20 May 2019 on certain aspects concerning contracts for the sale of goods, amending Regulation (EU) 2017/2394 and Directive 2009/22/EC, and repealing Directive 1999/44/EC

[9] See Art 7 (3) and Art 10 (2) Directive (EU) 2019/771

[10] Art 1 (2) GDPR

[11] Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation)

[12] Art 4 (1) GDPR

bound to the processing of personal data.[13] This is much more likely in domestic/residential settings where a single household is using the IoT heat pump, than in a commercial setting, where heat pumps are used part of commercial offering or an industrial process. Heat pump usage data in the residential setting may reveal building occupancy and therefore clearly affects user privacy and can easily be abused (i.e. by buglers or stalkers). At the same time, it is important the right users remain in control of the heat pump system. Otherwise after an ownership change, former building occupants may remain in control of the heat pump without the new occupant's awareness.

However, if it is unclear whether the IoT heat pump system is used in a consumer or industrial setting, it is recommended to assume personal data is being processed.

3.3.2 Controllers and Processors

Another important distinction is between data controllers and data processors. Controllers determine the "means and purposes of the processing of personal data"[14] while processors "process personal data on behalf of the controller".[15] The distinction is important because many data protection obligations apply directly to controllers. The controllers are then in turn responsible for ensuring the processors meet the requirements set out by the GDPR.[16] This can be achieved by contractual agreements between data controller and processor. Standard contractual clauses approved by the European Commission[17] are often used for this purpose.[18]

An example for a processor would be an external cloud, providing storage and computing power used by an OEM to analyze personal data collected from an IoT heat pump system. Note however, that multiple controllers can be involved in the same data processing activity.

For example, if the external cloud provides an analysis platform where not all processing purposes are decided upon by the OEM, the cloud provider would become a joint controller together with the OEM. While joint controllers may have an agreement how the responsibilities are distributed,[19] data subjects still may choose which controller to address when exercising their rights under the GDPR.[20] The European Data Protection Board (EDPB) Guideline 07/2020 offers additional information on the concepts of data controller and processor.[21]

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[13] For further information see the section on data protection

[14] Art 4 (7) GDPR

[15] Art 4 (8) GDPR

[16] Art 28 (1) GDPR

[17] https://web.archive.org/web/20230313072101/https://commission.europa.eu/publications/standard-contractual-clauses-controllers-and-processors-eueea_en

[18] Note however that these contractual clauses have been updated in 2021 by the European Commission after a decision by the European Court of Justice. Older data processing contracts may therefore require an update in order to stay GDPR compliant.

[19] Art 26 (1) GDPR

[20] Art 26 (3) GDPR

[21] https://web.archive.org/web/20230226212620/https://edpb.europa.eu/system/files/2021-07/eppb_guidelines_202007_controllerprocessor_final_en.pdf

3.3.3 Rights of the Data Subjects

The data subject enjoys multiple rights under the GDPR. Among others these include the right of access to the stored personal data,[22,23] the right to rectify inaccurate personal data,[24] the right to data portability,[25] as well as the right to demand the erasure of personal data or restrict its processing under certain conditions.[26] In addition, the data subject shall also be provided with a range of information when personal data are obtained.[27] These data subject rights apply to processing of personal data in general and are not specific for IoT systems.

3.3.4 Principles

The GDPR contains multiple principles when processing personal data.

The processing must be lawful and for an explicit purpose.[28] Of particular relevance is the principle of data minimization, which states that the purpose of any data processing shall be "adequate, relevant and limited to what is necessary" for the specified purpose.[29] In addition the data shall only be stored as long as necessary for the specified purpose and be kept up to date in order to remain accurate.[30] The GDPR also contains responsibilities from the information security perspective, namely that integrity and confidentiality of the processed data shall be maintained.[31] The controller is responsible for demonstrating compliance with these principles.[32]

The definition of a data processing purpose is therefore essential when designing IoT Systems, as compliance with many these principles is only possible relative to a given purpose. In addition, the more concrete the stated purpose is, the easier it is to follow the principles of privacy by design and privacy by default, as these principles require knowledge about the required information and processing steps of specific applications.

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[22] Art 15 GDPR

[23] See the EDPB guideline 01/2022 for further guidance on the right to access: https://web.archive.org/web/20230313072418/https://edpb.europa.eu/our-work-tools/documents/public-consultations/2022/guidelines-012022-data-subject-rights-right_en

[24] Art 16 GDPR

[25] Art 20 GDPR

[26] Art 17 and 18 GDPR

[27] Art 13 and 14 GDPR, this is often done by a privacy notice

[28] Art 5 (1) (a) and (b) GDPR

[29] Art 5 (1) (c) GDPR

[30] Art 5 (1) (d) (e) GDPR

[31] Art 5 (1) (f) GDPR

[32] Art 5 (2) GDPR

3.3.5 Lawfulness of Processing

In addition, the GDPR also requires a legal basis for each of the processing purposes. In the private sector, controllers often use consent, processing which is necessary for a contract or legitimate interest as legal basis.[33] Each of these legal bases carries their own requirements.

Consent is often used as a legal basis but requires careful management by the controller. First, the burden of prove that the data subject has in fact given consent rests with the controller.[34] The data subject must be informed of the right to withdraw consent at any point in the future, after which future processing for this purpose must be stopped. Second, data subjects may consent to specific purposes only, while not giving consent for other processing purposes. The separate consent must be possible for each purpose and the purpose must be described “using clear and plain language”.[35] Third, the consent must be freely given not i.e. taken as precondition in order to obtain another service. If this other service could also be performed without processing the data, then the consent is usually not considered to be freely given. If at least one of these conditions is not fulfilled, using another legal basis may be appropriate.

If the processing is strictly necessary to fulfil a contract, then it usually preferable to use this instead of consent as a legal basis. For an IoT heat pump system, this could for example be maintenance contract requiring the technician to access to the heat pumps data to perform maintenance. Note however that this is limited to what is strictly necessary for contract performance. If for example no maintenance contract is active for a specific heat pump system, then under this legal basis maintenance data may not be collected from this system to ease possible future onboarding.

Another legal basis is legitimate interest for a specific processing purpose. In this case, the controller must additionally demonstrate that the given interests outweigh possibly conflicting interests of the data subjects. For this, a balancing test is usually performed and documented. Only if the balancing tests shows a positive result this legal basis may be used. For IoT heat pump systems, this could for example include system monitoring to prevent unsafe and potentially hazardous operating conditions or the prevention of cybersecurity risks.

3.3.6 Privacy by Design

Data protection principles are most effective when they are incorporated early into the product lifecycle. The GDPR therefore requires controllers consider these principles already during the design phase of a product, where the means of processing are determined.[36] Note that this applies for all data protection principles and may require measures beyond pseudonymization.[37]

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[33] Art 6 (1) (a) to (c) and (f) GDPR

[34] Art 7 (1) ARt

[35] Leg cit

[36] Art 25 (1) GDPR

[37] Data minimization and pseudonymization are listed as possible measures in Art 25 GDPR. However, they only servers as examples and shall not be regarded as exhaustive list.

These protections shall be implemented by appropriate technical and organizational measures. A risk-based approach is used to determine which measures are appropriate given the concrete application. The risk is determined by considering the severity and likelihood of threats caused by the processing to the privacy of natural persons. At the same time the “state of the art, the cost of implementation and the nature, scope, context and purposes of processing”[38] shall be considered for this as well.

For example, a heat pump used for residential heating is also essential for comfort within the building. Loss of operation may therefore critically affect users, especially during the winter months. The extend of risk strongly depends on the way the IoT heat pump operates. If the heat pump can be controlled over the internet likelihood of this threat will be much higher than if control is only possible over the local network. Similarly, the severity will depend on the degree of control an attacker may obtain over the IoT heat pump system. If physical damage to the heat pump system is possible, the severity will be much higher than a simple increase or reduction of building temperature.

When used in a residential setting, an IoT heat pump may also provide information about building occupancy. The information can be considered personal data, even if the information is only collected on a household level. It may pose a threat if abused (i.e. by buglers, stalkers, etc.). Again, the risk of this threat depends on degree and extend of information accessed (accessible). Note that this considers not only external attackers but also the availability of the information within the organization or authorized external partners. The intent of privacy by design is therefore to combine technical with organizational measures in order to achieve system wide safeguards for privacy.

An important characteristic of heat pump systems is their long lifespan, which can be over 20 years.[39] It is important to consider technological changes for users as well as suppliers during that lifetime. The technological lifecycle of user devices is usually much shorter than for commercial applications. For example, 20 years ago today’s most widely used mobile operating systems[40] did not exist. The field of smart home standards is also developing, where many systems are currently based on vendor specific solutions,[41] while vendor neutral solutions[42] are gaining ground.

Considering the long lifespan of heat pump systems, it is highly likely that changes both technological and security standards will occur over the systems lifetime. The GDPR therefore requires that the analysis is not only valid during system design but also when the data processing is actually performed.[43]

Another issue arising from the residential setting in combination with the long lifetime of IoT heat pump is ownership change. When the occupants of the household change, it should not be possible for the old users to monitor and control the heat pump of the new users. Likewise,

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[38] Art 25 (1) GDPR

[39] European Heat Pump Association, European Heat Pump Market and Statistics Report 2019

[40] As of the time of this writing, these are Android and iOS

[41] At the time of this writing examples include Apple Home Kit, Samsung smartThings, etc.

[42] i.e. matter and thread

[43] Art 25 (1) GDPR

the new user should not gain access to the occupancy data of the old user. The IoT heat pump should therefore provide a mechanism to delete usage data and disconnect the old users account from the heat pump. In addition, the new user should be able to connect their device without further interaction with the old user, i.e. by using a pairing procedure. Even though the heat pump system stays the same, it collects data from different people, which are supposed to be secured by privacy norms.

A precise processing purpose can also provide valuable guidance when implementing privacy by design. Implementing data minimization is much easier if the exact amount and granularity of data required is evident for each purpose. For example, if it is known a maintenance technician only requires time averaged values from certain components for diagnosis, only storing these time averaged values may help data minimization while at the same time speeding up the diagnosis process.

In addition, if the entire process, from data collection over storage and computation up to deprecation and deletion, is considered, it becomes much easier to determine who needs to access the data when and for what reason. This also helps to protect data confidentiality, may additionally facilitate the purpose limitation principle, and guide appropriate policies for storage limitation.

When designing interfaces and applications for these systems, it is therefore important to keep technological obsolescence in mind and use connectivity standards and platforms which are likely to remain available during the lifetime of the IoT heat pump system. In some cases, it may also be possible to provide software updates allowing older systems to become compatible with newly developed standards. However, it is often beneficial for both users and manufactures to use long lived standards. That way privacy by design can also benefit system design.

3.3.7 Privacy by Default

Privacy by default is again closely connected with the processing purpose. In essence, it states that the default system settings should limit data processing to the absolute minimum necessary in order to perform the specific purposes.[44] Specifically, this implies without further user interaction, data processing will remain minimal. Besides data collection, this applies to storage, computing, and data access as well.[45]

Importantly, this provision applies to the data processing system as a whole and is not limited to the parts supplied by the controller. For IoT heat pump systems, this implies that a manufacturer may need to assess all system components for data protection settings. This includes i.e. parts supplied by different vendors or third-party software or services for data analytics.

[44] Art 25 (2) GDPR

[45] Leg cit

General information on this privacy by default and by design can also be found in the EDPB guidelines.[46]

3.3.8 Security of Processing

The GDPR also contains provision regarding the security of processing. As for privacy by design, it is based on a risk-based approach that shall take the “state of the art, the costs of implementation and the nature, scope, context and purposes of processing”[47] into account. The phrasing suggests the test is to be performed in a similar manner than for privacy by default.

In also contains exemplary list of possible measures, including pseudonymization and encryption as well as confidentiality, integrity, availability, and resilience of the systems.[48] These properties need to be ensured for the system as a whole and are not limited to specific parts of the system.

Especially availability and reliability are critical for essential utilities such as heat pump systems. The heat pump should therefore continue to function even if the internet connectivity is lost. In the event of connectivity loss, the heat pump should remain available, using a graceful degradation mode where all functions not requiring connectivity remain available. Likewise, control of the heat control of basic heat pump functions shall always be possible by the user. This can be achieved by e.g. using a panel directly controlling the heat pump. Similarly, the essential operational features of a heat pump should be always accessible independent of any server connection.

The taken measures shall also be regularly tested and evaluated.[49] From the supplier side, this may imply a need to support and update the technological infrastructure for the IoT heat pump systems. This is especially relevant if the IoT heat pump can be monitored or controlled externally, as the information security standards and protocols are likely to change during the long lifetime of the system. This also necessitates the need for a secure update mechanism, as it is likely impossible to predict all necessary changes ahead of time. Otherwise, the IoT heat pump may become vulnerable to cyberattacks, e.g. by holding the heat pump function for ransom until a payment is made.

Another potential security hazard is the integration of the IoT heat pump into the home automation system. Such networks may contain insecure devices which may be compromised and provide a launch pad for attackers into the local network. Protection of IoT heat pump against cybersecurity hazards is therefore not only needed against attacks from the internet but also from within the local network.

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[46] See European Data Protection Bord, Guidelines 4/2019 on Article 25, Data Protection by Design and by Default, adopted 20.10.2020

[47] Art 32 (1) GDPR

[48] Art 32 (1) (a) and (b) GDPR

[49] Art 32 (1) (d) GDPR

3.4 Conclusion

In summary, it is important to consider the specific characteristics of IoT heat pumps when implementing privacy by design and by default. Due to both the long lifecycle as well as the systems importance for building comfort and user privacy it is paramount to take a long-term perspective.

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

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

3.5 FAQ

Am I processing personal data when I don't know the identity of the heat pump user?

The general data protection regulation (GDPR) does not require that the specific user is identified. It is sufficient that the user is identifiable by using reasonable means. This implies that a pseudonymous identifier (i.e. a device ID) can be personal data as well, if the identity of the user can be inferred by cross-reference with another database available to the controller.

True anonymization of fine granular data can be difficult. If in doubt, it is therefore recommended to assume personal data is being processed and to apply the data protection norms accordingly.

As a heat pump OEM, do these provisions apply to me?

Whether data protection norms apply directly depends on if you decide the means and purposes of the data processing. If this is the case then you are considered a data controller and directly responsible to show that the GDPR provisions are implemented for the system. Otherwise, the means and purposes are decided elsewhere, you may be considered a data processor.

However, the GDPR requires controllers to ensure that processors uphold data protection principles when processing personal data. It is therefore highly likely the norms will still apply indirectly, as downstream controllers will most likely require data protection principles on a contractual basis. Even if acting as a processor, knowledge of GDPR principles is therefore essential.

As a heat pump manufacturer, do I need to monitor my suppliers for data protection?

If you decide the means and purposes of the processing of personal data, then you will need to ensure your suppliers uphold the GDPR principles as well. Note that this also includes additional processing performed by the suppliers and default settings deciding which data processing is performed.

For further information, please refer to the section controllers and processors of this document.

In order to show the security of processing personal data, is it sufficient to fulfil the relevant security norms and standards?

Norms, standards, certifications and codes of conduct can help to show that the security of processing is upheld. As such it is usually a good idea to follow them during system design and implementation, and document their application.

However, codes of conduct need to fulfil the criteria of Art 40 GDPR and certifications of Art 42 GDPR for official recognition. In all other cases, the compliance with the security of processing under GDPR will need to be assessed and documented separately.

4 Research literature

The Internet of Things (IoT) has the potential to revolutionize the way we interact with heating and cooling systems in buildings. In particular, IoT technologies have the potential to improve the efficiency and performance of heat pump systems, which are widely used for space heating and cooling in residential and commercial buildings. Heat pumps are highly efficient devices that can transfer heat from the environment to the interior of a building, providing an eco-friendly and cost-effective alternative to traditional heating and cooling systems.

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

During the Annex 56 an assortment of literature resources has been collected into a public Zotero group available at this link: https://www.zotero.org/groups/4871439/annex56/library

This collection aims to provide an overview of the current state of research on IoT technologies for heat pump systems. The resources include literature material on the various types of IoT devices and sensors used in heat pump systems, as well as the benefits and challenges of IoT integration. Additionally, the Zotero library includes papers and articles on the latest research on IoT-enabled control strategies, optimization algorithms, and predictive maintenance techniques for heat pump systems.

5 IoT use cases: products, services and research projects

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

For each use case, all the information is summarized in a dedicated factsheet that is available on the IoT Annex website. Furthermore, a framework was established to structure and summarize information from the use cases. The aim of the framework is to achieve a consistent description of all important aspects, ranging from stakeholders, participants, connection and data requirements, perceived benefits to technological readiness (see Figure 38).

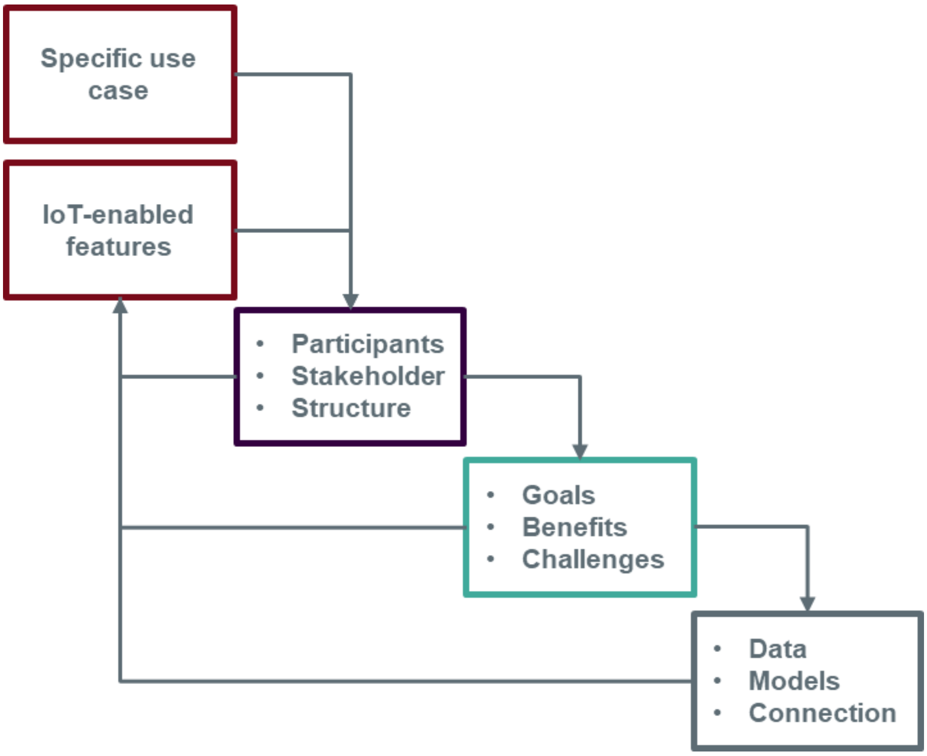

Figure 38: Framework for structure and describe use cases for IoT-enabled heat pump products and services

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

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

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

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

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

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

In total, 44 use cases were collected, thereof 19 products and services and 25 research projects. Most of the use cases were provided by the Danish team (23 examples), followed by Austria (10). In the following, a short introduction to each use case is presented.

5.1 Austria

Contributors: Veronika Wilk, Reinhard Jentsch, Regina Hemm, Philipp Ortmann, Bernd Windholz, Christoph Reichl (AIT Austrian Institute of Technology)

5.1.1 Intelligent heat pump components

As part of the Austrian national research project, not only projects and use cases on IoT heat pumps were analyzed, but also intelligent heat pump components adding another level of interaction to the heat pump system. Examples for intelligent heat pump components are compressors, expansion valves and protective equipment.

5.1.1.1 Bitzer Heat Pump Eco System

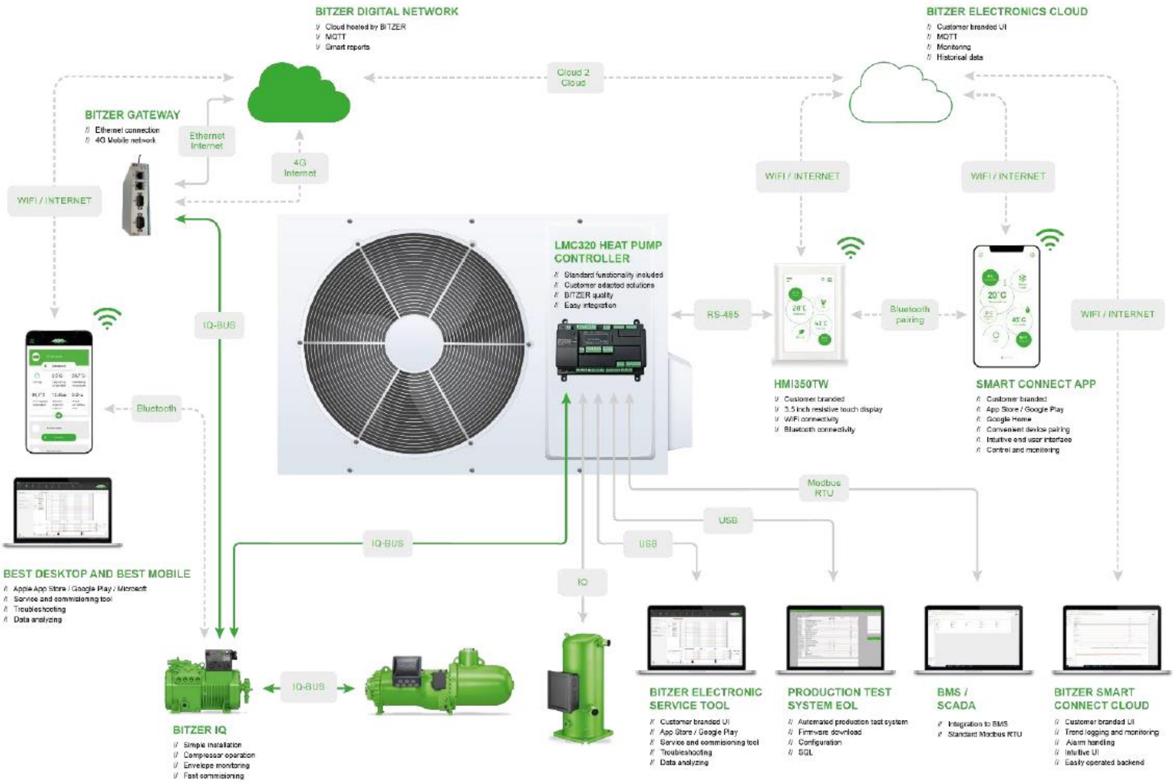

Figure 39: Overview of the Bitzer Heat Pump Ecosystem

IoT category: Heat pump operation optimization, predictive maintenance, heat pump operation commissioning

Link: https://www.bitzer.de/gb/en/bdn.jsp

The Bitzer Heat Pump Ecosystem is provided by BITZER Electronics, a company in the BITZER Group. BITZER Electronics targets OEMs, installers, owners, and service technicians of domestic and industrial heat pumps. The core component is an intelligent smart grid ready system controller or intelligent compressor module. The intelligent compressor module allows connection between compressors and the heat pump control unit plus to a gateway simultaneously by using an IQ-Bus.

There are two possible use cases for the Ecosystem. The first uses the Bitzer Gateway to load data into the Cloud via Wi-Fi or a 4G signal. The cloud is hosted by Bitzer and is fully compliant with the General Data Protection Regulation. The data stored there can be accessed via the BEST App which is available for Android, iOS and Microsoft and allows for troubleshooting and data analysis and provides multiple service and commissioning tools and apps for end-users.

