15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

"Digital Heat Pump Lab" – a new laboratory for teaching and development of digital services for heat pumps

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Abstract

Digital services for heat pumps enable more optimal design, operation and maintenance of heat pumps in the field. Thereby, they are contributing to energy efficiency and longevity of the installed systems. With the number of heat pumps and cooling units expected to increase, ensuring the most energy efficient operation of the installed systems is of uttermost importance. The validation of newly developed services and thus the further roll-out is, however, often hindered by the unavailability of close-to-real-time two-way communication with heat pumps in realistic environments.
To overcome this problem, a new research and teaching lab is being built at the Technical University of Denmark allowing close to real-time two-way communication with the physical units via an MQTT server. The lab is designed to be able to test water-to-water and air-to-water units with capacities of 4 kW to 12 kW heating, further testing of serial coupling of heat pumps and integration with storages is possible. Temperature and flow to the heat pumps can be controlled based on signals sent by the user in close to real time, while the actual heat pump response is measured and the data is sent back to the user. This set-up enables testing of many kinds of digital services for heat pumps including advanced control, fault detection, hardware-in-the-loop testing, etc.

Keywords: Heat pump; laboratory design;digital services; real-time communication, hardware-in-the-loop

1. Introduction

Heat pumps are a key element of the future renewable energy system. The number of installed units has been increasing rapidly over the past years and is projected to accelerate further [1]. The UNEP estimates that 25 % to 30 % of the global electricity consumption is related to refrigeration, air conditioning and heat pump systems and the electricity consumption of these systems is expected to increase by a factor of 33 until the year 2100 [2]. Given this, strategies to optimize the operation of these units can significantly reduce the resources needed for heating and cooling. Key steps towards this goal include minimizing, detecting or diagnosing the faults in heat pump systems [3], [4] and coordinating heat pump operation to support the optimal operation of connected buildings and grids [5].

Heat pumps in the field are often equipped with sufficient data collection technology. This data is a rich source of information on the performance of individual units and system fleets but is currently underutilized [3]. By leveraging this data, digital solutions can enhance heat pump performance, reducing operational costs and downtime through services like performance monitoring, predictive maintenance, and fault detection and diagnosis. These services may employ physics-based models, data-based models, and machine learning algorithms. The optimal model design and choice of algorithms remain active research areas.

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Further, the connection of heat pumps to online services can enable flexible operation, such as cost-optimal operation, provision of ancillary services to the power grid, and supporting the optimal operation of district heating grids. This potential has been emphasized in two recent IEA HPT Annex projects [5], [6].

The development of suitable digital services for monitoring, optimal maintenance and optimal control of heat pumps requires benefits from laboratory experiments, where operation conditions including faults can be enforced in a controlled way. Thus, generating data that can serve to train and validate models and algorithms that can then be applied to field data later on. This approach has been demonstrated for fault detection in domestic heat pumps using photovoltaic-thermal (PVT) panels as heat source [7]. Without additional laboratory experiments, the faults in operational data are often difficult to identify, since the training of suitable algorithms require timely and correctly labeled operational data, which is not available in all cases in practice [8].

At the same time, it has become apparent that educated personnel are highly demanded [9] not only in the heat pump and refrigeration sector, but in the renewable energy sector in general. The development and application of digital solutions will be further in focus of industry research and development and should thus be represented in today's engineering education. This requires access to physical systems that can serve to test digital services, such as advanced model predictive control, fault detection and diagnosis, advanced system modelling.

The purpose of the project is to establish a new heat pump laboratory targeting education and research on digital services, the "Digital Heat Pump Lab" at DTU Construct, Section of Thermal Energy. The laboratory will provide a platform to develop, test and learn about digital services supporting the efficient and fault free operation of heat pumps and refrigeration units. The laboratory will be a place where research, companies, and education meet. Thereby, we can offer state-of-the art education and leverage the creative potential that lies within collaboration for applied research.