The second possibility uses the heat pump controller by Bitzer which features USB, Modbus and RS-485 connectivity and a customer hosted cloud. The Smart Connect App for Android and iOS features a user interface to control and monitor the heat pump. Furthermore, it is possible to use a customer branded GUI via the Smart Connect Cloud which features alarm handling, trend logging and monitoring.

5.1.1.2 XBALL® Smart Expansion Ball Valve

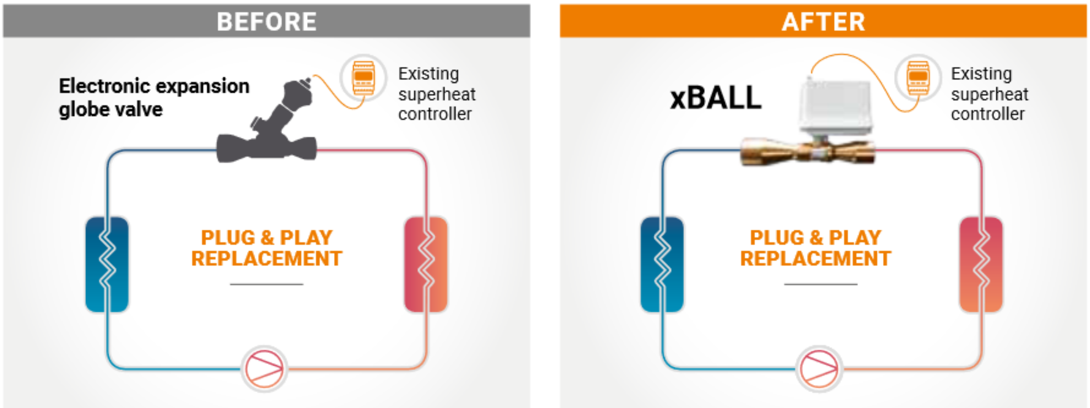

Figure 40: Bereva XBALL® integration example

IoT category: Heat pump operation optimization

Link: https://bereva.it/products/

The Bereva Smart Expansion Ball Valve is a replacement expansion valve for HVAC systems for superheat control. The main applications are chillers and air condensing units with capacities from 30 – 500 kW and machines with inverter driven compressors. The XBall valve is assembled without tools by snapping-on and is configured via Bereva's Syncra App. It is also suitable for retrofitting existing systems and can be used with existing superheat controllers with stepper signal. It allows for elimination of solenoid valves thanks to a supercap that drives the fail to close feature. The XBall valve improves control and performance by optimization of partial loads, avoiding starting jumps and energy savings. It is compatible with CFC, HFC and HFO refrigerants and can be used from -20 to 70°C. It is directly connected to the chiller control unit but can also be controlled via Bluetooth and Apps for Android and iOS. Data can be transferred to the cloud using Bereva Gardian cloud service.

5.1.1.3 KRIWAN protective equipment

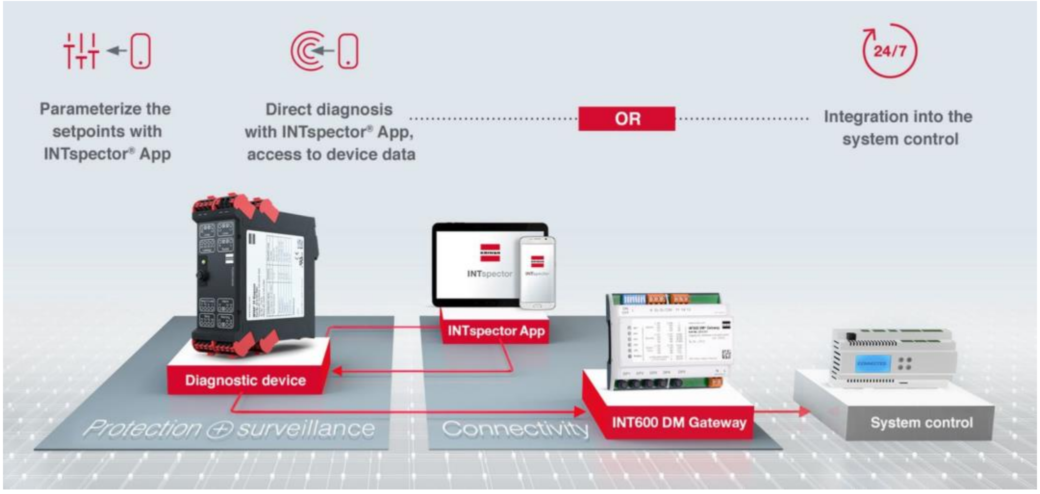

Figure 41: KRIWAN Gateways Diagnostic System

IoT category: Heat pump operation optimization, predictive maintenance, heat pump operation commissioning

Link: https://www.kriwan.com/en/connectivity

KRIWAN offers protective gear for heat pumps and cooling units. These include monitoring of refrigerant and oil levels, differential pressure measurements for monitoring oil pumps or temperature sensors for surfaces, windings of motors or screw-in sensors. Furthermore, a module for the monitoring of compressors used in heat pumps is offered. It consists of temperature, hot gas, power supply, current and switch cycle observations and offers a quick solution for diagnostics in case of failures. All the mentioned sensors can be combined with a gateway that enables the data to be linked via Modbus protocol to individual plant control systems. Furthermore, an app allows to get diagnostic data quickly onto mobile devices, it assists with commissioning and parameterization of the equipment as well as with maintenance and servicing tasks.

5.1.2 Energie Burgenland HP Neusiedl am See

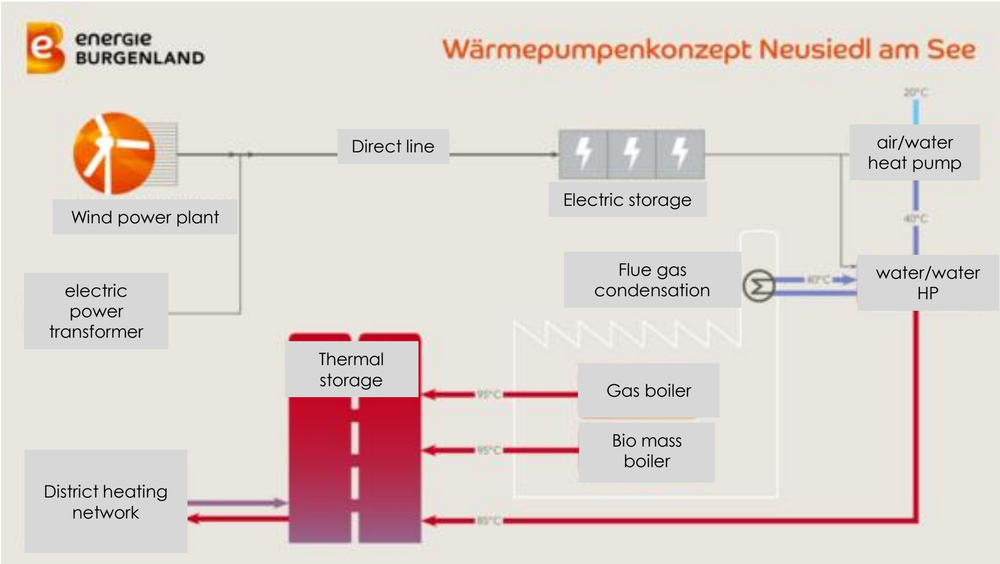

Figure 42: Heat pumps are supplied by excess wind electricity to substitute gas in the district heating network

IoT category: Heat pump operation optimization

Link: https://heatpumpingtechnologies.org/annex56/wp-content/uploads/sites/66/2023/06/iot-annex-56-case-at-energie-burgenland.pdf

In Neusiedl am See in Austria, a district-heating network with a biomass boiler was extended by a direct line to the nearby wind park, a battery storage and four heat pumps. Two air-water heat pumps with 600 kW heating capacity each use ambient air as the heat source, two water-water heat pumps recover heat from flue gas condensation. Thereby excess electricity is used for heating purposes and allows for significant reductions in biomass and natural gas consumption and CO_2 emissions.

5.1.3 myiDM +energy - iDM Energiesysteme

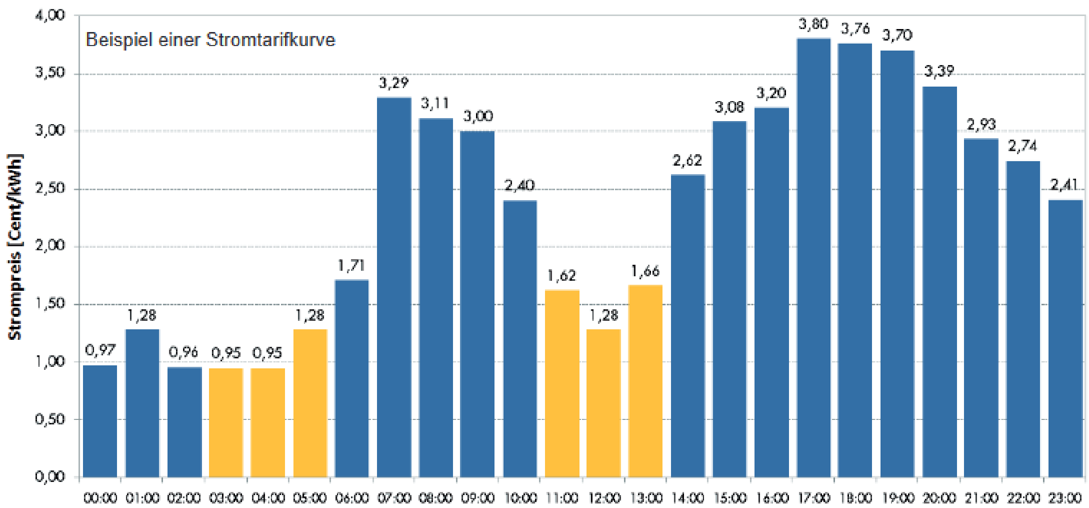

Figure 43: Variable electricity tariffs are used to optimize costs of heat pumps electricity consumption

IoT category: Heat pump operation optimization

Link: https://www.idm-energie.at/myidm-energy/

“iDM Energiesysteme” is an innovative Austrian heat pump manufacturer located in Eastern Tirol. Their product “myiDM +energy” aims to consume electricity preferably when electricity prices are low. The application mainly targets residential heating/end consumers. The heat pump system can use the heating buffer, the domestic hot water storage as well as thermal building masses as energy storages to shift electricity consumption in time. To optimize the electricity consumption for spatial heating, room temperature set points are tuned. Further, domestic hot water preparation can be shifted by a certain amount of time, which can be chosen manually. In combination with a photovoltaic system, the heat pump can use the surplus energy for spatial and domestic hot water heating, to increase the self-consumption of the household.

5.1.4 KNV S Serie – KNV / NIBE

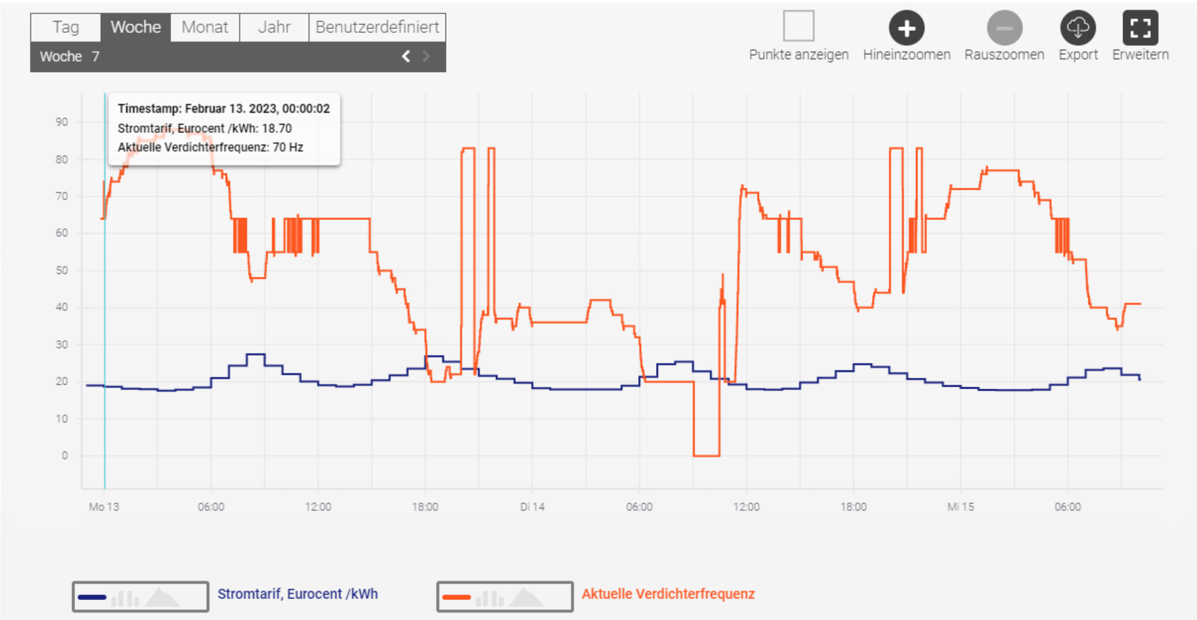

Figure 44: Adaption of heat pump operation according to price signals (blue = electricity price, orange = current frequency of the heat pump compressor)

IoT category: Heat pump operation optimization

Link: https://www.knv.at/

KNV is an Austrian heat pump manufacturer that merged with NIBE AB from Sweden in 2008. Heat pumps from KNV/NIBE have been connected to the Internet since 2012. The new generation of heat pumps, the "S-Series", and myUplink allow for a quick overview of the status of the heat pump via the Internet. If a malfunction occurs, the user will be notified directly via push-note and e-mail. The automated logging of heat pump parameters gives full control of the heat pump, and, with the help of remote monitoring and control, heat pump operation can be optimized and possible faults can be detected or prevented. Furthermore, smart functions such as "Smart Price Adaptation" and "Weather Forecast" are possible in connection with myUplink, which saves costs for the customer and increases the system efficiency in heating and cooling operation.

5.1.5 DIGIBatch

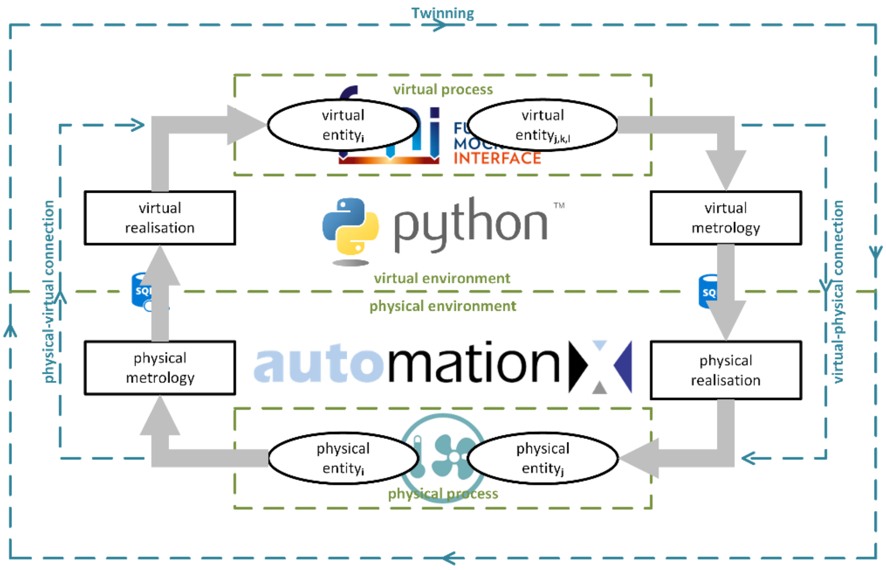

Figure 45: Visualization of the Twinning cycle and digital twin environment

IoT category: Heat pump operation optimization

Link: https://heatpumpingtechnologies.org/annex56/wp-content/uploads/sites/66/2023/06/iot-annex-56-project-case-at-digibatch.pdf

The research project DIGIBatch research project optimizes batch processes using digital twins. One focus is on heat pump testing, where a virtual representation of the heat pump on a test rig is created. During heat pump testing, specific operating points need to be achieved, which can only be reached iteratively due to on/off-modes and temperature dependencies. The digital twin application provides simulated temperatures, reducing the need for iterative processes. First, a physical model of the heat pump in Modelica was developed and simplified to the lowest possible number of parameters. An adaptive selection method was used to choose a subset of parameters for each operating point, and these are fitted and used in the prediction model. The digital twin is integrated as a functional mock-up unit (FMU) in a cloud application, facilitating integration with the test rig SCADA system. The results demonstrate the effectiveness of the adaptive parameter selection method in finding optimal parameters. The correct temperatures for virtual operating points can be predicted starting from just two provided operating points, speeding up the testing procedure and saving time and energy. Additionally, a parametrized model suitable for predicting thermal performance is obtained during testing, which can be reused in the heat pump's product life cycle.

5.1.6 Flex+

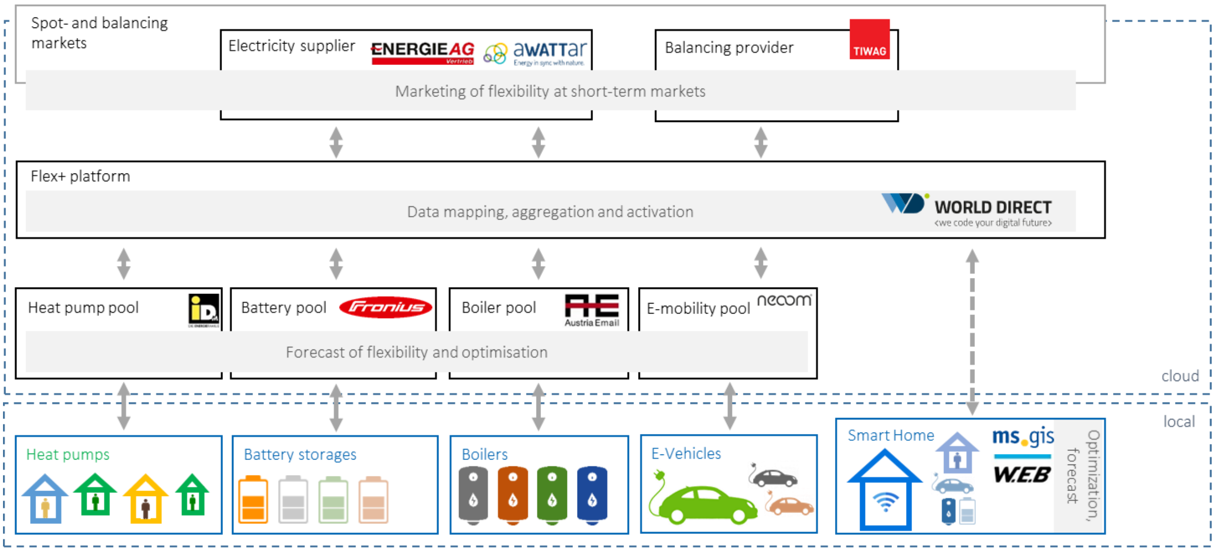

Figure 46: Overview on Flex+, interaction and data processes between stakeholders

IoT category: Flexibility provision

Link: www.flexplus.at

The Flex+ project explores heat pumps' flexibility in providing automatic and manual frequency restoration reserve (aFRR, mFRR). Different use cases were tested, including conventional operation, optimized scheduling based on market prices, and reservation of free capacities for frequency restoration reserve. Mixed integer linear programming algorithms were used to schedule the heat pumps. The buildings were depicted as thermal network models with thermal resistances and capacitance to include building dynamics. Domestic hot water and heating water have been used for load shifting. Measured heating curves were provided by the heat pump manufacturer and linearized. The project's architecture involves communication between suppliers, the Flex+ platform, and component pools. The regulatory framework in Austria was proven to be suitable for market integration of component pools. Prediction of user behavior and determining the right modeling depth posed challenges. Demonstrations proved technical feasibility, but further research is needed for seamless implementation.

5.1.7 EDCSproof

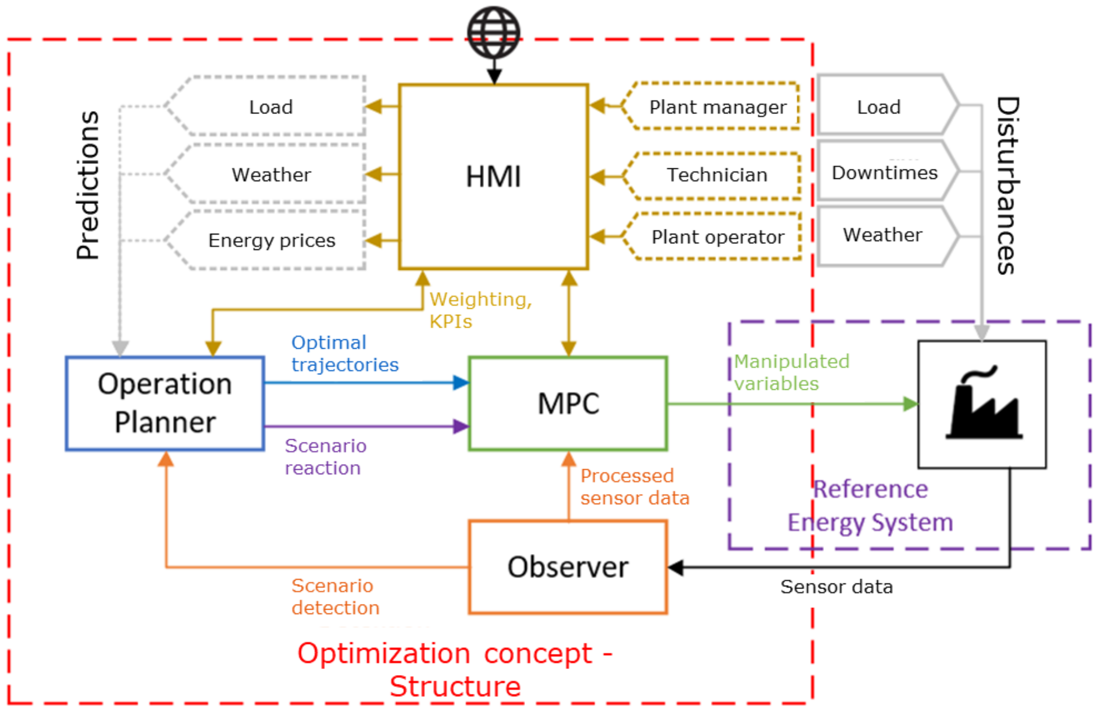

Figure 47: Visualization of the Energy Demand Control System EDCS

IoT category: Heat pump operation optimization, flexibility provision

Link: https://www.nefi.at/en/project/edcsproof

The Energy Demand Control System – PROcess Optimization For industrial low temperature systems (EDCSproof) developed a sustainable concept for decarbonizing industrial energy supply systems through digitalization. The concept includes online predictive control, thermal energy storage, flexible consumers, system optimization, and waste heat recovery. The laboratory-optimized concept was evaluated for scalability and applicability across different industrial sectors. The focus was on optimal process control for small and medium enterprises, enabling them to act as flexible consumers and optimize waste heat utilization.

The control concept mainly consists of (i) an operation planner with a prediction horizon of e.g. 24 hours (comparable to electricity markets) regularly calculating optimal trajectories for the actuators of the energy supply system, (ii) a model predictive controller with a shorter period (typically a few hours) to follow the trajectories of the operation planner as exact as possible, (iii) an observer to estimate the current state of the system from measurement data, and (iv) a human machine interface (HMI) for the operator interaction (e.g. input of the production plan, weighing of optimization objectives). Challenges include high implementation costs, human interactions, computational effort, and uncertainties in load and weather predictions.

The control system has been successfully tested and will undergo further testing in different industrial sites.

5.1.8 Soft sensor for heat pump icing

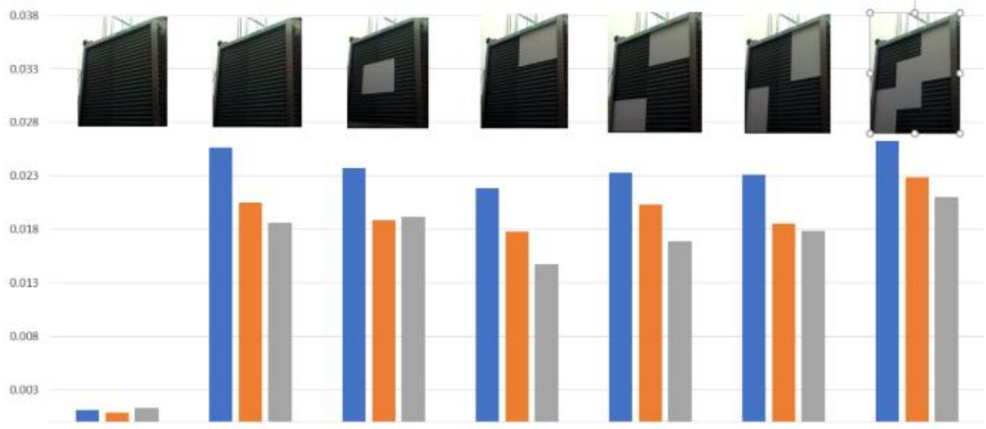

Figure 48: Acceleration measurements visualized as vertical bar charts for artificial ice coverage as shown in the images. The first set show the level of vibration with the fan not operational.

IoT category: Heat pump operation optimization

Link: https://heatpumpingtechnologies.org/annex56/wp-content/uploads/sites/66/2023/06/iot-annex-56-project-case-at-soft-sensor.pdf

A soft sensor was developed to detect icing on the evaporator of a heat pump using vibration signals measured at the fan. The study involved experiments conducted in a climate chamber, simulating various climatic conditions. Vibrations increase depending on the blockage and its symmetry-breaking of the heat exchanger area. During defrosting, the vibration signals showed an initial increase due to fan startup, followed by further acceleration during the clearance of the air path through the heat exchanger. Thus, the decrease in vibration can be linked to the onset of defrosting possibly allowing an accelerometer being used as a soft sensor for heat exchanger frosting. Developing soft sensors requires suitable correlation models and extensive experimental efforts, but may improve operation optimization, provide maintenance insights, and product design enhancements.

5.2 Norway

Contributors: Kristian Stenerud Skeie (SINTEF Community), John Clauss (SINTEF Community) and Cansu Birgen (SINTEF Energy)

5.2.1 BAC in Action: Connected heat pumps in the ZEB Laboratory building

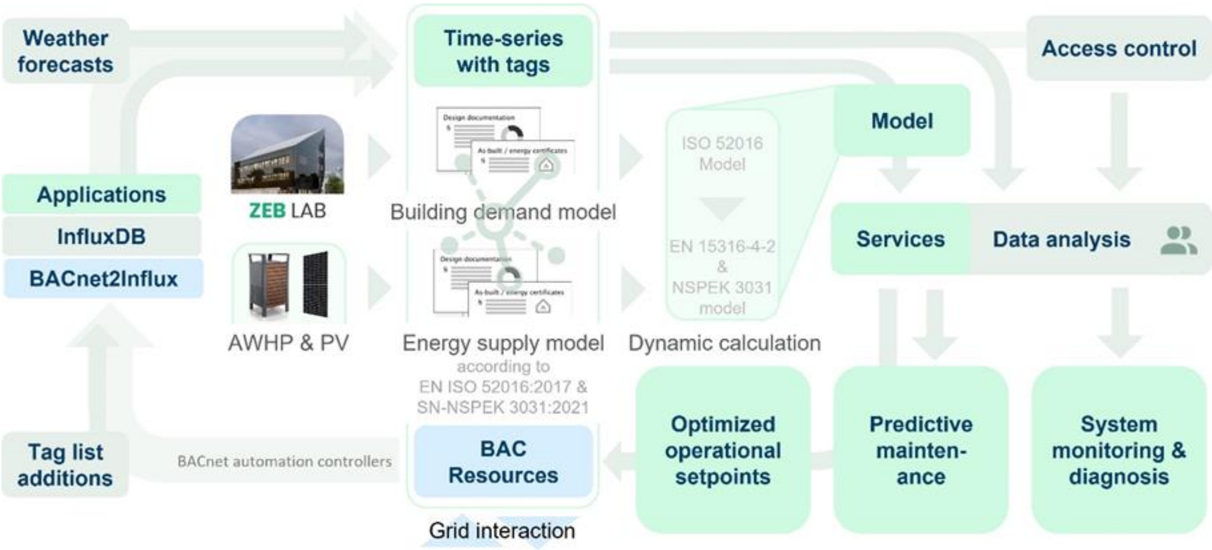

Figure 49: ZEB Laboratory project

IoT Category: Heat pump operation optimization, Predictive maintenance

Link: https://zeblab.no/

Commercial buildings generate large amounts of data over various protocols that can be ingested into databases for operational use of the data downstream. Analyzing the information from daily operations can help create new and innovative services. In the ZEB Laboratory office building located in Trondheim, Norway, connected heat pumps are central to the energy concept and offer potential to optimize the use of on-site generated electricity and heat storage. In this project monitoring data from the heat pump units, the plant and room level automation controllers is combined with design and as-built information to:

- Analyze the heat pump operation by extracting time-series from a database and writing back model outputs or metrics for visualizations.
- Model the heat pump COP and emitted power based on the exergetic approach in EN 15316-4-2.
- Model the heating demand using an RC-model informed from as-built documentation.

The hourly model regularly executed on actual weather provided a benchmark of design performance pre-requisites and demonstrated potential in forecasting applications. These capabilities may be utilized to optimize setpoints and operating strategies, such as defining the optimal time to transition from night setback mode or operating heat pumps based on the predicted photovoltaic production, heating demand and capacity. Work will proceed on the services and integration layer aiming for a computation-friendly architecture that can be applied to other buildings with BACnet devices.

5.3 Sweden

Contributors: Yang Song (KTH), Davide Rolando (KTH), Tommy Walfridson (RISE), Markus Lindahl (RISE)

5.3.1 Data-driven lab for heat pump systems

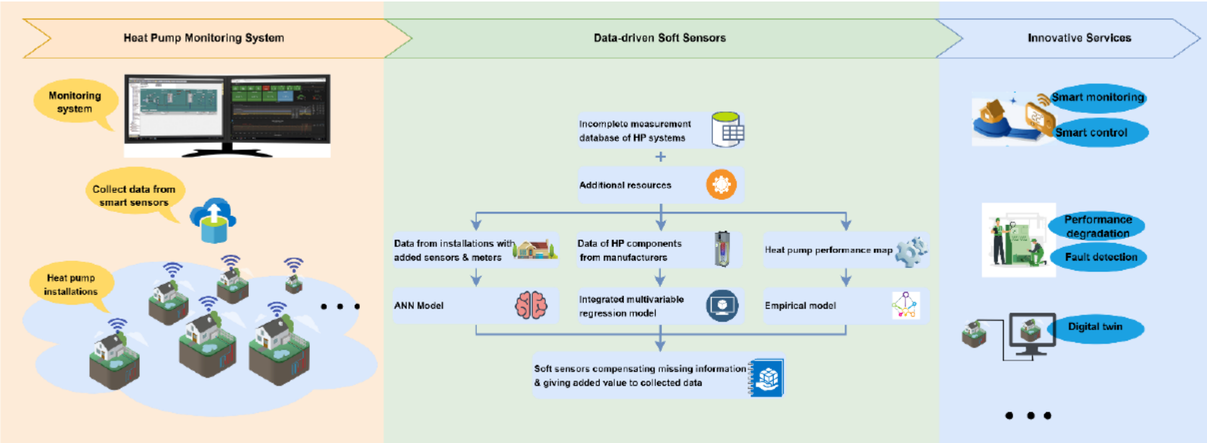

Figure 50: Data-driven lab for heat pump systems

IoT Category: Heat pump operation optimization, Predictive maintenance

Link: https://www.energy.kth.se/data-driven-lab-for-building-energy-systems

Modern heat pump systems potentially generate a large amount of data every day that can be stored in databases. Appropriate analysis of the information collected in measurement databases facilitates the development of different innovative services. In a common project between KTH Royal Institute of Technology, AIT Austrian Institute of Technology and heat pump manufacturers, a data driven lab is developed for heat pump systems, which acts as a virtual platform to improve heat pumps control strategies, fault detection and diagnosis and communication with local energy grids.

Based on the data-complete measurements after the process of soft sensors, this project goes towards to providing innovative services including but not limited to the end-users and manufacturers and smart monitoring, smart control, performance degradation, fault detection, and digital twins.

5.3.2 Data-driven models for estimating heat pump power consumption

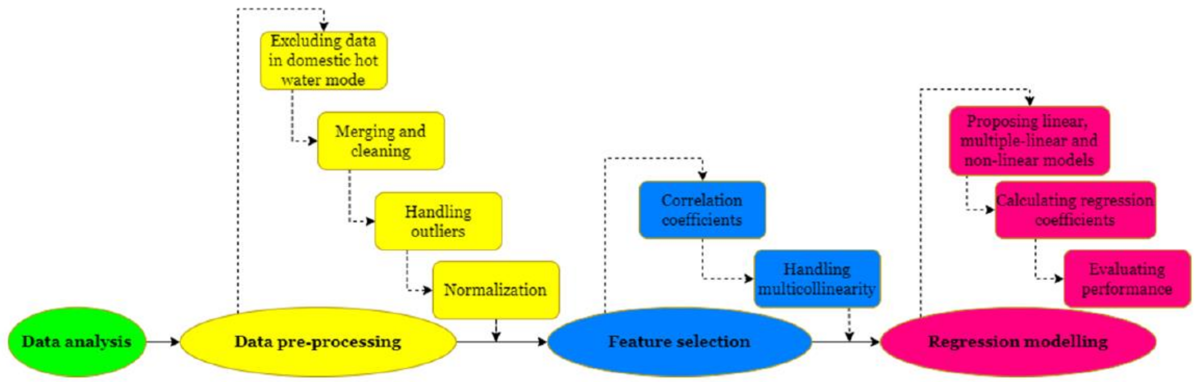

Figure 51: Flowchart of data-driven estimation of heat pump power consumption

IoT Category: Heat pump operation optimization, Predictive maintenance

Link: https://heatpumpingtechnologies.org/annex56/wp-content/uploads/sites/66/2023/04/iot-annex-56-project-case-se-data-driven-heat-pump-power-estimation.pdf

The aim of this project is to develop data-driven heat pump models which would estimate the power consumption of a heat pump using features measured during heat pump operation from installations that are currently in operation. Thus, this project analyses anonymous real time monitoring data from residential heat pump installations, which are obtained from heat pump manufacturers or other stakeholders. Further, this project identifies which features from the obtained data sets are most relevant for developing models which can be used for estimating heat pump power consumption. The objective of this project is also to evaluate the proposed models based on their accuracy.

The goal of the project is to answer the following research questions:

- What are the most important features measured during heat pump operation for modelling heat pump power consumption?
- How can the power consumption of a heat pump be estimated using a limited number of input features measured during heat pump operation?

This project developed both polynomial and machine learning models to estimate heat pump power consumption. Prior to model development process, one essential step: feature selection was conducted. The main benefits of feature selection include reducing dimensionality, the risk of overfitting, training time of the model and improvements in model accuracy. In this project, feature selection also means the number of sensors can be reduced, which can make the power estimation work more convenient in practice. So the most important features for modelling heat pump power consumption were identified based on the correlation coefficients between power consumption and the measured parameters. Further, the number of selected features as the input features to the models were reduced based on variance inflation factor (VIF) so that the features had no multicollinearity problems. Apart from this method, a built-in feature importance method in machine learning algorithm was also applied.

5.3.3 Large scale demand response of heat pumps to support the national power system (SLAV)

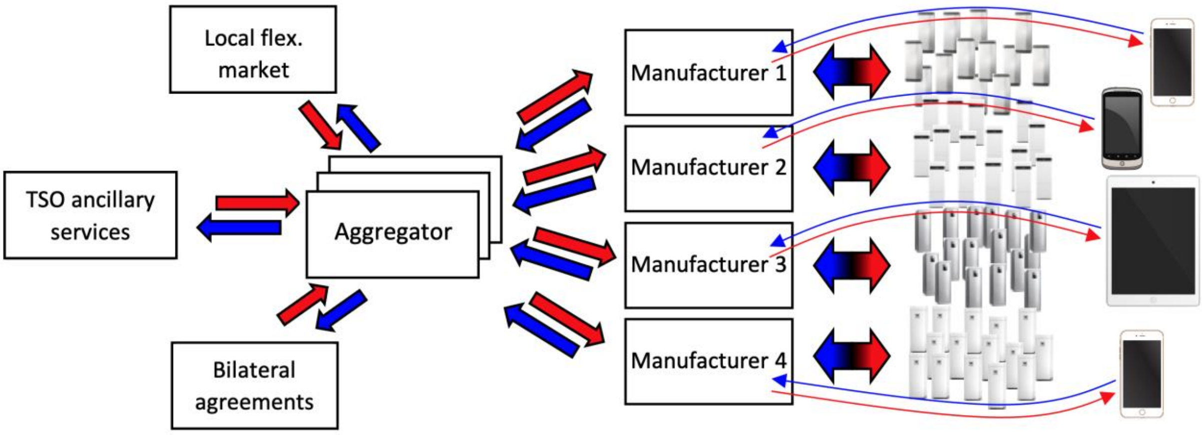

Figure 52: Overview of the communication flow for demand response from heat pumps using the manufacturers cloud solution

IoT Category: Flexibility provision

In a power system with an increased share of electricity from intermittent renewable sources, such as wind and solar, a more flexible electricity consumption will be needed. The project has investigated possibilities and constrains for a concept where residential heat pumps are aggregated and controlled via the manufacturers cloud service to support the power system with demand response with focus on Svenska kraftnäts ancillary services, local flexibility markets or bilateral agreements. The project covers several aspects, such as barriers related to technical constrains in the heat pumps and the electricity market as well as potential communication standards and cybersecurity. The results are based on expert interviews, literature review and field tests. Even though the project focuses on Swedish conditions the results are likely relevant in several countries.

5.4 Switzerland

Contributors: Raphael Agner (HSLU) and Beat Wellig (HSLU)

5.4.1 Avoidance of heat pump efficiency losses by digital operation analysis (DIBA-WP)

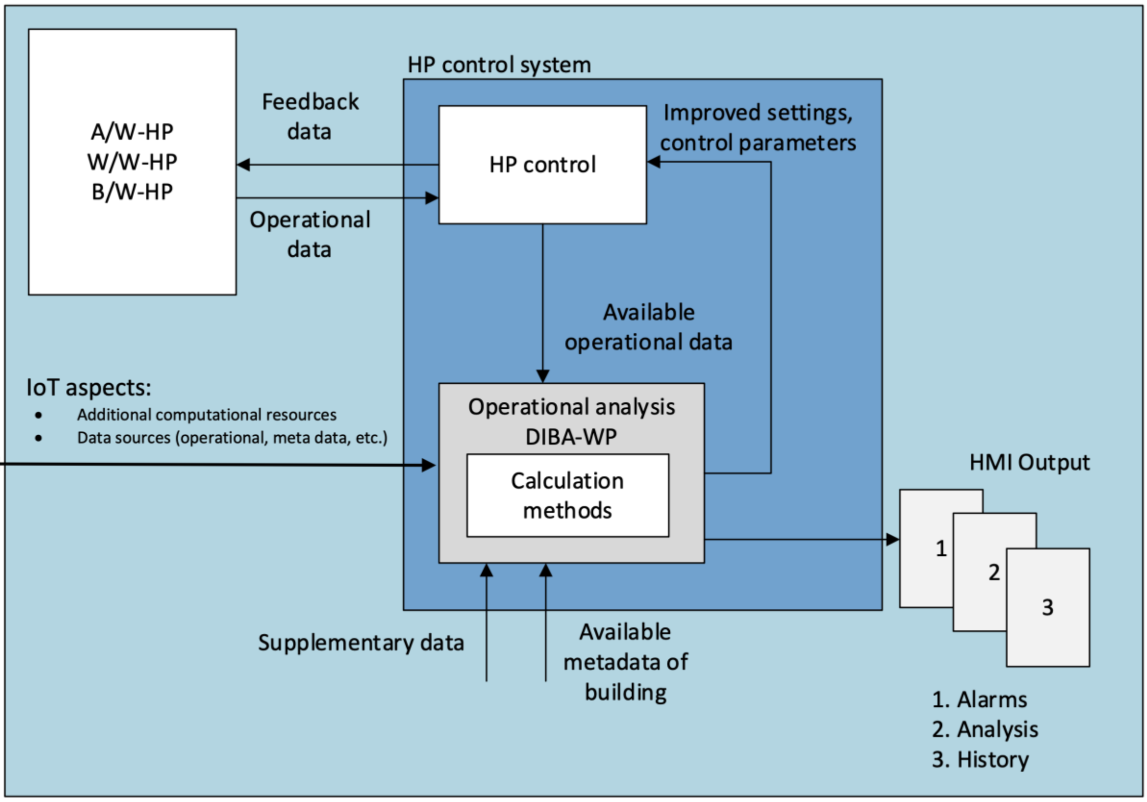

Figure 53: Overview of the DIBA-WP Topology

IoT Category: Heat pump operation optimization

Link: https://www.hslu.ch/de-ch/hochschule-luzern/forschung/projekte/detail/?pid=6382

In Switzerland roughly 30% of the end energy demand is used for space heating and domestic hot water. Until 2050 most of this is expected to be covered by heat pumps. While this already increases the efficiency of the energy system significantly, the optimal operation of these heat pumps is gaining relevance in respect to their impact on the energy system. The research project "Avoidance of Heat Pump Efficiency Losses by Digital Operation Analysis", supported by the Swiss Federal Office of Energy, aims at minimizing efficiency losses in heat pump operation. The underlying motivation of the project is the presence of wrong parameter settings that cause efficiency losses and that are often not recognized by the end use because they do not have an impact on the comfort for the user.

The aim is to create the foundations for a digital operation analysis of heat pump systems in single family and smaller multi-family houses. This is achieved by collecting typical faults of heat pump systems in the field and evaluating their relevance by the means of system simulations with Modelica. The resulting simulation data is used for identifying detection methods, and such methods are derived based on thermodynamic principles and statistics. These methods are again tested with system simulations. The results from the methods are to indicate to the user which settings should be controlled and corrected. In a later stage the results can also enable automatic correction of the setpoint settings.

One key error that is well known is the suboptimal setting of heating curves. If the heating curve of a heat pump is set too high, the heat pump provides the heating water at a higher than necessary temperature and thus runs with a lower efficiency.

The necessary analysis to detect wrongful settings was found to be computationally demanding for local execution on heat pump controllers. The Internet of Things (IoT) framework would be relevant in addressing this challenge using cloud computing resources for the execution of the analysis. Furthermore, IoT enables connection of multiple components (e.g., the HP with the room heating controllers) leading to a reduction of measurement equipment.

The main conclusions can be summarized as follows:

- Suboptimal settings have a significant impact on the energy efficiency of heat pump systems.
- Their detection should be based on physical principles that are to a minimal extent dependent on the effective implementation.
- The most significant errors can be detected with appropriate analysis methods using operation and meta data.

5.4.2 Virtual energy storage network based on residential heating systems: Tiko Energy Solutions AG

Figure 54: Overview of the Tiko system

IoT Category: Flexibility provision

Link: www.tiko.energy

To ensure stability of power grids, the energy supply and demand must be balanced. Traditionally, the demand for electricity was assumed to be unchangeable and production-side balancing was applied to the system. With the increase of fluctuating renewable energy sources, electricity production itself is becoming difficult to control. To enable a reliable power grid operation with fluctuating supply, flexibilization of the demand side must be achieved. Due to the high inertia of the thermal energy demand in the buildings sector, the demands are well suited for load side flexibilization if they are covered by heat pumps or other forms of electrical heating.

The company Tiko Energy Solutions AG started with the development of its ancillary service business in 2012 and entered the market with its solution in 2014. In 2017, Tiko's virtual power plant already included over 10,000 electrically based heating systems throughout Switzerland. More than half of these installations are heat pumps. Tiko offers the grid operator both primary control quality (frequency stability) and secondary control quality (balancing between planned power and actual power in the grid). Since 2017, tiko has been expanding its market internationally and has established a customer base in several countries in the EU.

The Tiko system can be divided into 4 parts (see Figure 54). As actors and sensors, two devices are connected directly to the heating system. The “K-box” measures the power consumption and at the same time serves as a control switch using a relay. The T-sensor is used to ensure comfort, so that the room or water temperature does not drop out of the desired temperature range due to a switch action. Both devices communicate within the house power line carrier (PLC) with the “M-box” (gateway). The “M-box” collects all data and communicates via 3G/4G network with the private cloud (backend) of Tiko. All processing work is performed on the cloud server. This backend system collects all information about the connected devices and combines it with additional information such as local weather forecasts, past consumption patterns and estimation of the current state of the devices. Based upon this information and employing proprietary algorithms the system determines the removal or addition of the individual loads to achieve the necessary balance throughout the entire system. On the private user side, customers can monitor and manage their own energy consumption via a webpage or app (frontend). This enables them to make better use of their energy-saving potential. Apart from comfort limits, switching limits have also been implemented. Especially for heat pumps, frequent switching on and off can lead to a performance loss and increased wear of the equipment. The switching limits were developed by Tiko in cooperation with leading HP vendors. Figure 55 shows an example of an air/water heat pump being switched off for 52 minutes by the Tiko system. The typical heat pump in the Tiko system is switched less than five times per day on average.