Thereby, with the Digital Heat Pump Lab we address both the need for further research and development on the optimal design and implementation of digital services for heat pumps and refrigeration units and the need for hands-on education that can attract students to the field.

2. System design

2.1. Definition of functionalities of the Digital Heat Pump Lab

Before planning the lab, the desired functionalities have been defined. It was important that the laboratory infrastructure could be used for future research projects as well as to integrate experiments into several courses at B.Sc. and M.Sc. level. The expected lifetime was >10 years. This required a versatile design and led to the definition of the following requirements for the physical laboratory infrastructure:

- Ability to test water-source and air-source heat pumps with thermal capacities of 4 kW to 12 kW
- Measurement uncertainty allowing for publication of experimental results
- Easy exchange of heat pump units
- Up to 4 parallel heat pump units in operation to allow for efficient use of the laboratory in DTUs courses
- Flexible set-up that allows to couple other equipment, e.g. thermal storage, chiller, etc. to the test-rig to utilize the laboratory facility broadly

Further, the following desired functionalities have been defined to allow for advanced experiments and control, aligning with the objective of using the laboratory to develop and teach about digital services for thermal energy units:

- Ability to control the sink and source temperature and flow dynamically according to inputs via the digital platform
- Two-way, real-time communication between physical units and digital platform as a basis for digital twin based services
- Online retrieval of runtime and historic data, and contextual information
- Online visualization of data
- Open access to historic data and contextual information
- Possibility to classify data and information for third party testing and unpublished research data
- Authenticated login to be able to send signals to the units to allow to control who is assessing the laboratory units when

2.2. Physical laboratory set-up

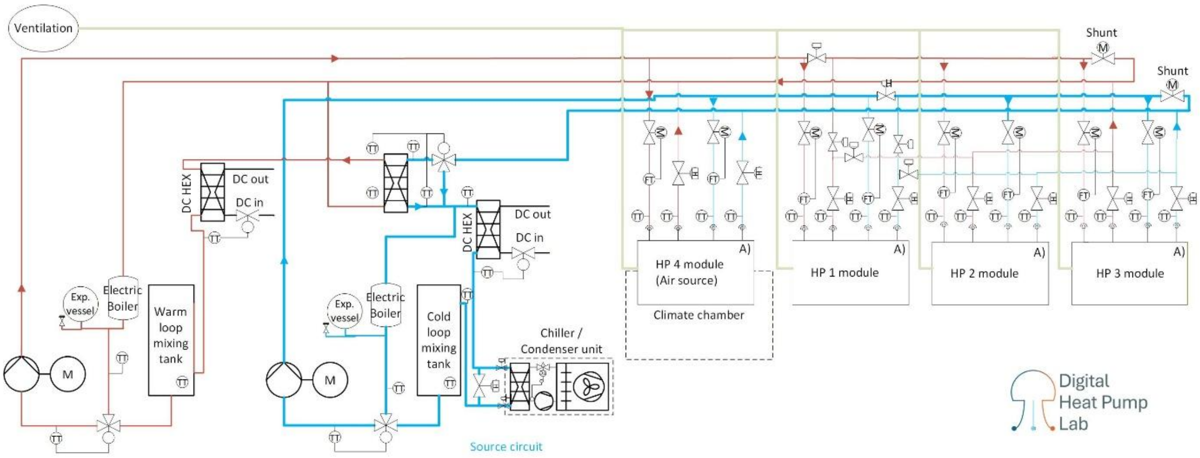

Figure 1 Simplified diagram of the laboratory system

Figure 1 shows the simplified diagram of the laboratory set-up. The system is designed to connect up to three water-to-water heat pumps (or other units requiring similar water connections) in parallel. Two of the three water-to-water heat pumps can further be coupled in series on the sink and/or source side to allow for larger flexibility for future experiments. The fourth heat pump that can be connected is an air-to-water heat pump. For this purpose a climate chamber of 24 m^3 has been installed. The sink streams (red circuit) are expected to be pure water, while the source stream (blue circuit) has been dimensioned to use either pure water or glycol water mixture to allow for tests with source temperatures down to -12 °C. The sink and source streams are conditioned using first a heat recovery heat exchanger recovering heat from the sink to the source circuit. Both loops are designed with external cooling from district cooling and additional heating in electric boilers to allow for dynamic control of the heat supply temperature to the heat pump units. This temperature is controlled using a mixing valve. Further, each loop includes a buffer tank to dampen any dynamics of the heat pump return temperatures and thus being able to control the supply temperature independently of the return temperature.