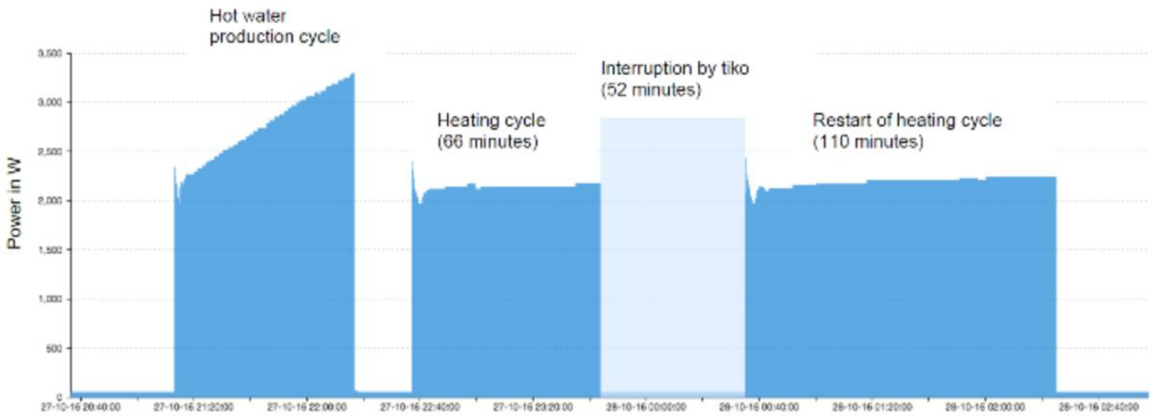

Figure 55: Heat pump cycle interrupted by tiko control

Summary of the results:

- Ancillary services based on residential heating devices can be provided economically.
- The key elements for a successful solution are:
  - Simple and cost-efficient hardware
  - Secure and reliable communication
  - Efficient handling of big amounts of data
  - Simple and efficient control algorithms
  - Value proposition for all involved parties

5.4.3 Smart Guard: Meier Tobler AG

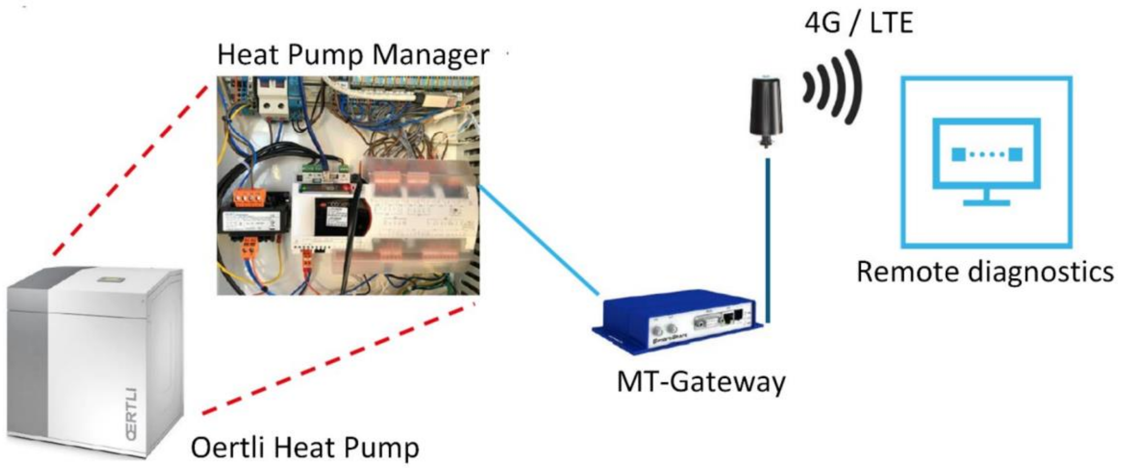

Figure 56: SmartGuard system setup

IoT Category: Heat pump operation optimization, predictive maintenance, Heat pump operation commissioning

Link: https://www.meiertobler.ch/de/loesung-und-produkte/smart-guard

Heat pump malfunctions are often not detected until comfort loss is experienced by the occupants of the building. The resulting analysis of the malfunction through service personnel of the HP supplier then usually takes place on-site. Only after an on-site inspection by the service personnel can the defect in the HP be identified and determined whether spare parts are needed for repair. The necessary spare parts must be obtained and installed in a subsequent step. By the time the HP is fully operational again, the building may have cooled down and affected customer satisfaction.

Meier Tobler AG developed an IoT solution called “SmartGuard” to enable remote diagnostics for heat pumps. The goal is to guarantee efficient and safe operation of the HP and facilitate maintenance workflows. SmartGuard is offered as a service with an annual subscription cost (free during the warranty period of the heat pump).

The SmartGuard system setup is divided into three parts: The heat pump manager, the MT-Gateway, and the remote diagnostics. The heat pump is controlled and monitored by the heat pump manager. The heat pump manager can redefine various control parameters. In addition, the HP- manager collects over 200 data points of the heat pump in a resolution of up to 1 second. The heat pump manager is directly connected to the MT-Gateway. The MT-Gateway has its own antenna on the building facade and thus communicates via 4G/LTE (LTE CAT1M) with Meier Tobler's remote diagnostics.

The remote diagnostics are carried out both automatically and manually by trained service personnel. In particular, the detection of faulty heat pumps is done by an automated algorithm. The service personnel have the power to decide on the resulting actions. Detailed technical details on data analysis and fault detection are not publicly available.

SmartGuard enables the correction of simple settings and minor faults remotely. If a heat pump fails, SmartGuard can detect this, and service personal has the possibility to contact the customer before comfort loss occurs. Due to the remote diagnostics, the technician is able analyze the fault and identify the required spare parts. Another aspect of the remote diagnostics is the optimization of the control parameters of the HP in the first years of operation, to increase the efficiency of the heat pump. These functions are based on the heat pump's previous operating behavior.

Achieved Results:

- Automated fault detection and facilitation of repair of heat pumps through real time diagnostics enabled.
- Optimization of heat pump operation based on past performance can be done remotely. With the mobile app, the customer can customize his desired user profile and has insight into all changes made by the personnel.

5.5 France

Contributor: Odile Cauret (EDF)

5.5.1 Losange Project

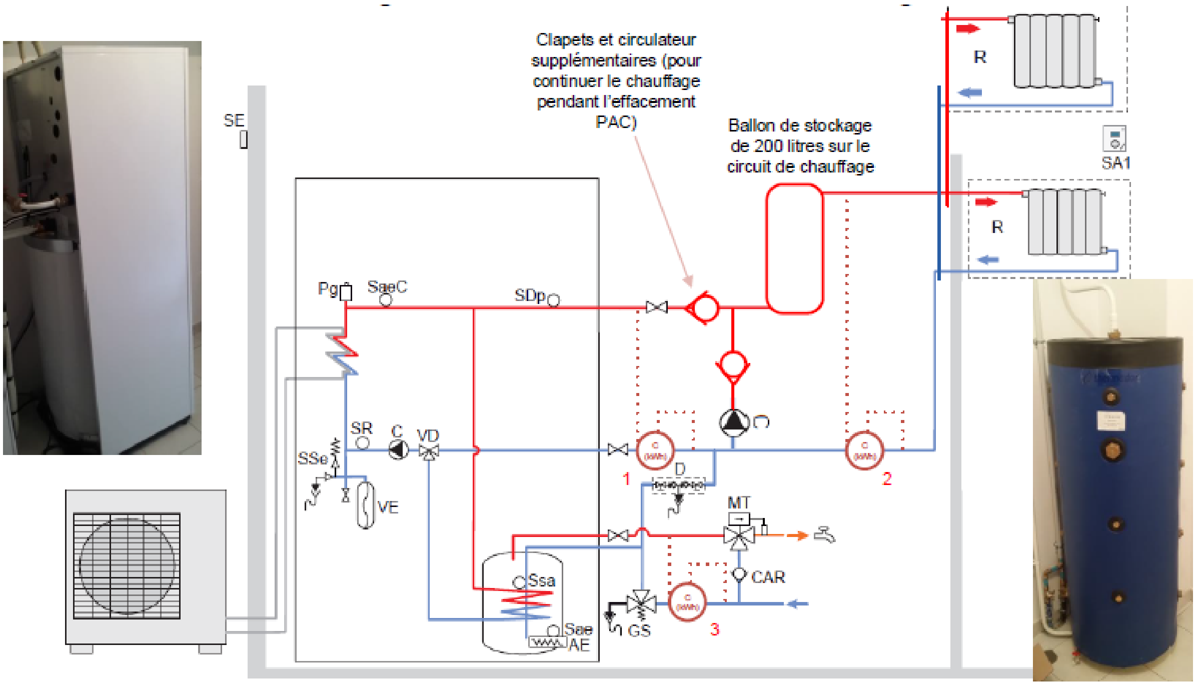

Figure 57: HP installation in Losange Project

IoT Category: Flexibility provision

The project involved two new single-family houses in Villenauxe, in the north-east of France. Each was equipped with an air-to-water heat pump and a 200-liter storage tank positioned on the heating circuit. The heat pumps were directly controlled via a contactor in order to test different shift-load periods. It was found that it was possible to do short shift-load without discomfort for the customer. It was necessary to install additional equipment to receive signals from the electrical network (Linky), from the Internet or to do local programming. Additional (bulky) equipment was necessary to store thermal energy to avoid discomfort, the cost and additional volume of this equipment is difficult to accept by the client without financial advantage (tariff).

5.6 Germany

Contributors: Sebastian Borges, Fabian Wüllhorst, Stefan Goebel, Tim Klebig, Christian Vering (RWTH Aachen); Tim Rist, Lilli Frison, Simon Gölzhäuser (Fraunhofer ISE)

5.6.1 Digital twin of heat generator systems as an enabler for the development of low-emission building energy technology (DZWi)

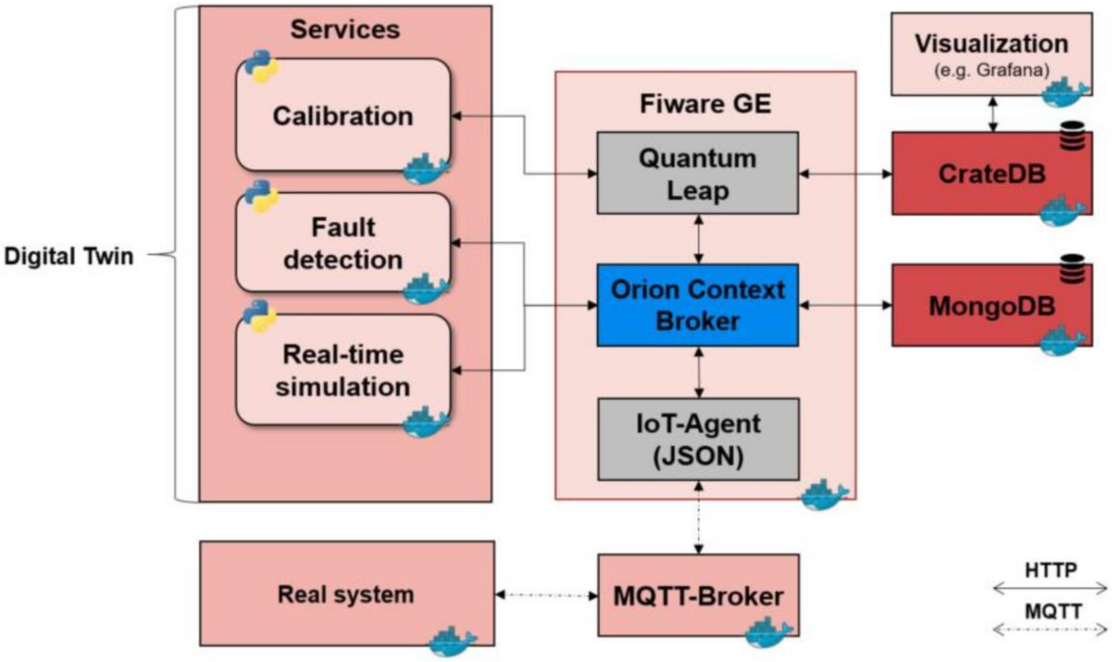

Figure 58: Fiware architecture for communication of virtual/real system and implemented services

IoT Category: Heat pump operation optimization, Predictive maintenance, Heat pump operation commissioning

Link: https://dzwi-waerme.de/

The DZWi project aims to develop a digital representation of different energy conversion systems (heat pump/fuel cell) for building energy systems, to significantly shorten R&D times. The combination of scientific institutions and producers of modern heating technology is ideal, as the digital twins to be created can be tested directly on practically relevant products (high TRL8-9). Based on "Hardware-in-the-Loop" (HiL) tests (also known as field tests in the lab), fundamental parameters for heat pumps and fuel cells are to be determined. In addition to the analysis, an essential component is the description of the dynamic and static behavior, e.g., of the refrigeration cycle. Here, a generally applicable methodology is to be developed that also considers future refrigerants concerning the F-gas regulation. The core of all development work is a cloud environment, which should enable scalability of the results for the system's entire life cycle. Using the open-source middleware Fiware (Figure 58) to enable communication between real systems, virtual models, and integrated services like Fault Detection, ensures a holistic approach to a digital twin replica.

5.6.2 DZWI - Fault Detection and Diagnosis

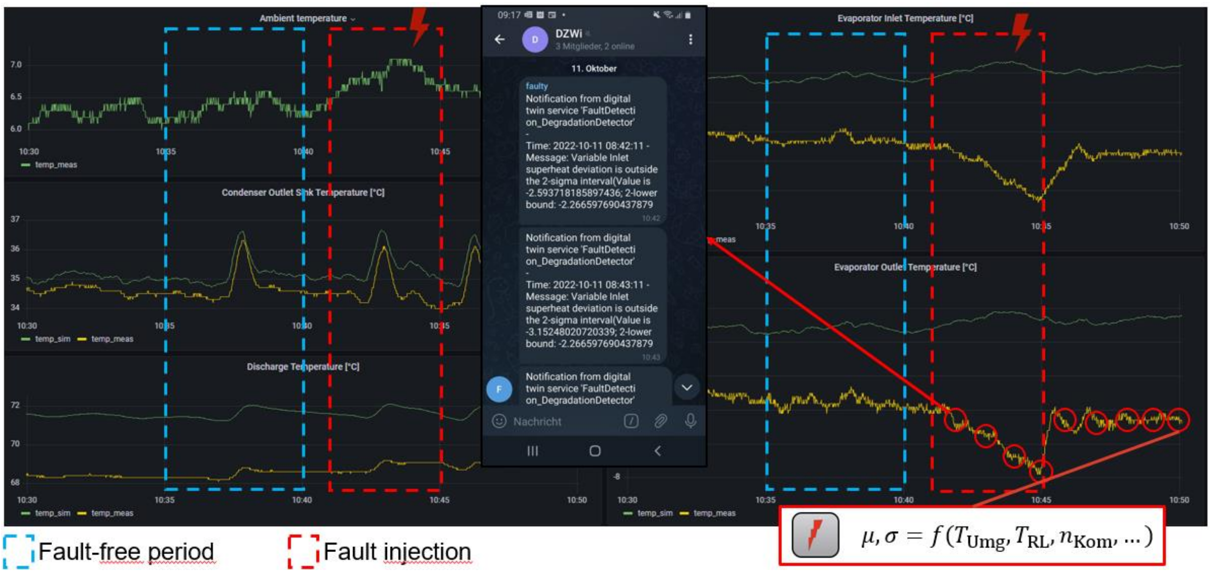

Figure 59: First results of fault detection service for evaporator fouling and resulting user notification.

IoT Category: Predictive maintenance

Link: https://dzwi-waerme.de/

Developing algorithms for FDD is an important goal of the DZWi project. They detect, localize and eliminate efficiency reductions. The first results of a proof-of-concept of fault detection are shown in Figure 59, where the blue area is used to learn the fault detection module, a fault-free operation, and the fault was initiated in the red area. A physical simulation model is compared to the real measured data via the monitoring service, and increased fouling in the heat pump evaporator could be detected by calculating the standard deviation. In this case, the notification module provides information about the occurrence of a fault to the user afterward.

5.6.3 Artificial Intelligence for Heat Pumps (AI4HP)

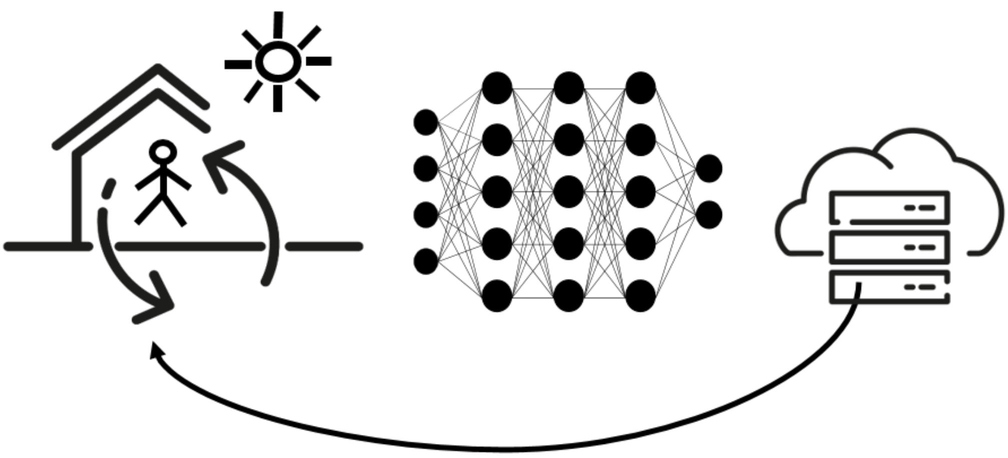

Figure 60: AI-pipeline for adaptive heat pump operation

IoT Category: Heat pump operation optimization

Link: https://www.ise.fraunhofer.de/en/research-projects/ai4hp.html

Heat pumps are an effective solution for reducing energy consumption and the environmental impact of buildings, and for introducing renewable energy into the heat supply. However, the actual efficiency of heat pumps in practice does not always meet expectations. In addition to high occurring heat losses, the energy efficiency is reduced by an inappropriate system design, by wrong parameterization of the heat pump control and by undetected operating deficits. Therefore, the subject of the "AI4HP" project is the development of a new generation of "intelligent heat pumps", which adaptively adjust to changing boundary conditions with the help of artificial neural networks and thus increase energy efficiency while maintaining user comfort.

Until today, the control of residential heat pumps is mainly realized with very simple heuristic methods that do not consider real user needs or the prediction of external influences such as a change in user habits or aging or renovation of the building. Therefore, the aim of the collaborative project between German and French experts from the field of heat pumps and energy supply and from the field of AI research is to develop novel artificial intelligence (AI) methods based on artificial neural networks (ANN) for adaptive heat pump control and monitoring. The new intelligent AI-powered heat pumps integrate new functionalities and interactions with a changing environment for the first time to provide the highest energy efficiency and comfort to the user, facilitate maintenance tasks, and avoid performance degradation due to fault detection.

An adaptive AI pipeline is being developed for the three use cases of "adaptive heating curve control", "adaptive control of hot water heat pumps based on load forecasts" and "adaptive fault detection and diagnosis", integrated into heat pump control and validated in laboratory tests and pilot buildings. By using the advanced AI methods, we expect to achieve up to 20% energy savings and CO_2 emission reductions without sacrificing comfort.

5.7 Denmark

Contributors: Jonas Lundsted Poulsen (DTI), Wiebke Brix Markussen (DTI), José Joaquín Aguilera (DTU, Department of Civil and Mechanical Engineering), Henrik Madsen (DTU Compute), Christian Ankerstjerne Thilker (DTU Compute), Tobias Dokkedal Elmøe (Energy Machines™)

5.7.1 Project cases

5.7.1.1 Digital Twins for Large-Scale Heat Pump and Refrigeration systems

IoT Category: Heat pump operation optimization, predictive maintenance, flexibility provision, heat pump operation commissioning

Link: https://www.digitaltwins4hprs.dk/

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 61 shows a diagram of the Digital Twin system operator integrated in heat pump or refrigeration system.

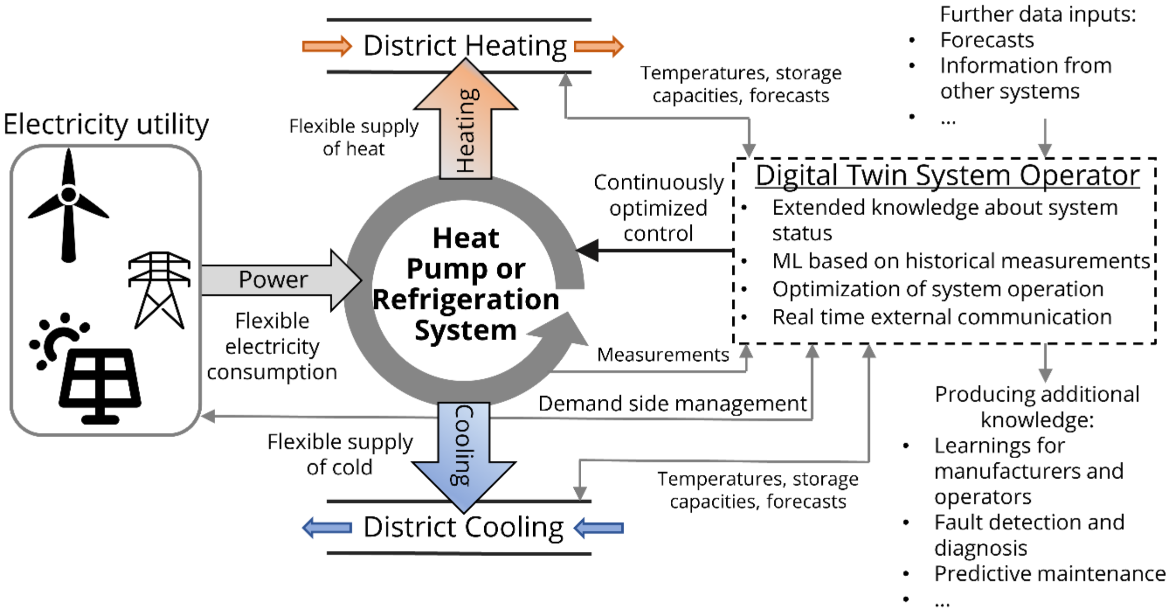

Figure 61: Diagram of the digital twin system operator.

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.

5.7.1.2 EnergyLab Nordhavn

IoT Category: Heat pump operation optimization and flexibility provision

Link: http://www.energylabnordhavn.com/

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 62. 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.

Figure 62: Heat is recovered from a supermarket refrigeration system to the local district heating grid in Copenhagen.

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.

5.7.1.3 Flexheat System - Intelligent and Fast-regulating Control

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://www.hofor.dk/baeredygtige-byer/udviklingsprojekter/fremsynet-fjernvarme/flexheat-intelligent-varmepumpe-i-nordhavn

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 63. 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.

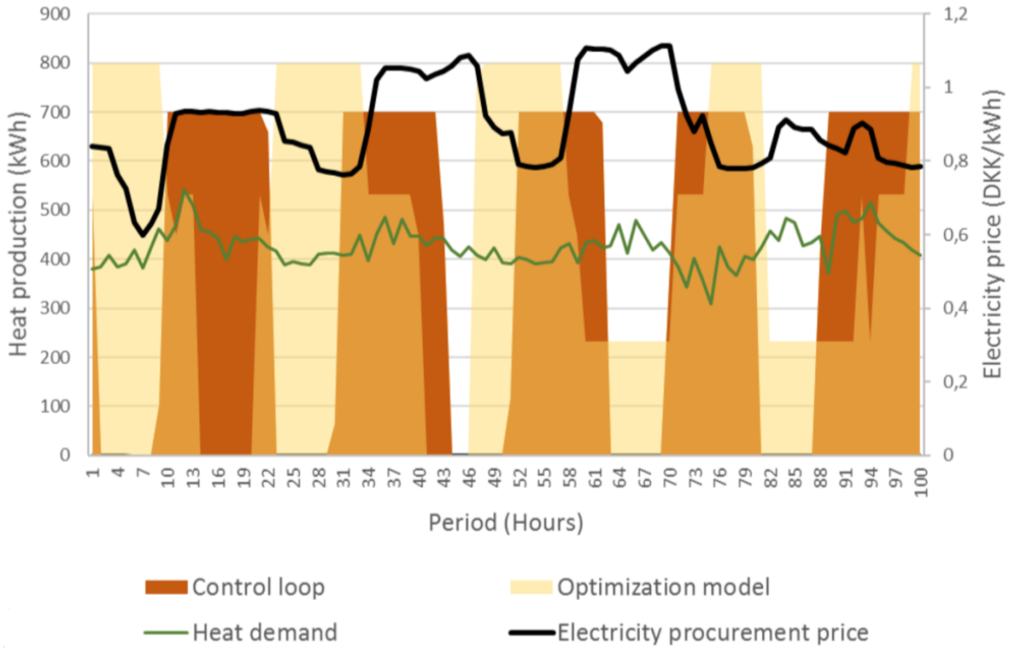

Figure 63: Flexible heat production for 100 hours period. “Control loop” with dark orange columns: Periods with heat production primarily from heat storage, and “Optimization model” with bright orange: Cost optimized heat production from heat pump (800 kW max. production). “Heat demand” is the heat demand 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.