The sink- and source flow rate are measured using turbine flow meters and controlled at the inlet to every heat pump unit using seated valves with continuously operated actuators.

To allow for precise energy balances, all heat pump connections are equipped with PT 100 temperature sensors in the supply and return of sink and source, plus the already mentioned flow meters and power meters to determine the compressor consumption.

2.3. Implementation of digital infrastructure

The digital infrastructure including data acquisition is sketched in Figure 2. At the core of the digital infrastructure is the platform Energydata.dk [10]. This platform has been developed to allow sharing of energy related data sets online as both historic data and real time data. The platform includes cloud storage and comes with access control, aligning well with our defined functionalities. The data exchange with the platform is based on an MQTT broker that allows to both upload data to the platform and subscribe to data from the platform. The communication can be realized in close to real time (approx. 10 Hz), which is fast enough for the expected fluctuations in the heat pump lab. As a default, we have set the sampling rate for data from and to the heat pump to 1 Hz, this may however be reduced for certain tests if deemed necessary.

The data acquisition is realized using NI hardware. The acquired data is then passed on via USB to the local laboratory control computer. The NI data is read into a Python based interface. From there the information is passed on to the Energydata.dk MQTT broker. Students and researchers can subscribe to the heat pump data and integrate it with their local models and algorithms via a Python platform. Set point values for the local controllers (temperatures and flows) can then be published to the MQTT broker. The local PC in the lab has subscribed to these set point values and passes these on to temperature and flow control. The operational control is based on PI control loops that are programmed in Python on the local PC.

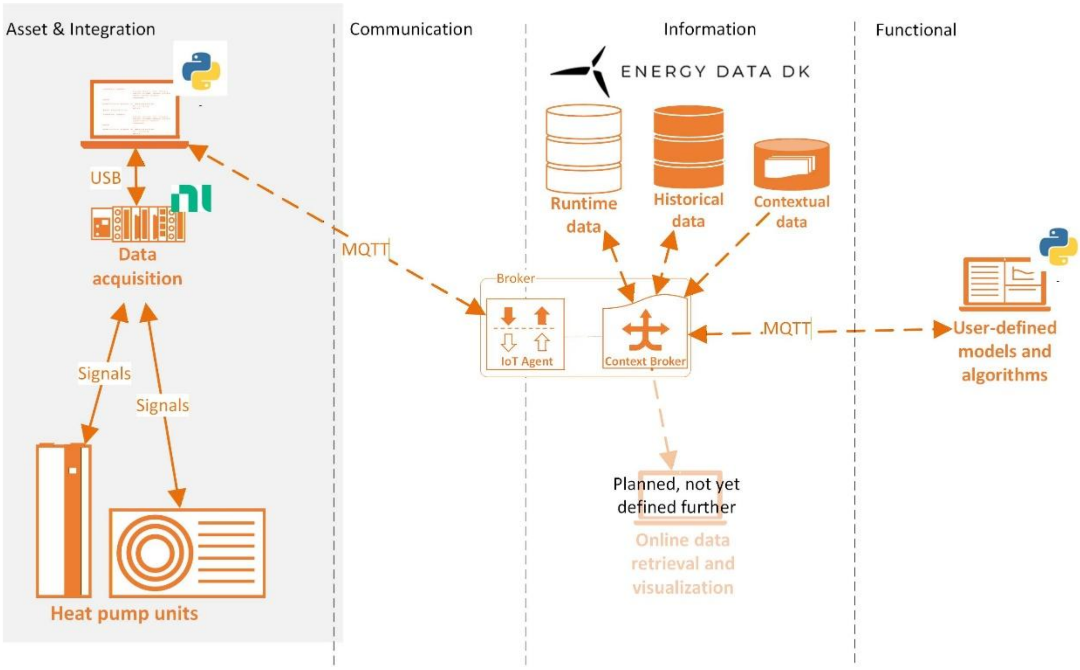

Figure 2 Sketch of the digital infrastructure of the Digital Heat Pump Lab, labelling of communication levels referring to [12]

3. Testing the two-way communication

To test the two-way communication via the MQTT broker of the Energydata.dk platform, two tests have been conducted. Firstly, the communication with physical sensors and actuators to be used in the laboratory has been tested. The second test was the simulation of a hardware-in-the-loop experiment.

For the first test flow meters, temperature sensors, pressure sensors and voltage meters of the kind implemented in the lab have been connected to NI data acquisition modules and the values have been read using Python on the local laboratory PC. The data has then been sent to the MQTT broker from where it could be retrieved by subscribing to the measurement values using a different PC. This was realized using Python, too. In a next step, the actuators and control set-up was tested. A simple PI control loop was programmed in Python on the local laboratory PC. The sensor data was read and compared to a set-point value sent from a different PC and retrieved by the local laboratory PC via the MQTT server. The required response of the actuator was the send via the NI DAQ hardware to a valve actuator of type AME 435 by Danfoss. The tests showed that the sensor data could be read out via the digital platform and that signals could be sent back to the actuator. Thereby, proving the basic functionality of the digital platform to allow for the envisioned use of the laboratory.

The second test assessed the option of using the digital heat pump lab for hardware in the loop tests of a MetroTherm Delta PVT heat pump. In this case the PVT panel behaviour was modelled based on historic weather data from DTU's climate station [11] in Python. The temperature at the evaporator outlet was given to the PVT panel model as inlet temperature via the MQTT broker. The model then determined the corresponding outlet temperature which was sent back via the MQTT platform. As it has not yet been possible to test this set-up using the physical laboratory set-up, a model of the laboratory infrastructure and a connected heat pump was built in Modelica and run on a different PC to simulate the behaviour of the physical laboratory.

Figure 3 shows a sketch of how the PVT model and the model of the heat pump laboratory have been coupled to each other and how weather data has been used to simulate realistic behaviour of the PVT model.

Figure 4 demonstrates that the input temperature given to the model of heat pump laboratory corresponds to outlet temperature calculated by the PVT model and vice versa, despite the unrealistic control of the heat pump in the model that effectively cools down the brine to a constant temperature.

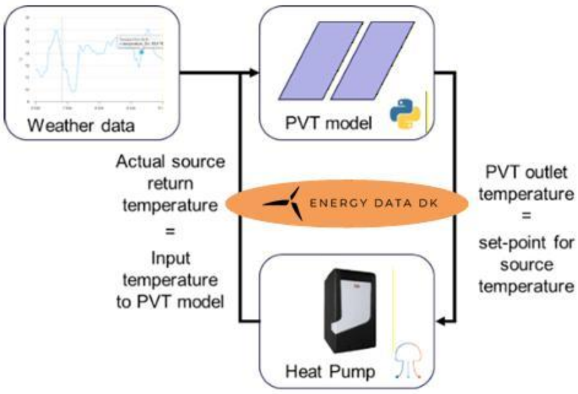

Figure 3 Sketch of how the heat pump data is coupled to a PVT model using weather data as input to realize testing of the heat pump under realistically fluctuating source conditions.