5.7.1.4 Smart-Energy Operating-Systems

IoT Category: Flexibility provision

Link: https://www.citiesinnovation.org/smart-energy-operating-system/

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 64. 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.

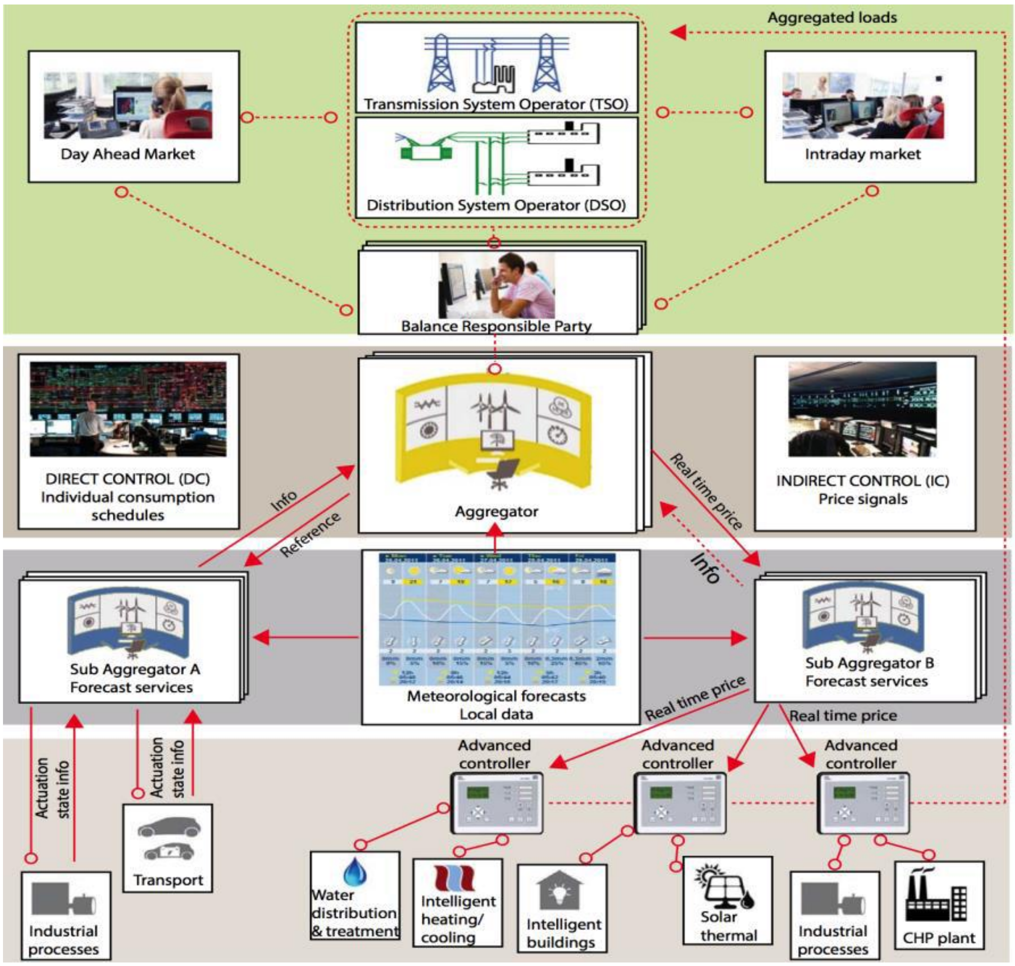

Figure 64: The Smart-Energy Operating-System (SE-OS) for digitalization of integrated energy systems.

5.7.1.5 OPSYS 2.0

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://www.teknologisk.dk/projekter/projekt-opsys-2-0/40581

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 65

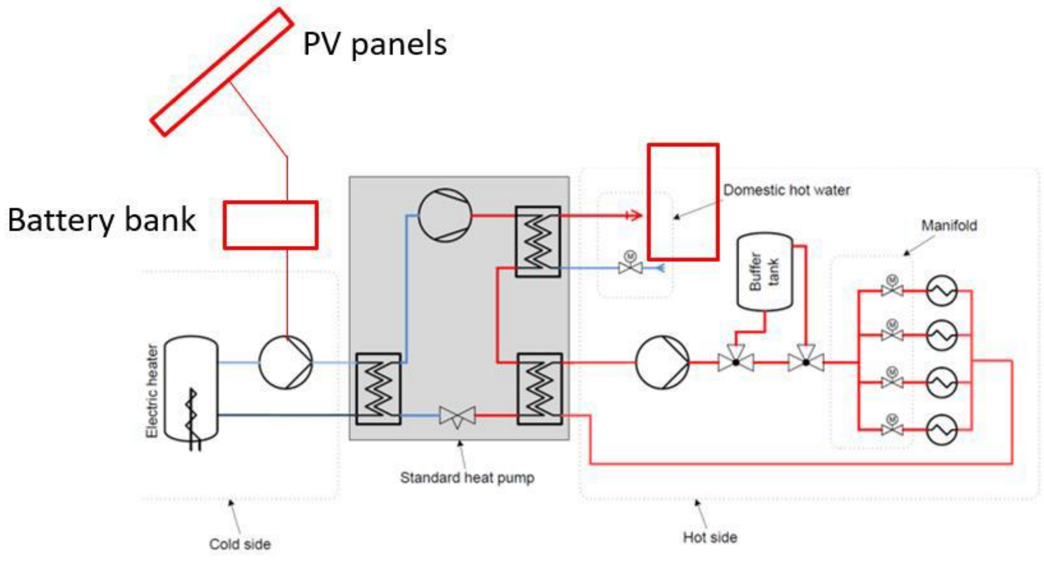

Figure 65: Sketch of experimental setup (on the test rig PV and battery are virtual).

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.

5.7.1.6 Cool-Data

IoT Category: Flexibility provision

Link: https://cool-data.dtu.dk/

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 66. 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.

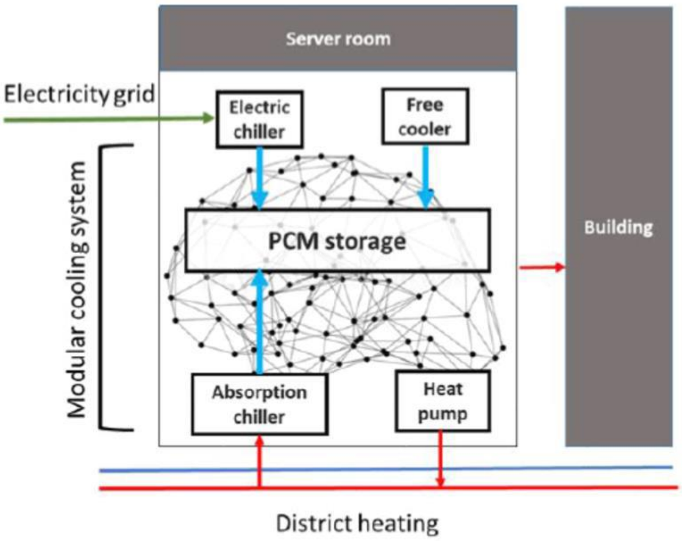

Figure 66: Overview of Cool-Data application.

5.7.1.7 SVAF phase II

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://www.dti.dk/projects/project-experimental-development-of-electric-heat-pumps-in-the-greater-copenhagen-dh-system-phase-2/37419

The overall purpose of the project is to accelerate the use of large-scale electric heat pumps (HPs) for district heating (DH) through industrial cooperation, 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 67).
- HP Doctor, for monitoring purposes and fault detection.

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).

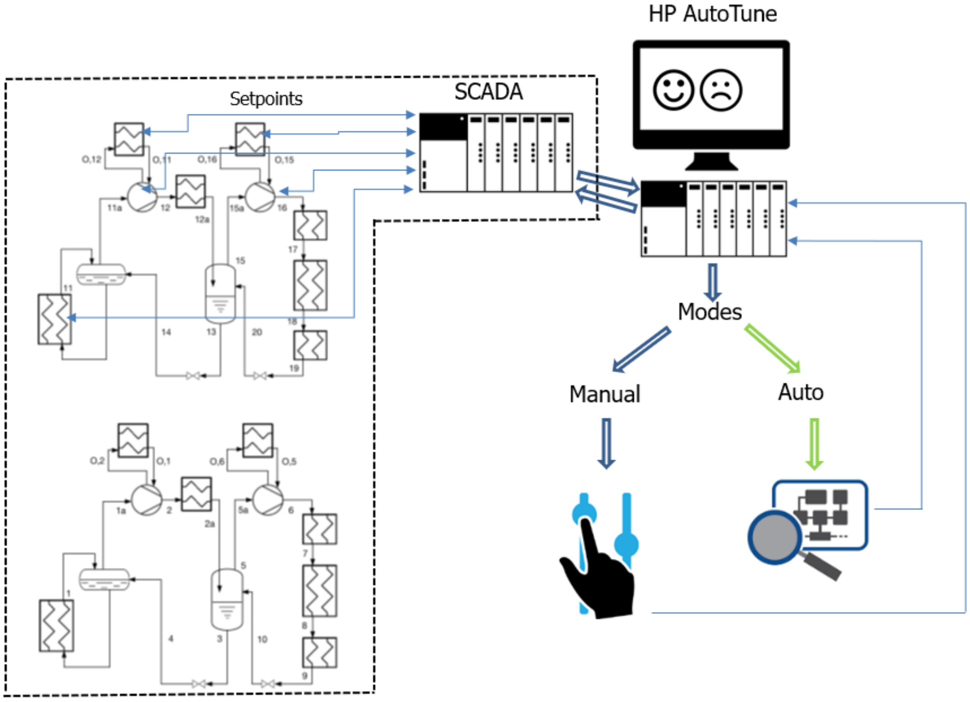

Figure 67: Diagram of the HP AutoTune concept.

5.7.1.8 HPCOM

IoT Category: Heat pump operation optimization, predictive maintenance, and flexibility provision

Link: https://www.teknologisk.dk/projekter/projekt-hpcom/37449

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, represented in Figure 68.

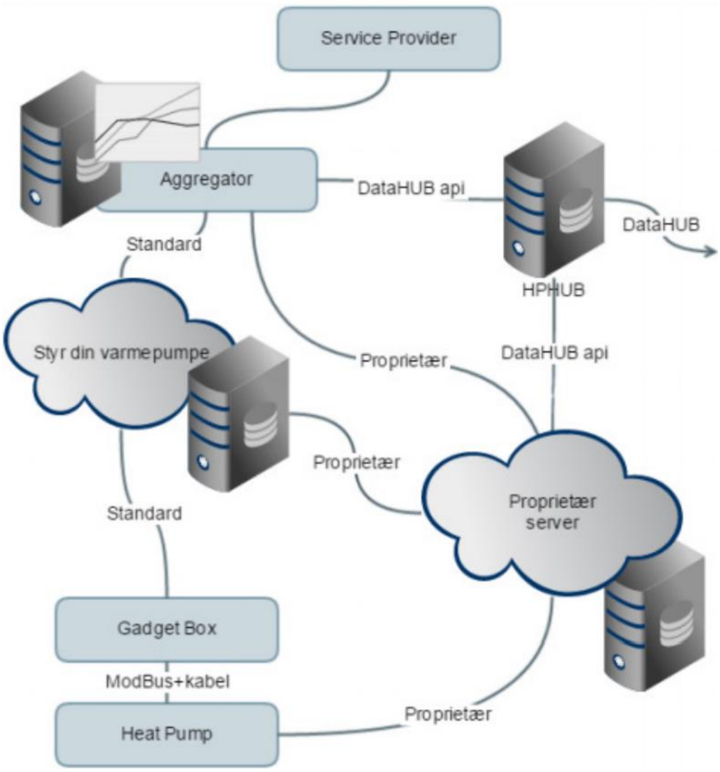

Figure 68: Principle for heat pump datahub (high level) developed in the HPCOM project.

The project focused on knowledge sharing and was centered on 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.

5.7.1.9 Flexible Energy Denmark

IoT Category: Flexibility provision

Link: https://www.flexibleenergydenmark.com/

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 5.7.2.9) 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 using a smart control developed for heat pumps, where both balancing and grid services could be provided. Figure 69 shows the predicted carbon intensity of electricity production and periods for heat pump operation in the case study installation.

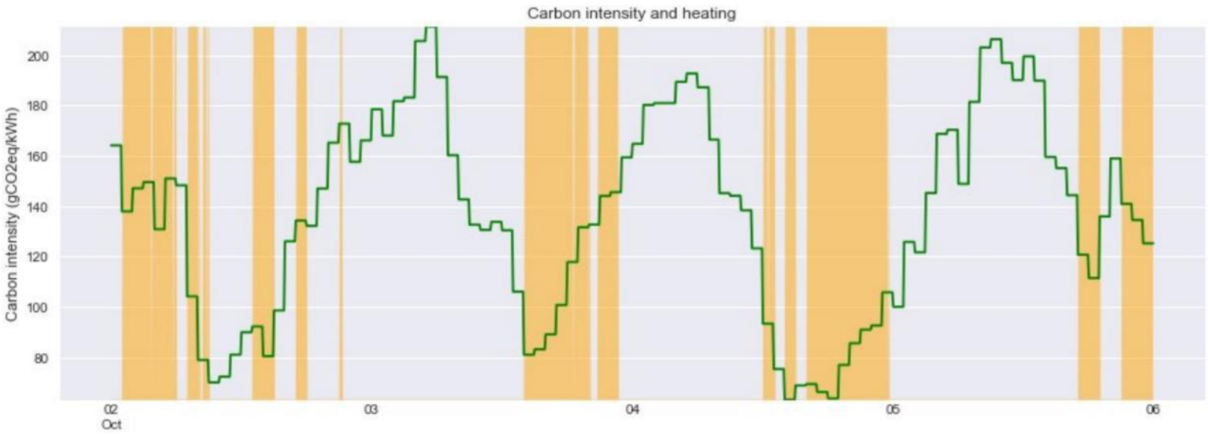

Figure 69: Predicted carbon intensity (green) and periods at which the heat pump is turned on (orange).

5.7.1.10 Res4Build

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://res4build.eu/

This is a Horizon 2020 project that 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 multisource heat pump in a cascade configuration (see Figure 70), 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.

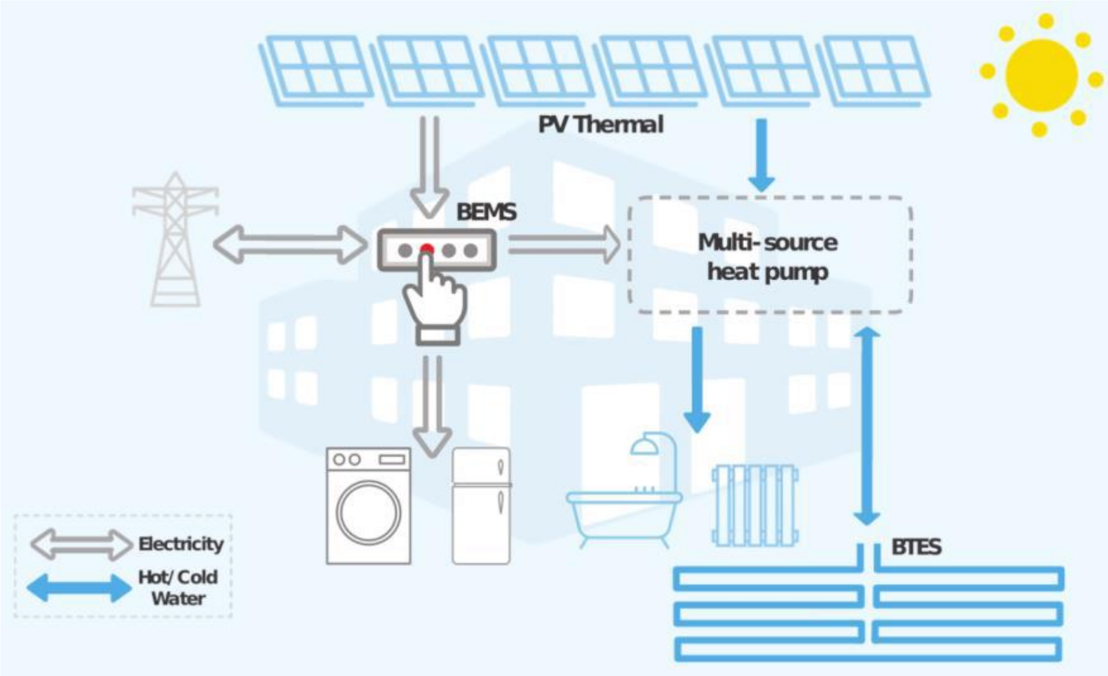

Figure 70: Concept overview for components in the RES4BUILD energy system.

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.

5.7.1.11 Development of Fast Regulating Heat Pumps Using Dynamic Models

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://www.dti.dk/dynamic-modelling/42634

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. Figure 71 shows the concept for developing fast regulating heat pumps.

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.

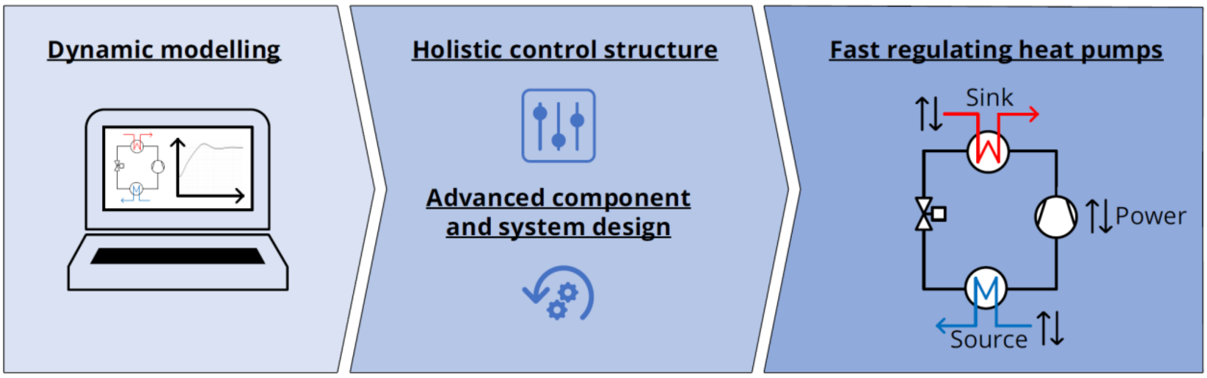

Figure 71: Concept of development of fast regulating heat pumps based on dynamic modelling.

5.7.1.12 CEDAR

IoT Category: Heat pump operation optimization

Link: Not available yet

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 72 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.

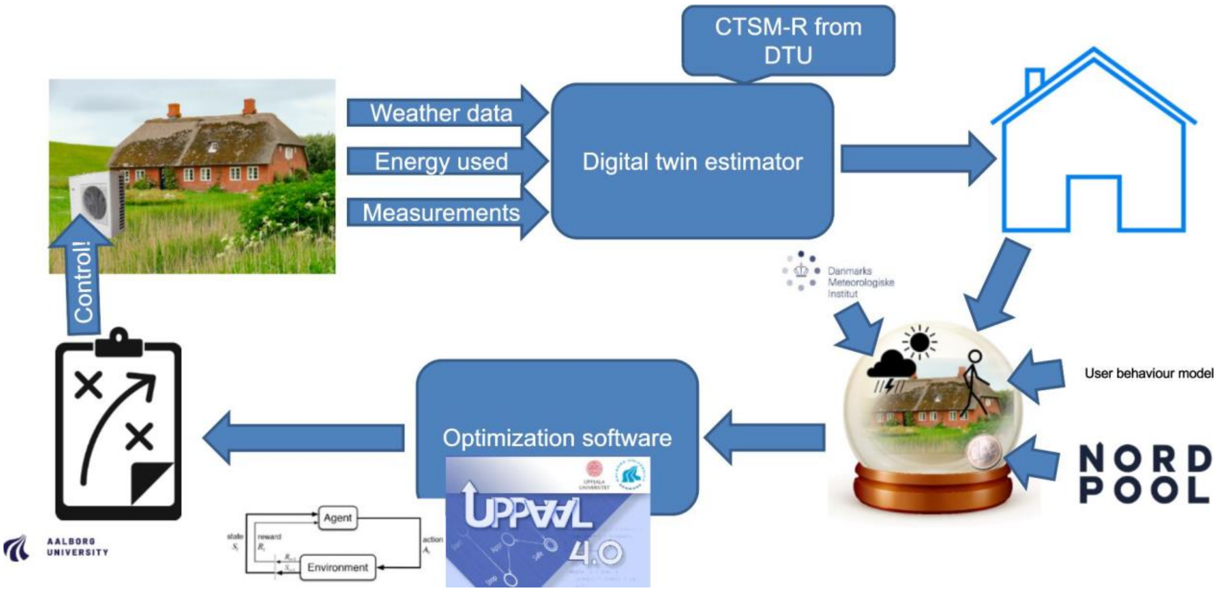

Figure 72: General flow of the approach studied in the CEDAR project.

5.7.2 Use Cases

5.7.2.1 Energy Machines™

IoT Category: Heat pump operation optimization and predictive maintenance

Link: https://www.energymachines.com/services

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 73, 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 73: EMV dashboard with quick overview of current performance (left) and an Energy Machines heat pump installation with sensors placed inside the boxes (right).

5.7.2.2 Neogrid

IoT Category: Heat pump operation optimization, predictive maintenance, and flexibility provision

Link: https://neogrid.dk/preheat/

Neogrid is a cleantech supplier working with intelligent energy visualization, monitoring and control. Neogrid has developed the PreHEAT heat pump controller, shown in Figure 74. 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.

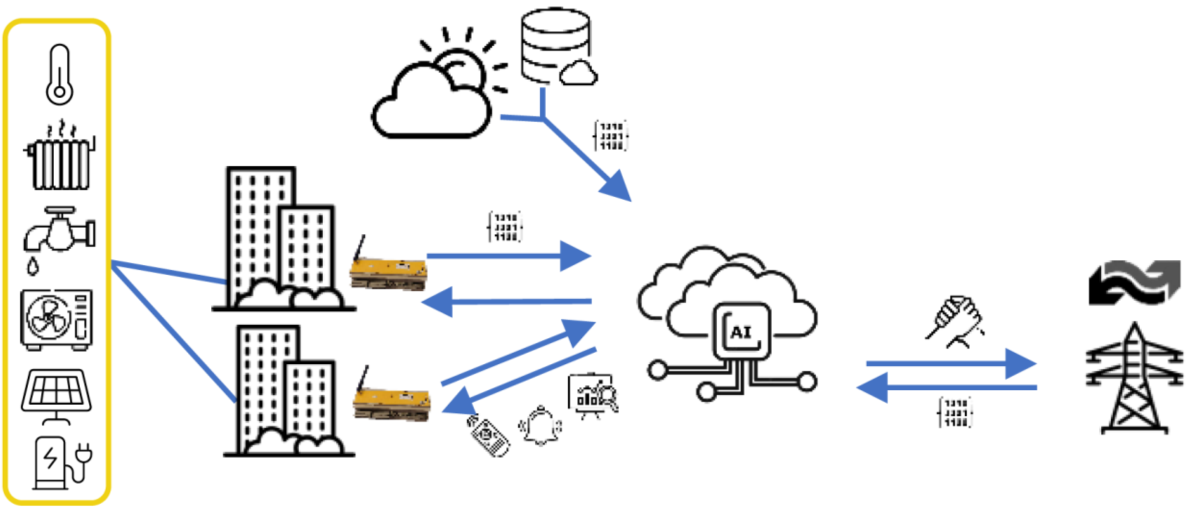

Figure 74: Neogrid PreHEAT Cloud.

The Neogrid PreHeat controller 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.

5.7.2.3 LS Control

IoT Category: Heat pump operation optimization and predictive maintenance

Link: https://lscontrol.dk/en/customized-standard-product/ls-smartconnect-center

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 75.

Figure 75: Swift overview of products and data with LS SmartConnect Center.

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.

5.7.2.4 Centrica Energy Marketing and Trading

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://centricaenergytrading.com/

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 76.

Figure 76: 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.

5.7.2.5 Climify

IoT Category: Heat pump operation optimization

Link: https://climify.com/

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 77, where the user can rate the indoor air quality and receive an overview of all the responses received from a particular room.

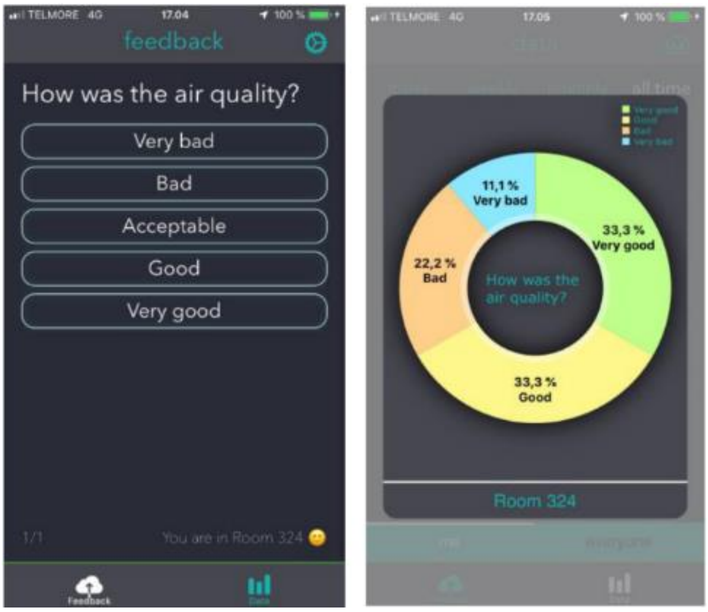

Figure 77: User interface of the FeedMe App from Climify.

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.

5.7.2.6 Nærvarmeværket

IoT Category: Heat as a service and predictive maintenance

Link: https://naervarme.dk

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 cooperative community, which ensures an overall solution with installation, service, and maintenance of the heat pump, as the system shown in Figure 78. 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. Vaillant, Pico Energy, DVI, and HS Tarm.

Figure 78: 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 knows the existence of a potential fault beforehand and have all necessary spare parts available the first time the heat pump is being serviced.

5.7.2.7 AI-nergy

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://ai-nergy.net/

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 79. 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.

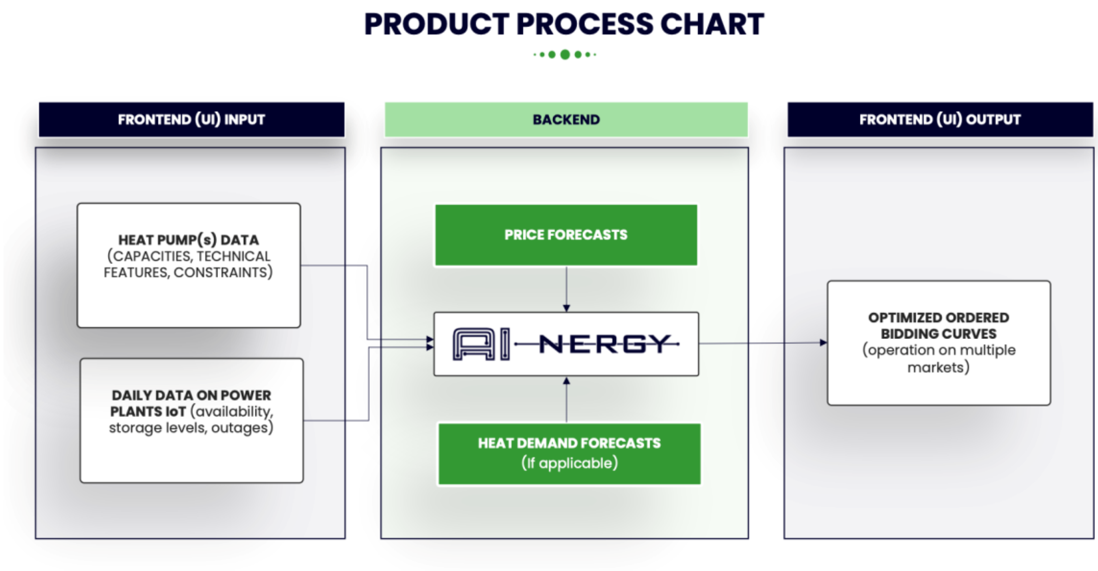

Figure 79: Scheme of the heat pump bidding product from AI-energy.

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.

5.7.2.8 ENFOR

IoT Category: Flexibility provision

Link: https://enfor.dk/

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 Danish district heating supply companies have adopted the energy forecasting and optimization platform from ENFOR, called Heat Solutions, shown in Figure 80.

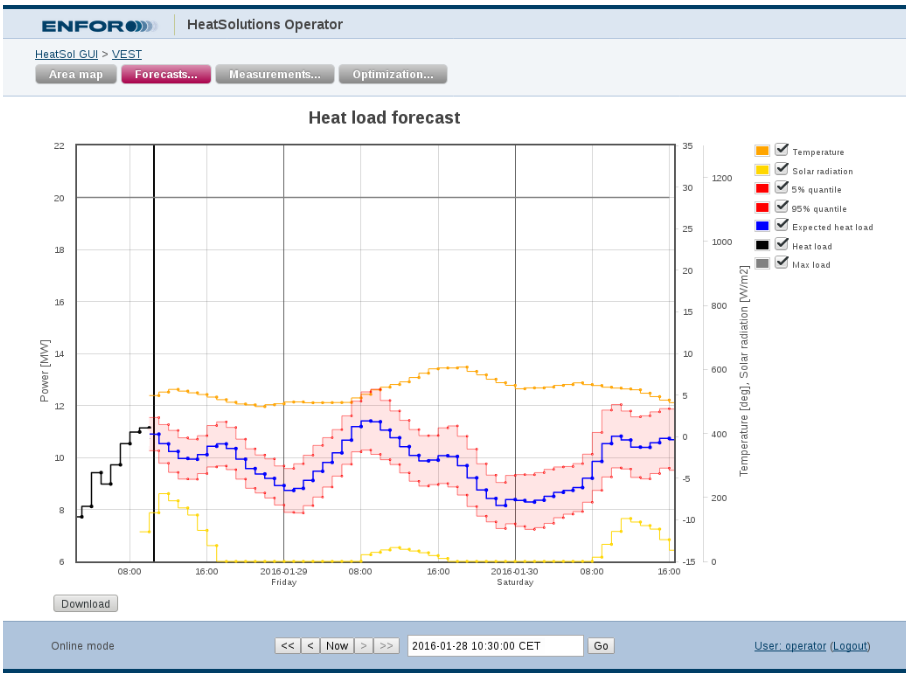

Figure 80: Example of forecast for heat load, temperature, and solar radiation.

5.7.2.9 Center Denmark

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://www.centerdenmark.com/

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 81.

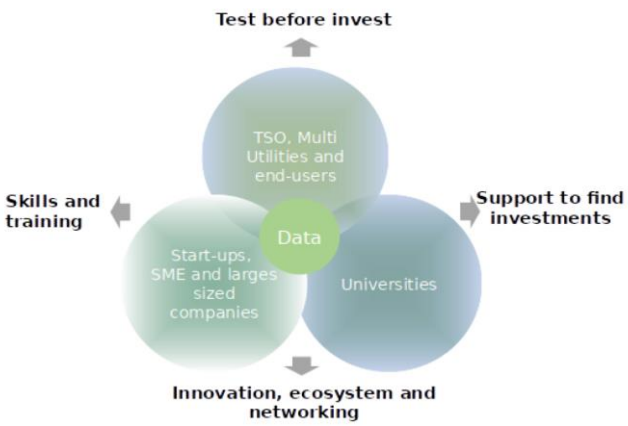

Figure 81: Data is at the core of the development, innovation and business thinking at Center Denmark.

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 bidirectional 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.

5.7.2.10 EnergyFlexLab

IoT Category: Heat pump operation optimization and flexibility provision

Link: https://www.dti.dk/testing/energyflexlab-testing-of-intelligent-and-flexible-energy-components/42590?cms.query=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, as seen in Figure 82.

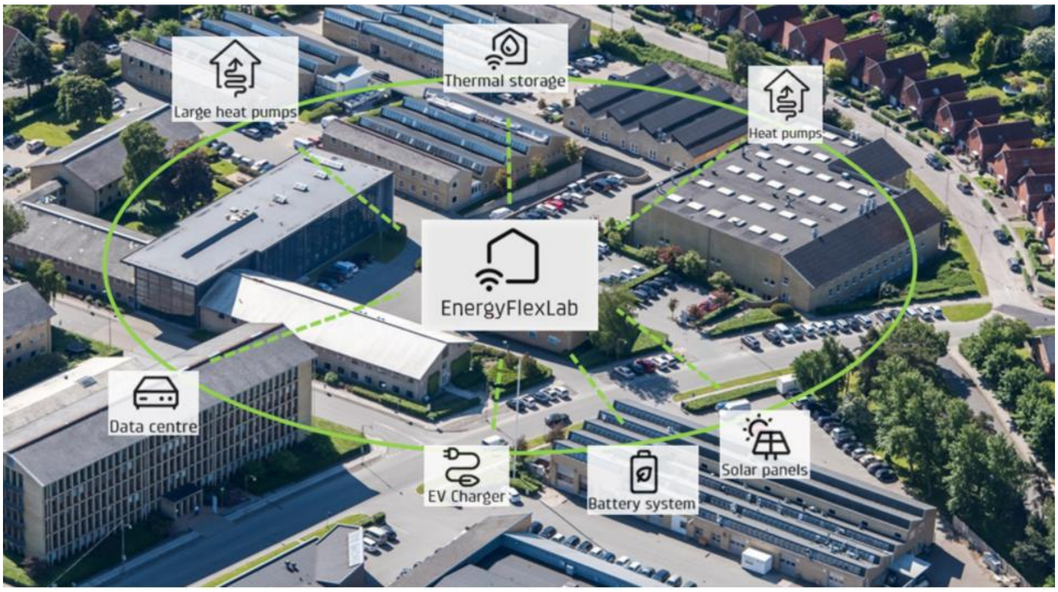

Figure 82: Main energy components in EnergyFlexLab.

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.

5.7.2.11 METRO THERM

IoT Category: Heat pump operation optimization, predictive maintenance, and flexibility provision

Link: https://www.metrotherm.dk/

MyUpwayTM represents METRO THERM's version of the online service platform from its parent company NIBE named NIBE UplinkTM. 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 myUpwayTM 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 83 shows the homepage for myUpwayTM and the interconnection with a desktop.

Figure 83: Representation of the interconnection between METRO THERM heat pumps and desktop through myUpwayTM (left) and homepage of the online service myUpwayTM (right).

Moreover, heat pumps integrated with myUpwayTM 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 myUpwayTM includes a feature called Smart Price Adaption, which enables the automatic adjustment of heat pump operational periods to minimize electricity consumption costs.

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

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

In addition to this the participants in the Danish national Annex project 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 84. 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.

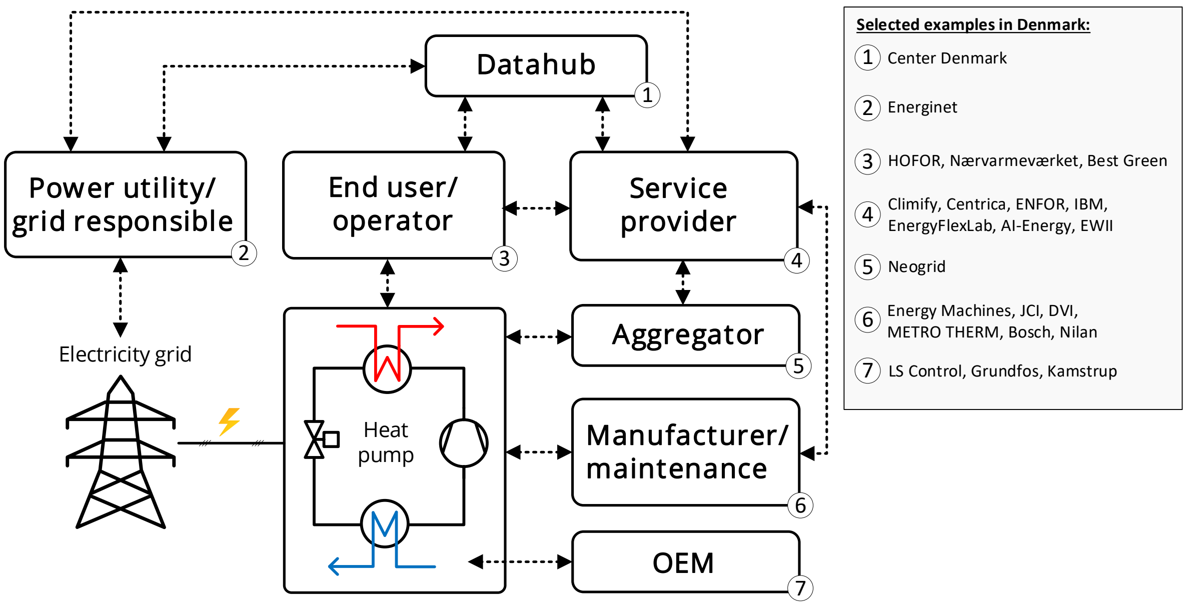

Figure 84: Visualization of supplier groups and examples of associated suppliers in an IoT-based energy system for heat pumps.

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 (Danish District Heating Association, 2022b). 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 85. 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 (Danish Energy Agency, 2022).

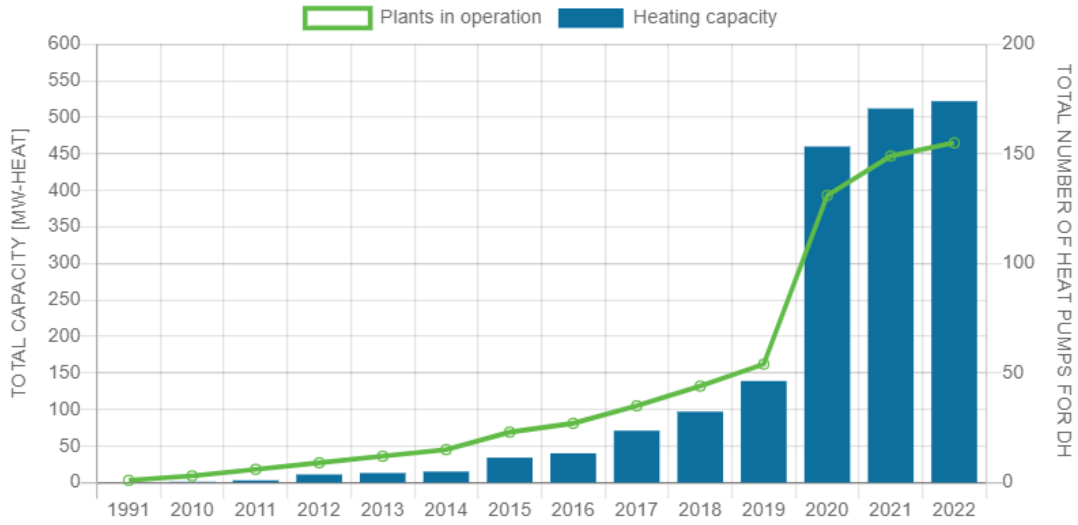

Figure 85: Overview of large-scale heat pumps for the Danish district heating network (Danish District Heating Association, 2022a).

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 (Energinet, 2021). 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 increase in tariffs around 1.8 DKK/kWh (0.24 €/kWh) compared to the cheapest period applies (FDM, 2022). 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 (Norlys, 2023). 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 (Lund et al., 2021).

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 5.7.1.3). 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 5.7.1.1 and 5.7.1.12), 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.

6 Market report (France)

Contributors: Odile Cauret (EDF)

AFPAC gathers almost all actors of the HP sector in France. Its activities are focused on lobbying, support to the sector and technical studies. In 2019, one of these studies was dedicated to the Heat Pump of the future and was entitled « Heat Pump of the future: smartness and connectivity ».

The main topics addressed in this document are the following:

- Ideal HP for all
- Hybrids in terms of heat sources, energy sources, etc.
- Use of waste energy, warm loops at various scales (buildings or quarters)
- Flexibility aspects
- Smart and connected HP
- Data aspects
- Interactions with the grid

These topics have been addressed through three main questions to be answered:

- What is a smart heat pump?
- Which technologies for smart heat pumps?
- What are the perspectives? These perspectives being connectivity and sources optimization

6.1 What is a smart heat pump?

Global definition

"A smart heat pump is a thermodynamic generator that provides heating and/or domestic hot water and/or cooling in a building while ensuring the comfort desired by the occupants (thermal comfort, comfort of use, acoustic comfort), while minimizing environmental impact, energy consumption and bills, and facilitating installation, commissioning and maintenance, without affecting indoor air quality and aesthetics."

Technical definition

The Smart HP adjusts its operation, power and temperatures by processing and interacting with one or more of the following elements, depending on their observed, current, or anticipated values:

- Building and occupant comfort needs,
- Indoor, outdoor, and cold source thermal conditions,
- Requirements or signals received from the electrical grid (energy supplier, network operator),

- Operation of other heat generation systems or local electricity production,
- Status of heat storage and heat distribution network.

The smart heat pump can provide information, through appropriate interfaces, to building owners, occupants and operators on actual energy consumption, energy efficiency, energy bill, operating status. It can also signal malfunctions and preventive maintenance needs. In this way, a smart heat pump optimizes its operation for three use functions: heating, cooling and DHW production. To do that, some actions have to be ensured:

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

To address these five crucial actions, the study defines many aspects to be considered. These aspects are gathered on figure 70 and linked with the action that they can facilitate.

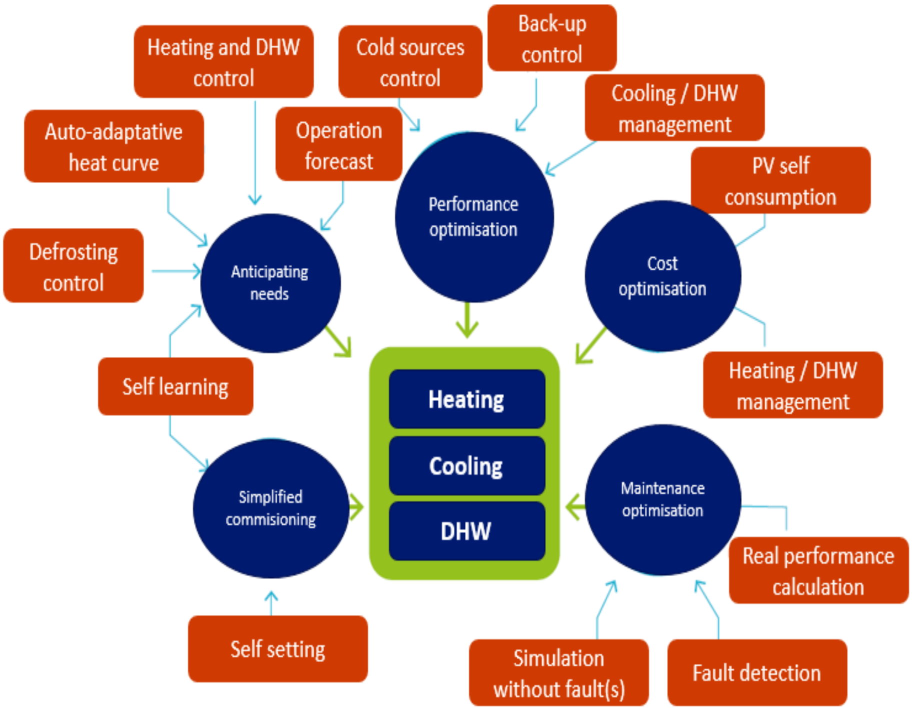

Figure 70: Use functions fulfilled by a smart heat pump

6.2 Which technologies for smart heat pumps?

The report details the smart actions just described for each use functions, including commissioning and maintenance, in the form of tables describing the action, the objective and means in terms of smartness, the needed data to be collected, the "physical" technologies that can be, or need to be associated and then the possible interactions with other smart actions.