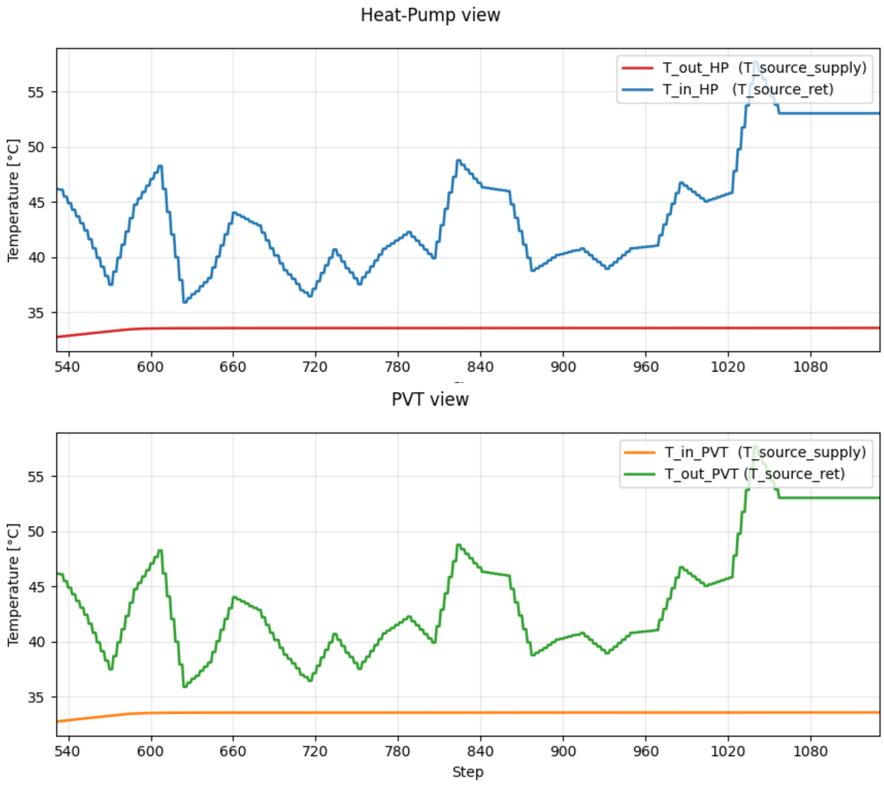

Figure 4 Comparison of signals send to and from simulated laboratory unit (Heat Pump view) and to and from PVT model (PVT view)(Figure used with allowance by Ignacio Martínez Moreno)

The option to alter the temperature to the heat pump in both sink and source loops dynamically opens-up for many interesting tests replicating real life scenarios more closely than standard laboratory experiments. Future variants may include coupling dynamic model of thermal storages, buildings, etc. to test the interaction of heat pump units with neighbouring systems and understand the interactions under realistic conditions.

4. Conclusion and outlook

The laboratory is currently being finalized, and we expect to test the full functionality using a water-to-water during spring 2026. The test and preliminary studies have shown that the set-up chosen for two-way communication from any PC is suitable and that data can be sent in both directions in close to real time. This provides the basis for a broad range of experiments in future, e.g. altering the temperatures to the heat pump in both sink and source loops dynamically. This opens up for many interesting tests replicating real life scenarios more closely than standard laboratory experiments. Future variants may include coupling dynamic model of thermal storages, buildings, etc. to test the interaction of heat pump units with neighbouring systems and understand the interactions under realistic conditions Further extensions planned for the future include testing and optimization of optimal defrosting for air-source heat pumps, adaptive digital twins for heat pumps accounting for degradation over time, development of algorithms for fault detection, etc.

Acknowledgements

The Digital Heat Pump Lab has received funding from COWI Fonden, Myhrwold Fonden and DTU Construct.

The laboratory would not become reality without our amazing colleagues in DTU Construct's workshop, instrumentation group and TES: Jan Horn Jansen, Benny Edelsten, Niels Steenfeldt Jensen, Claus Suldrup Nielsen and Jeppe Mathias Madsen Hagedorn. Further, we would like to acknowledge the contributions of Ignacio Martínez Moreno and Zsombor Benedek Szabó to develop use cases for the lab in their B.Sc. and M.Sc. thesis, respectively.

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