Fonctionality		Commissioning simplification and optimisation
Smartness	Objectives	COP optimisation Optimisation of commissioning costs
	Means	Integrated sensors Secure connexion (embedded or via the cloud) Self learning algorithms Self setting algorithms
Inlet data		Inside temperature Available cold source(s) temperature(s) Weather and position data Inlet / Outlet water temperatures
Technologies		Digital tablets BIM Digital logbooks
Interactions with other functionalities		Do not degrade comfort

Figure 71: Actions for commissioning optimization

Fonctionality		Reach the setpoint inside the building
Smartness	Objectives	Needs anticipation COP optimisation Cost optimisation
	Means	Integrated sensors Secure connexion (embedded or via the cloud) Algorithms (self learning, self setting, PV self consumption, auto-adaptative heat curve, optimized defrosting, heating/ECS management, operation forecast, etc.) Optimized control, cold sources management
Inlet data		Temperatures (indoor, available cold source(s), water tank, Inlet / Outlet water, etc.) Compressor On / Off durations, Water flow, 3WV position, etc. Weather and position data, occupant presence, tariff forecast
Technologies		Multi cold sources combination (air, water, sun, sewage) Storage, PV coupling Low GWP refrigerants
Interactions with other functionalities		Do not degrade DHW comfort Sanitary security (refrigerants, pressure, temperature)

Figure 72: Actions for heating optimization

Fonctionality		Supply DHW in quantity and at temperature desired by users
Smartness	Objectives	Needs anticipation COP optimisation Cost optimisation
	Means	Integrated sensors Secure connexion (embedded or via the cloud) Algorithms (self learning, self setting, PV self consumption, auto-adaptative heat curve, optimized defrosting, heating/ECS management, operation forecast, etc.) Optimized control, cold sources management
Inlet data		Temperatures (cold water, available cold source(s), water tank, etc.) Compressor On / Off durations, etc. Weather and position data, tariff forecast
Technologies		Multi cold sources combination (air, water, sun, sewage) Storage, PV coupling Low GWP refrigerants
Interactions with other functionalities		Do not degrade heating comfort, DHW / cooling simultaneous production Sanitary security (refrigerants, pressure, temperature)

Figure 73: Actions for optimization of DHW production

Fonctionality		Reach the setpoint inside the building (air conditioning or reduced temperature)
Smartness	Objectives	Needs anticipation COP optimisation Cost optimisation
	Means	Integrated sensors Secure connexion (embedded or via the cloud) Algorithms (self learning, self setting, PV self consumption, auto-adaptative heat curve, cooling/ECS management, operation forecast, etc.) Optimized control, cold sources management in cooling mode
Inlet data		Temperatures (indoor, available cold source(s), water tank, Inlet / Outlet water, etc.) Compressor On / Off durations, Water flow, 3WV position, etc. Weather and position data, occupant presence, tariff forecast
Technologies		Multi cold sources combination (air, water, sun, sewage) Storage, PV coupling Low GWP refrigerants
Interactions with other functionalities		Do not degrade DHW comfort Sanitary security (refrigerants, pressure, temperature)

Figure 74: Actions for Cooling optimization

Fonctionality		Optimising and sustaining the HP operation
Smartness	Objectives	Fault detection and analysing, anomaly data transmission COP optimisation, Cost optimisation
	Means	Integrated sensors Secure connexion (embedded or via the cloud) Algorithms (no default simulation, real performance, self learning, fault detection, etc.)
Inlet data		Temperatures (indoor, available cold source(s), water tank, Inlet / Outlet water, etc.) Compressor On / Off durations, Water flow, 3WV position, pumps and fans operation state, cycle pressures and temperatures Weather and position data, tariff forecast, electricity consumption
Technologies		Use of sensors to define breakdown scenarios Smartphone apps and services
Interactions with other functionalities		Do not degrade comfort

Figure 75: Actions for Maintenance optimization

6.3 Perspectives: Connectivity and sources optimization

In a second step, the heat pump of the future is seen as connected. And only at this stage, the heat pump is considered as an element of a global system.

A connected heat pump is physically made up of several modules that communicate with each other to regulate the indoor temperature of the home: link between the room module and the heat pump (wired or radio links) and necessarily link to the internet.

A connected heat pump must allow the provision of a manufacturer's application for control by the user and feedback:

- Easier time programming and multiple choice of comfort settings through a more ergonomic interface (via smartphone)
- Program deviation and remote modification of the setpoints.

The historical and statistical processing of the data collected by the connected heat pumps makes it possible to envisage a range of services of value to the user (better regulation via knowledge of weather forecasts, optimization of programming via knowledge of presence scenarios, etc.).

Making the collected data available to a third party (industrialist, installer, maintainer, supplier of various services, etc.) after the user's consent and via an API allows the data to be used.

An open policy on data sharing and exchange is desirable.

The exchange of data locally with other objects and connected equipment can enrich the range of services offered (e.g. control of hybrid heat pumps according to energy costs).

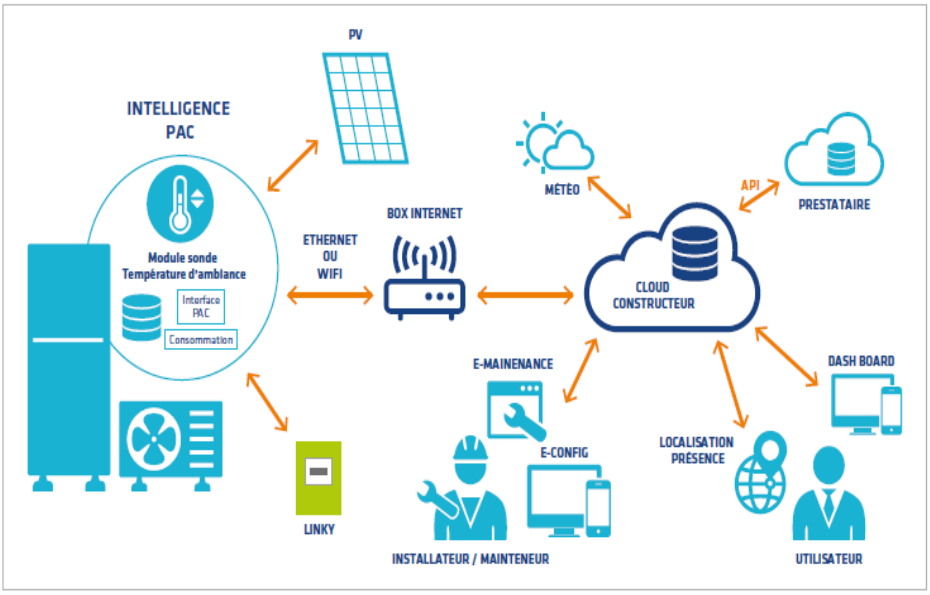

Figure 76: Connected heat pump (PAC) as an element of a global system

If connected and smart, the heat pump will be able to be the heart of a compact global concept

This technical package, which will tend towards autonomy, must integrate:

- A thermodynamic system, mainly with an electric or thermal compression thermodynamic cycle, with two heat sources: cold and hot.
- Access to the cold source (outside air, water, soil, rejection of fatal energy from stale air, wastewater, solar panels, etc.) with possible energy storage (sensible or latent heat).
- The connection to the comfort needs of the building, in heating, cooling and DHW, with the temporal constraints of power, temperature (possible storage of heat, as in the case of a thermodynamic water heater).
- An additional or complementary heat provided by an electric immersion heater, a combustion device (condensing boiler, fuel cell, micro-cogenerator).

- Intelligence for regulation/management/self-teaching/CAM, associated with information on the heating needs of the house, the climatic data of the site, the energy networks (electricity, gas, etc.).
- The intelligent interface with the user, the operator, the maintenance company, the manufacturer, etc.

Different generic schematics can be outlined, but first of all, it is necessary to know the characteristics and performances of the different needs, the cold sources, the thermodynamic machines.

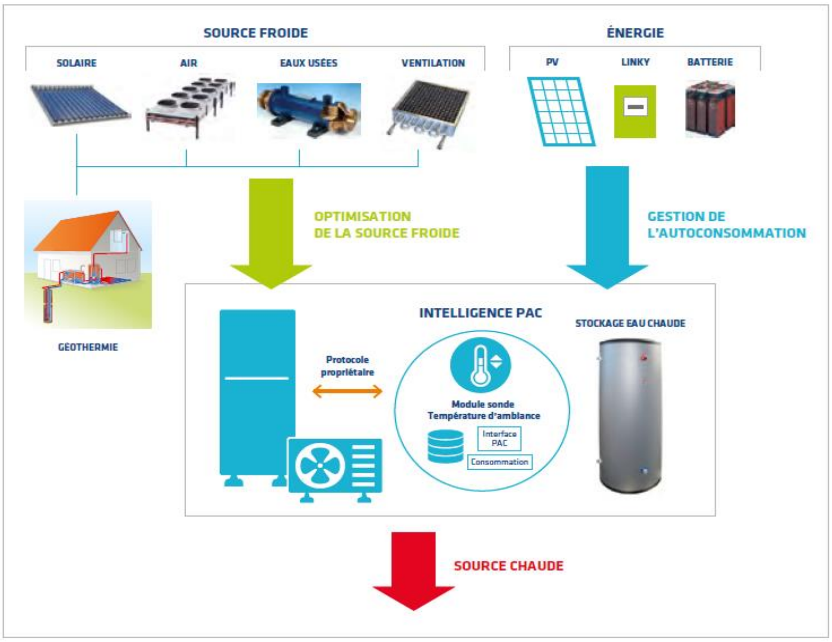

Figure 77: Smart and connected heat pump, cold sources optimization (source froide= cold source, solaire = solar, eaux usées = wastewater, gestion de l'autoconsommation = optimization of own consumption, intelligence PAC = heat pump intelligence, source chaude = hot source)

As a conclusion of the report, the heat pump of the future is seen as smart, at first (able to supply comfort without any breakdown, able to communicate with end users); and then connected (able to communicate with the grid and/or any source).

The impact of the connection to other elements, in particular the grid or PV, on the optimal operation of the « smart » heat pump was not addressed, and not detected as an issue.

7 Manufacturer survey (Austria)

Contributors: Veronika Wilk, Reinhard Jentsch, Tilman Barz (AIT Austrian Institute of Technology)

7.1 Methodology

The purpose of the survey was to collect feedback from companies in the heat pump market segment in order to gather and evaluate the general sentiment on the importance of IoT. The survey had more than 50 questions, which were single and multiple choice, rating and ranking as well as free text questions. The average time for completing the survey was about 20 min.

The survey was divided in two different parts. The first part was equal for all participants. The second part was different for participants active either on the residential, commercial and office buildings market (in the following referred to as Group A), or on the industrial heat pump market (in the following referred to as Group B), with specific questions relevant for each group.

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

7.2 Participants

A total of 16 companies participated in the survey. 13 participants answered all questions in the survey, 3 participants only answered a part of them (76%, 84% and 91% completion). All company sizes, from small SME to large companies are covered by the survey: 6 companies have less than 50 employees, 5 companies 50 – 250 employees, and 5 companies have more than 250 employees.

Most companies identified themselves as heat pump manufacturers and heat pump vendors (8), 3 are heat pump installers (thereof 2 also vendors) and 3 component manufacturers (thereof 1 also heat pump manufacturer and vendor), see Figure 86.

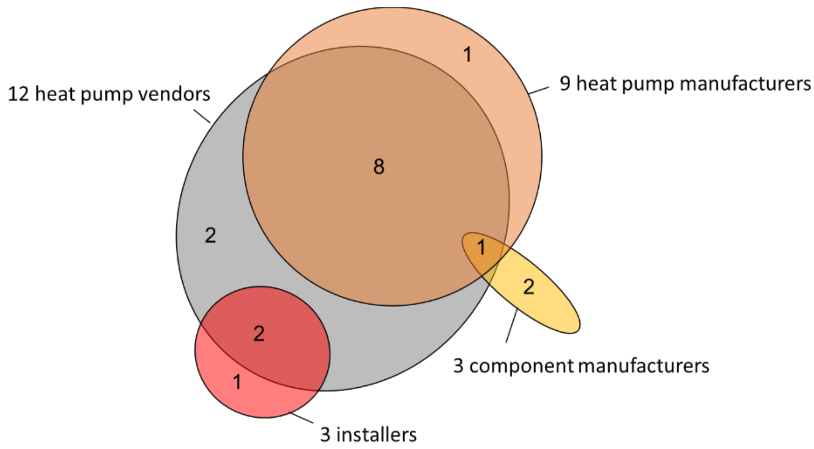

Figure 86: Participants in the Austrian IoT survey

Among the current members of WPA, there are 44 companies that manufacture or import heat pumps, thereof 17 that manufacture a part or all of their products in Austria and 12 component manufacturers. From the numbers of participating companies, it can be concluded that 53% of the heat pump manufacturers, 37% of the vendors and 17% of the component manufacturers were reached.

Activities in market segments: All 16 companies are active on the residential heat pump market including commercial and office buildings. They confirmed the use of IoT products and services in this market segment. From these 16 companies only 6 have indicated that their IoT products and services are also used in industrial and district heating market segment. However, because this second market segment is smaller, and because it is likely that not all companies address this second market segment, no direct conclusions can be drawn about different relevance of IoT products in the two different market segments, see Figure 87 for details.

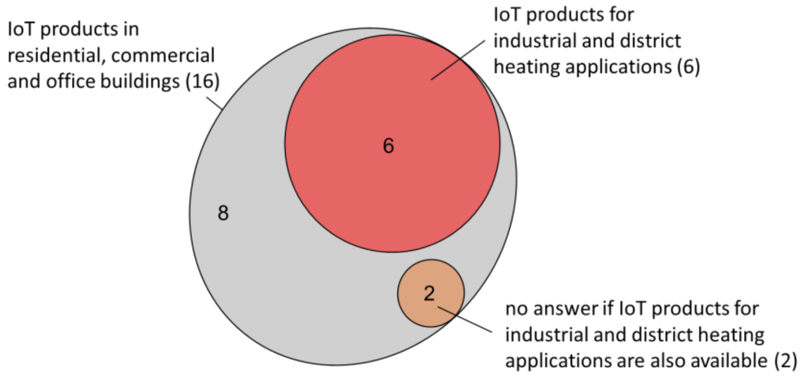

Figure 87: Market segments covered by participating companies

7.3 Availability of products and services

The collected feedback clearly indicates that participating companies have IoT products and services. 66 % are available, which means either in their product portfolio (in implementation), or in a large number in use (extensive implementation). 33% are currently under evaluation, under development or in a pilot phase. All companies offer both IoT products (e.g. heat pumps with connectivity or intelligent components such as compressors or sensors) and services based on IoT products (e.g. marketing of flexibility, remote service, monitoring, etc.). In 56% of the companies, the product and service portfolio have the same maturity level, in 31% the services are further developed than the products and in 13% the products are more advanced and the services still under development.

7.4 Relevance and implementation of IoT related products and services

A self-assessment and comparison to international competitors revealed that 2 companies identify themselves as a pioneer in offering IoT products. The remaining answers from manufacturers are more conservative, 8 regard their products as state of the art, 6 companies see development needs. Regarding the use of IoT services and business processes the feedback is very similar, 1 company regards itself as a pioneer, 7 regard processes and services as state of the art, 8 see development needs.

The feedback on the question who deals with IoT in the company is expectedly diverse, considering the different company sizes among the participants. It ranges from external developers and individual employees, as found in small companies to dedicated IoT departments and company-wide digitalization strategies in medium and large companies. Most commonly, project teams or a part of the development department deals with IoT.

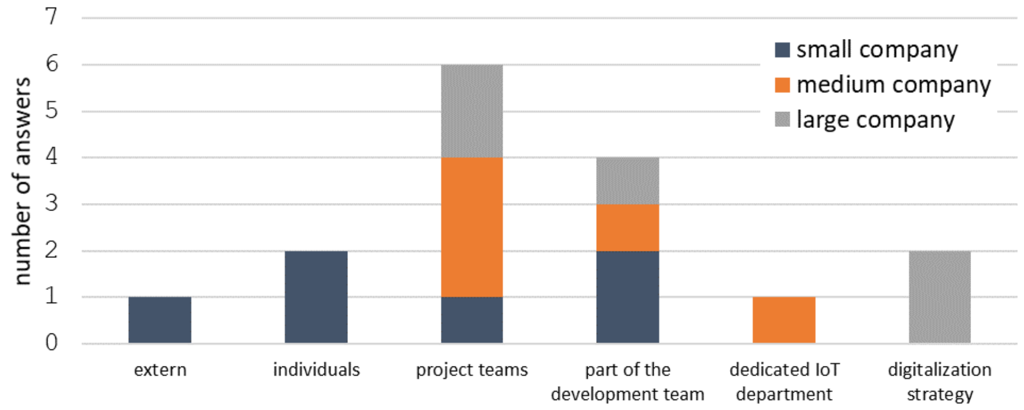

Figure 88: IoT development by company size

Asked about the motivation for adopting IoT products, the top three selected answers were customer loyalty, service improvement and new business models, see Figure 89. Moreover, certain IoT products and derived services are explicitly requested by customers (see below in section “Data analytics and applications”). Cost reduction has been ranked higher than environment awareness. For most companies, IoT products are not seen as a unique selling proposition.

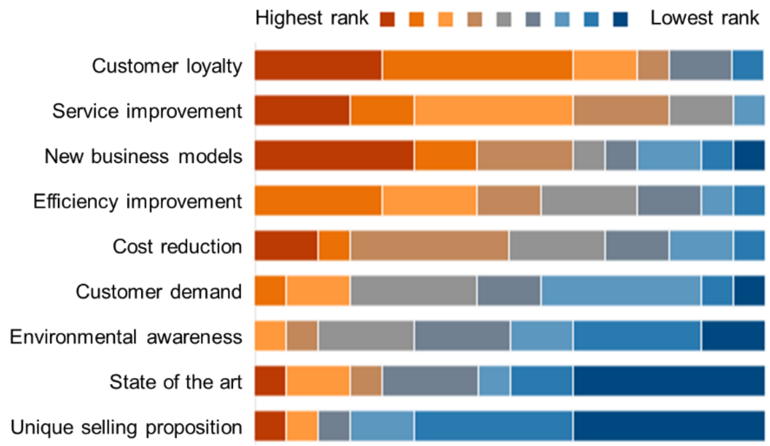

Figure 89: Motivation to introduce IoT products

The participants also see that the use of IoT technology can bring significant changes. These are especially expected in product development, business models, maintenance and partially in sales. Less or insignificant impact is anticipated in the customer segment, production, installation, and supply.

Finally, it should be noted that IoT technology is only one of several digital transformation technologies to which a high importance is attached for the future, see Figure 90. Equal or similar importance is attached to machine learning, predictive maintenance and building information modelling. Privacy requirements are ranked neutrally. In contrast, asset administration shell, semantic modeling and digital twin are considered as less important.

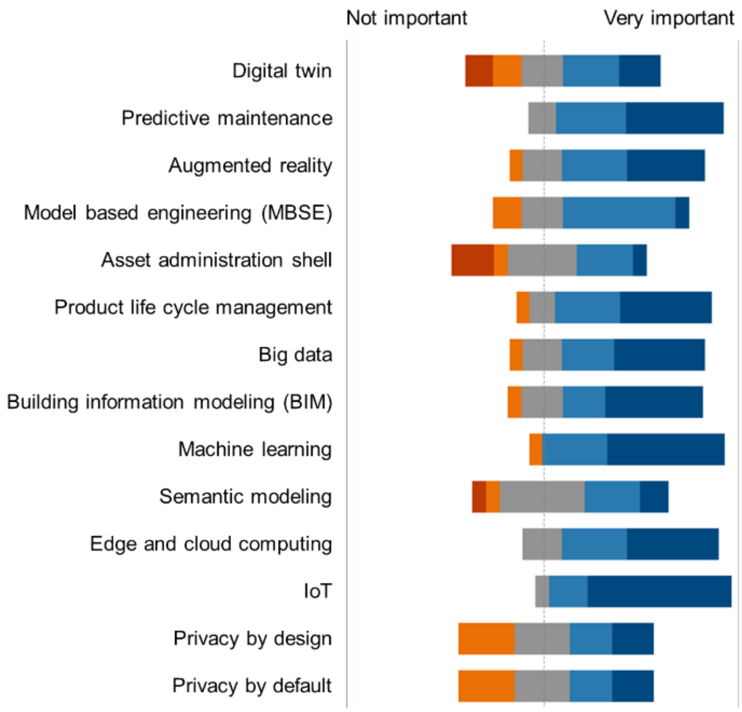

Figure 90: Importance of digital transformation technology for the future

7.5 Data collection, storage, and processing

Answers to multiple choice questions reveal that companies do not pursue a single strategy for handling and processing data.

While almost all participants state that operational data is collected, there is no clear preference regarding storage and accessibility for the user: local and cloud solutions are rated equally important. Moreover, most of the participants have both options. For heat pumps in residential, commercial and office buildings (Group A), 50% of the companies use both, local storage, and the cloud, 31% use the cloud and 13% only local storage.

A similar picture is obtained from the feedback about the functionalities made available to the customer based on this data (see Figure 91) and about the ways to access these functions (see Figure 92). For industrial heat pumps (Group B), all functions such as monitoring, visualization of operational and historical data, control, integration in home automation systems are available, for residential heat pumps (Group A), 50% of the participants offer all functions, 44% offer one or more functions and 6% none of them.

Both, local and different ways for remote access to these functions are equally supported. For residential heat pumps (Group A), an app is most common, followed by access to a website and integration in a home automation system. About half of the participants offer all four ways of access.

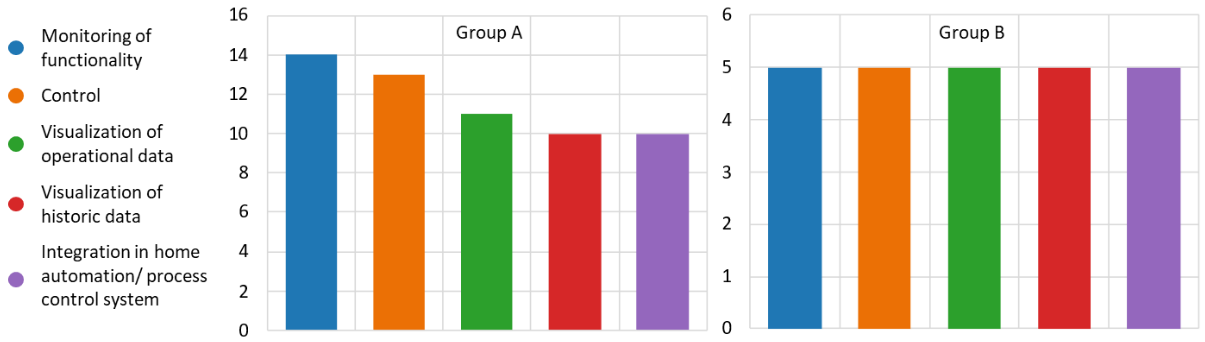

Figure 91: Functions made available to the customer; data taken from participants active on the residential, commercial or office buildings market (Group A) or the industrial heat pump market (Group B), multiple answers possible

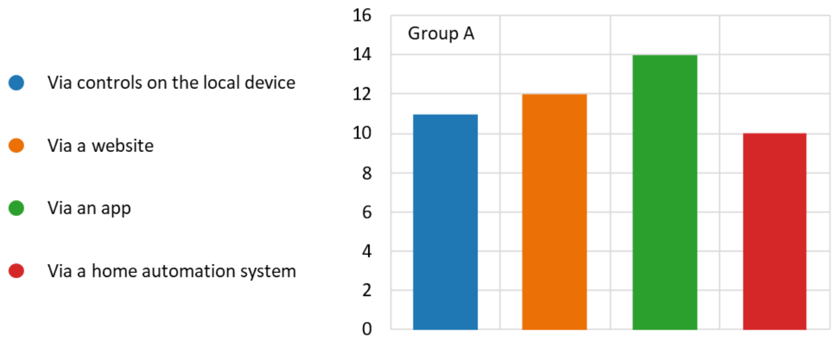

Figure 92: Access to functions; data taken from participants active on the residential, commercial and office buildings market (Group A), multiple answers possible

7.6 Data privacy/ data protection

Asked about the importance of data protection in the development of IoT technology and/or services the participants attached great to very great importance to this issue. Accordingly, data security is seen highly important in the development of IoT technologies and services.

Between all participants there is a general agreement that the biggest influence on the implementation of security and privacy measures has the heat pump manufacturer. In contrast, vendors and component suppliers were named only by one-quarter of the participants.

The participants rely on different regulations and guidelines when it comes to the selection of data security measures. Standards are primarily used by almost all participants. However, recommendations from public authorities, from relevant interest groups and own experience also play an important role in the selection process, see Figure 93.

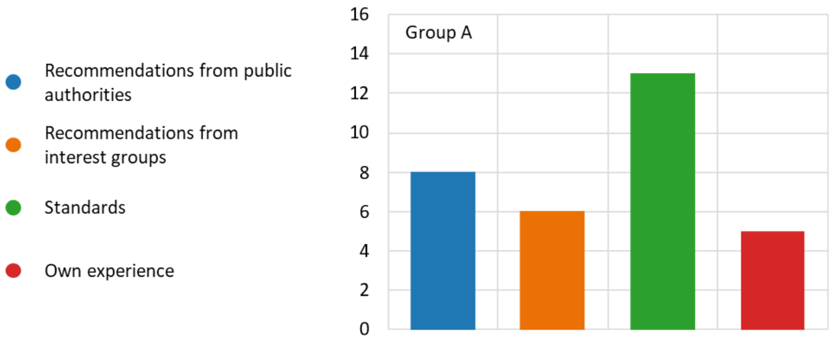

Figure 93: Guidelines and recommendations for selecting data security measures, multiple answers possible

Accordingly, encryption techniques on the server and on the end device, transport encryption and pseudonymization are used by most companies, see Figure 94. 31% of the companies use 3 out of 4 measures, 19% use 2 out of 4 and 31% did not select any of these measures nor provided an own answer.

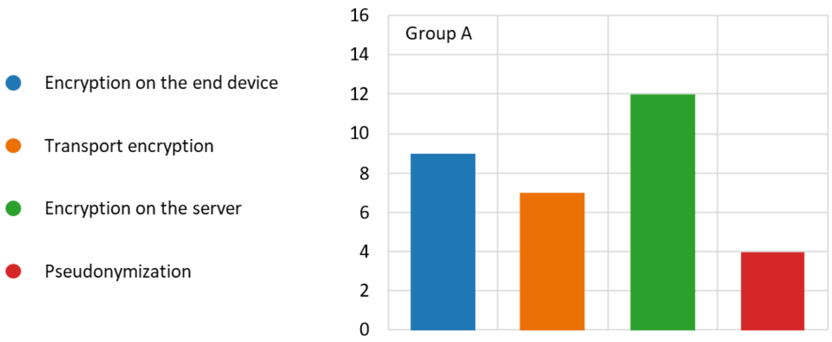

Figure 94: Data security measures, multiple answers possible

Regarding data privacy, it is interesting to note that some companies offer the customer to actively decide which data is evaluated, either by selecting (7) or de-selecting specific services (3). Four participants state that there is no option to make such a decision.

While most companies (9) do not make available the collected data to other companies, some share the data within the own group of companies (4) or share data with other companies on the basis of special agreements (2). According to the feedback, shared data can for example be used for maintenance purposes, or consumption data analysis.

7.7 Interfaces and communication protocols

Clearly, IoT enabled heat pumps are expected to be rather a part of a connected system in the future than autonomous smart components. As shown in Figure 95, this was found for both residential and industrial heat pumps.

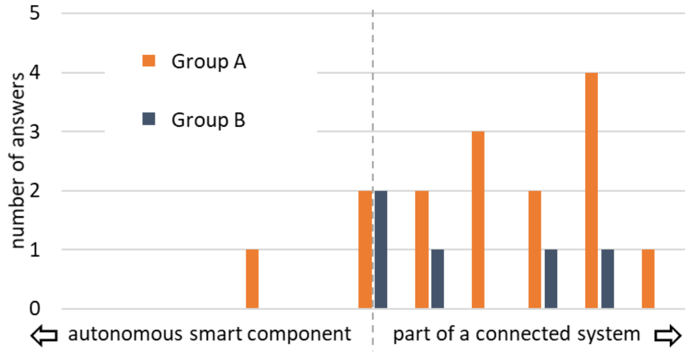

Figure 95: Future integration of heat pumps in the energy system; data taken from participants active on the residential, commercial or office buildings market (Group A) and the industrial heat pump market (Group B)

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

It should be noted that for this question the total number of all responses (multiple responses possible) is comparatively high with 48. This indicates that companies use and offer various interfaces. For Group A, 31% of the companies offer all interfaces that were mentioned.

Similar feedback with a relatively high number of 34 named options is obtained for the communication interfaces used for data collection. Modbus and KNX fieldbus are both prevailing. However, the feedback indicates a diverse use of protocols, BACnet, LonWorks, OPC UA and other are also named. It can also be noted that the distribution of the used communication protocols is very similar for participants active on the residential and industrial heat pump market, see Figure 96.

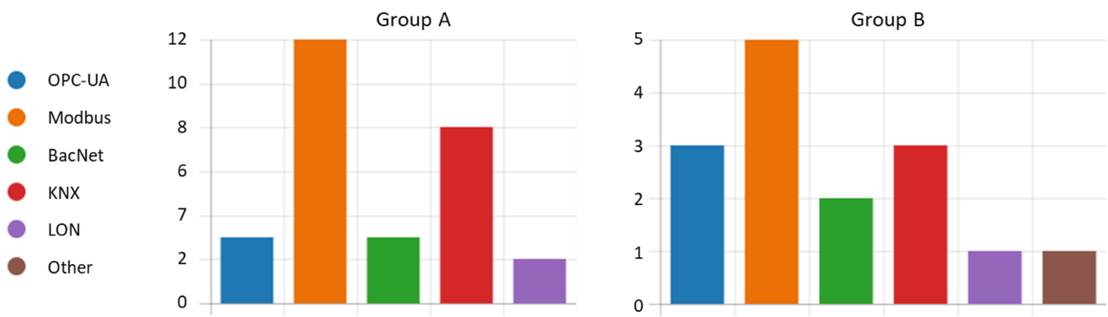

Figure 96: Transmission protocols for data collection; data taken from participants active on the residential, commercial or office buildings market (Group A) and the industrial heat pump market (Group B), multiple answers possible

Asked about the reasons for using the transmission protocol, the participants name data and transmission security as well as distribution of the protocols in the first place, closely followed by compatibility to other systems and existing experience with the protocol.

7.8 Data analytics and applications

The collected field data comprises the state-of-the-art heat pump measurements, that are flow and return temperatures, electrical power, source temperatures, heating capacity, switch cycles, set points and partial load condition, which are all almost equally named by all participants (minimum 10, maximum 13 notes).

The following basic data evaluation methods are named by almost all participants (between 9 and 11 notes): visualization and monitoring of real time data and calculation of Key Performance Indicators (KPIs), statistical analysis based on historic data. Advanced methods for data evaluation are named only 4 times, this is automated pattern recognition (e.g. based on machine learning, ML). Only two participants state that the collected data is currently not processed or evaluated.

The data is mainly processed in a proprietary cloud solution (10 notes), third-party cloud solutions or local/ on-site processing is only noted 5 times. These answers agree well with the given feedback about the institutions who assess and evaluate data and analysis results. 13 participating companies state that they do the evaluation themselves. Clients (4) and externals (3) do less frequently evaluation of data.

The participants confirmed that the following features and corresponding applications are important for their customers: monitoring; interfaces for home automation; interfaces for smart tariffs and marketing of flexibility; coordinated operation with local PV and storage; and optimized maintenance intervals. In addition, the companies state that the following features are of great (almost equal) importance for them: efficiency improvement; anomaly detection and operational monitoring; installation error detection; improved service offering (e.g. PV or price optimization); and product improvement and development. Interestingly, those features which are seen as important by the company are also those features which are already in use. A total of 88% of the companies currently apply data analytics for the following applications: installation error detection; efficiency improvement; anomaly detection and operational monitoring; product improvement and development.

In addition, most companies (except one) explicitly foresee the option to add or change IoT features through software updates after heat pump installation. This can be accomplished mainly over the internet or manually by service personal. Three participants state that customers can also manually do software updates.

For industrial and district heating applications, heat pump data is collected in the cloud and locally, most of the companies have both types. All of them offer integration of the data in the process control system and provide access to features in the cloud. The features comprise visualization of operation and historic data, monitoring and control and integration in the process control system. This is in good agreement with the IoT features requested by the customers. Unlike residential applications, smart tariffs are of less importance in industry.

7.9 Challenges in adopting IoT technology

Asked about their experience with the introduction of IoT technology the companies see major challenges in the availability of qualified personnel and missing legal frameworks, standards, and requirements for data protection. The increased complexity coming with IoT technology is also an issue. User acceptance, communication protocols, hardware, and software interfaces as well as methods for data analytics and modeling is seen less critical, see Figure 97.

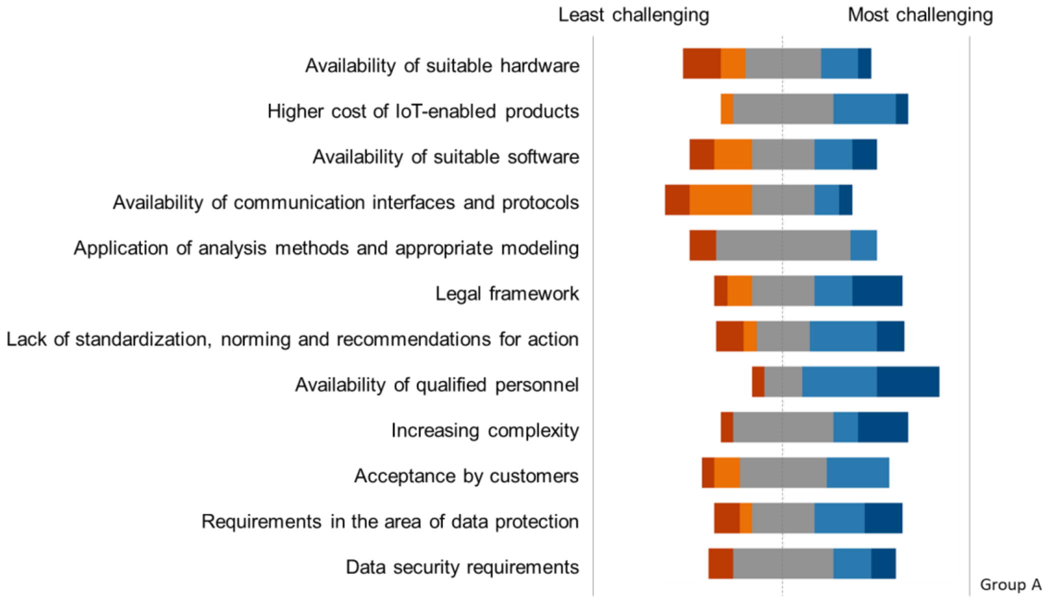

Figure 97: Biggest challenges in adopting IoT technology data taken from participants active either on the residential, commercial or office buildings market (Group A); data from participants active on the industrial heat pump market (Group B) is very similar.

7.10 Summary and discussion

A survey on the importance of IoT was carried out among companies of the Austrian heat pump industry. The survey is based on a comprehensive questionnaire which was designed by experts in heat pump technology and applications. The questions cover different aspects, such as company size, organization and market activities, availability of specific digital technologies and products, such as hard- and software, communication interfaces, data security, data analytics, availability of specific applications and services, and ask for general feedback on the motivation for adoption of IoT technology, relevant market and customer needs, challenges, current issues, and trends in the field.

Generally speaking, it can be said that the survey was successful. The participants represent 53% of the Austrian heat pump manufacturers and 27% of the heat pump vendors allowing for meaningful results. The company size ranges from small to medium and large companies. All companies are active on the residential heat pump market, some companies also offer products for the industrial and district heating market.

The participants generally attach great importance to the development and use of IoT solutions. All companies offer both, IoT products (e.g. heat pumps with connectivity or intelligent components such as compressors or sensors), and services based on IoT products (e.g. PV or price optimization, product improvement and development). Two thirds of the evaluated products are available, which means either in their product portfolio (in implementation), or already in a large number in use (extensive implementation). Another third is currently under evaluation, under development or in a pilot phase.

Clearly, most reported applications go beyond the mere collection and local and cloud-based storage of data. Only two participants state that the collected data is currently not processed or evaluated. From the gathered feedback it can be concluded that, companies have acquired advanced know how and methods for industrial automation, data processing and analytics, as well as user interface design and implementation on various platforms. Diverse applications for monitoring and control are reported which aim at efficiency improvement, anomaly detection and operational monitoring, installation error detection and improved or new service offering. It should however be noted that, most reported applications follow rather basic data evaluation methods: visualization and monitoring of real time data and calculation of Key Performance Indicators (KPIs), statistical analysis based on historic data. Advanced methods for data evaluation (such as automated pattern recognition based on machine learning, ML) were reported less frequently. While Modbus is still prevailing communication protocol in heat pump automation, the companies also offer other protocols, such as KNX, OPC UA or BACnet. The collected data is usually not directly shared with the customers. However, companies are aware of data privacy and protection issues, they follow standards and regulations for security measures.

Most commonly, IoT products and services are developed by project teams or by a part of the development department. The main drivers for these products and services are customer loyalty, service improvement and new business models. The most important barriers for IoT technologies are the availability of qualified personnel, data protection and legal requirements, as well as lack of standards. There is less concern about communication protocols and interfaces and the availability of suitable hardware.

The general expectation shared by all participants is that IoT technology will bring significant changes in product development, business models and maintenance. The main expected benefits are increased customer loyalty, improvement of services and new business models. It is further anticipated that IoT enabled heat pumps will be rather a part of connected systems than an autonomous smart component. In this context, IoT technology is seen as one of several important digital transformation technologies for the future.

8 Expert interviews (Sweden)

Contributors: Davide Rolando (KTH)

8.1 Methodology

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

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

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

8.2 What does IoT mean for you in the context of heat pumps? How central is the topic in everyday work?

All answers received highlighted the importance of IoT technologies in creating connectivity within heat pump systems. By leveraging IoT technologies, heat pumps can be integrated with a range of monitoring and maintenance services, allowing for real-time data analysis and predictive maintenance. Additionally, IoT technologies can enable communication between the heat pump and other devices in the building, such as smart thermostats or energy management systems, allowing for coordinated and optimized operation.

Connectivity with Monitoring Services: By connecting heat pumps to monitoring services, building owners and operators can receive real-time data on system performance, energy consumption, and environmental conditions. This data can be used to monitor system health, identify potential issues before they become critical, and optimize system performance. Additionally, monitoring services can provide insights into building occupancy patterns and user preferences, allowing for personalized and adaptive heating and cooling strategies.

Connectivity with Maintenance Services: IoT technologies can also enable connectivity with maintenance services, allowing for predictive maintenance and timely intervention in the case of system issues. By continuously monitoring system performance, predictive maintenance algorithms can identify potential faults and alert maintenance services, enabling timely and cost-effective maintenance interventions. This can help to reduce downtime and optimize system lifespan, resulting in cost savings and improved system reliability.

Connectivity with Users and Other Devices: IoT technologies can also enable communication between the heat pump and users or other devices in the building. By integrating with smart thermostats or energy management systems, heat pumps can be optimized for energy efficiency and coordinated with other building systems. Additionally, IoT-enabled heat pumps can be remotely controlled and adjusted by users, allowing for personalized and convenient heating and cooling options.

Overall, the experts emphasized the importance of connectivity in creating a more efficient, reliable, and user-friendly heat pump system. By leveraging IoT technologies, heat pumps can be integrated with a range of services and devices, enabling personalized and optimized heating and cooling strategies while minimizing energy waste and costs.

8.3 Can Heat Pumps from different manufacturers be interconnected? What are the challenges?

The expert's answer highlights a key challenge in the current state of heat pump technology - the ability to interconnect heat pumps from different manufacturers. While this may seem like a straightforward task, it is often quite challenging due to a lack of standardization and compatibility issues between different manufacturers and models.

Interconnecting Heat Pumps from Different Manufacturers: One of the main benefits of interconnecting heat pumps is the ability to create a more resilient and efficient system, where heat pumps can work together to optimize energy use and meet heating and cooling demands. However, achieving this goal is not always easy, as different manufacturers often use different communication protocols and interfaces, making it difficult to connect heat pumps from different brands.

Compatibility Issues Between Heat Pumps: Even within a single manufacturer's product range, compatibility issues can still arise. For example, different models of heat pumps may have different control systems, making it difficult to interconnect them without additional hardware or software modifications. This can result in a more complex and costly system that is more difficult to maintain and troubleshoot.

Lack of Standardization: Another major challenge is the lack of standardization in the heat pump industry. While some industry standards do exist, they are not always followed by all manufacturers, resulting in a fragmented and disparate landscape of different communication protocols, interfaces, and control systems. This makes it more difficult to develop universal solutions that can work with all heat pump systems, regardless of the manufacturer or model.

In conclusion, the answers highlight the current challenges with interconnecting heat pumps, both between different manufacturers and within a single manufacturer's product range. These challenges are primarily related to compatibility issues and a lack of standardization in the industry, making it more difficult to create a truly interconnected and efficient heat pump system. However, as the industry continues to evolve and standardization efforts gain momentum, it is likely that these challenges will be addressed, paving the way for a more seamless and integrated future for heat pump technology.

8.4 Digitalization and future outlook

The interviews highlight the importance of digitalization in the context of heat pump systems. As the use of heat pumps becomes more widespread, there is a growing need to store heat and implement smart strategies to optimize energy use and bring operational benefits to the grid. The expert suggests that while these strategies may result in less efficiency at the individual unit level, they can ultimately help to balance the grid and reduce overall energy consumption.

Digitalization is the key to achieving this goal. By establishing a way for heat pumps to be controlled and monitored remotely, data can be collected and used to develop new services such as fault detection and predictive maintenance. This can help to ensure that heat pumps are operating efficiently and reliably, reducing the risk of breakdowns, and minimizing downtime. In addition, by using data to optimize energy use, heat pumps can help to reduce overall energy consumption and support the development of a more sustainable energy system.

The expert also notes the importance of demand-side flexibility in connecting heat pumps to the grid. By implementing smart systems that can run heat pumps depending on availability, heat pumps can help to balance the grid and reduce the need for fossil fuel-based power generation. This is particularly important as more renewable energy sources, such as wind and solar, come online, as these sources can be variable and difficult to predict.

In this context, third-party aggregators can play an important role in balancing the grid. These aggregators can act as intermediaries between heat pump systems and the grid, helping to ensure that energy is used in the most efficient and effective way possible. By balancing supply and demand and optimizing energy use, these aggregators can help to reduce overall energy consumption and support the development of a more sustainable energy system.

In summary, the answers highlighted the importance of digitalization in the context of heat pump systems. By enabling remote control and monitoring, data collection, and the development of new services, digitalization can help to optimize energy use, reduce energy consumption, and support the development of a more sustainable energy system.

8.5 An interesting reflection: why can't heat pumps be like cars?

Cars are equipped with on-board diagnostic system, mandatory in most countries in the world. Heat pumps can have on-board diagnostics systems similar to those found in cars, and in fact, many modern heat pump systems do come equipped with diagnostic tools that allow users to monitor system performance and identify potential issues. However, there are some differences between cars and heat pumps that may impact the design and implementation of on-board diagnostics systems.

One of the main differences is the complexity of the systems, because heat pumps can have multiple components and subsystems that may be located in different parts of the building. This can make it more challenging to design on-board diagnostics systems that are effective in identifying potential issues and providing users with actionable information.

Another factor is the level of standardization in the industry. The automotive industry has established clear standards for on-board diagnostics systems, which has helped to ensure that these systems are reliable, interoperable, and user-friendly. However, the heat pump industry has yet to establish such standards, which can make it more challenging for manufacturers to develop effective on-board diagnostics systems that are compatible with a range of different systems and components.

By leveraging the power of IoT technologies, such as advanced sensors, data analytics, and machine learning algorithms, it may be possible to develop more effective and user-friendly on-board diagnostics systems for heat pumps in the future.

8.6 Objectives of IoT solutions for Heat Pumps

From the interviews, the main objectives of IoT solutions for heat pump systems were prioritized as follows: Reduce operating cost, service and repair improvement, emissions and environmental goals, higher indoor comfort, reduce capital cost, user engagement.

The top-ranked objective, "Reduce operating cost", is a key concern for many users and stakeholders, as it can lead to significant savings on energy bills and maintenance costs over time. IoT solutions can help achieve this objective by providing real-time monitoring and control of heat pump systems, optimizing their performance, and identifying potential issues before they become major problems.

The second-ranked objective, "Service and repair improvement", reflects the importance of ensuring that heat pump systems are reliable and easy to maintain. IoT solutions can help achieve this objective by providing remote diagnostics, predictive maintenance, and other features that help reduce downtime and ensure that the system is always operating at peak performance.

The third-ranked objective, "Emissions and Environmental goals", highlights the growing importance of sustainability and environmental responsibility in the design and operation of heat pump systems. IoT solutions can help achieve this objective by providing data on energy usage, emissions, and other environmental impacts, as well as supporting the integration of renewable energy sources and other sustainable technologies.

The fourth-ranked objective, "Higher indoor comfort", reflects the importance of ensuring that heat pump systems are not only energy-efficient and cost-effective but also provide a high level of comfort and convenience for users. IoT solutions can help achieve this objective by providing smart control features, such as zoning and scheduling, that allow users to tailor their heating and cooling preferences to their individual needs.

The fifth-ranked objective, "Reduce capital cost", highlights the importance of ensuring that heat pump systems are affordable and cost-effective to install and operate. IoT solutions can help achieve this objective by streamlining installation and commissioning processes, reducing the need for on-site inspections and other manual tasks.

Finally, the sixth-ranked objective, "User engagement", reflects the importance of ensuring that users are engaged and involved in the operation and maintenance of heat pump systems. IoT solutions can help achieve this objective by providing user-friendly interfaces and tools that allow users to monitor and control their systems easily and intuitively, as well as providing access to resources and information on system operation and maintenance.

What are the main problems that IoT might be able to solve or tackle in the future?

Data security, privacy, ownership: One of the main concerns with IoT is the security, privacy, and ownership of the data generated by connected devices. As more and more devices become interconnected, there is a growing need for robust data security and privacy protections to prevent unauthorized access or misuse of sensitive information. Additionally, there is a need to establish clear ownership and control of data generated by IoT devices to ensure that users have control over their personal information and can make informed decisions about how it is used.

IoT has the potential to solve or tackle these issues by implementing advanced security protocols and encryption technologies to protect data from cyber threats. Additionally, IoT can provide users with greater control over their data through the use of user-centric design and transparent data policies.

Modest saving capability of current solutions: Another challenge with IoT in the context of heat pumps is the modest savings capability of current solutions. While IoT-enabled heat pumps can provide some energy savings, these savings may not be sufficient to justify the investment in the technology.

IoT can tackle this issue by leveraging advanced data analytics and machine learning algorithms to optimize energy use and improve the efficiency of heat pump systems. By analyzing data in real-time and adjusting the system settings based on changing conditions, IoT can help to maximize energy savings and reduce energy waste.

Lack of standardization: A lack of standardization is another challenge with IoT in the context of heat pumps. As more and more manufacturers enter the market with their own IoT solutions, there is a risk of fragmentation and lack of interoperability between devices.

IoT can solve or tackle this issue by establishing clear standards and protocols for device connectivity and interoperability. By establishing industry-wide standards, manufacturers can ensure that their devices can communicate with other devices in a seamless and secure manner, improving the overall efficiency and effectiveness of IoT-enabled heat pump systems.

IoT has the potential to solve or tackle a number of key challenges in the context of heat pump systems, including data security, privacy, and ownership, modest savings capability of current solutions, and lack of standardization. By leveraging advanced data analytics and machine learning algorithms, establishing clear standards and protocols for device connectivity and interoperability, and implementing advanced security protocols and encryption technologies, IoT can help to maximize energy savings, improve the efficiency of heat pump systems, and support the development of a more sustainable energy system.

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