Final report

1. Project details

Project title	DH Sensor Power
File no.	64021-1062
Name of the funding scheme	EUDP
Project managing company / institution	Danish Technological Institute (DTI)
CVR number (central business register)	DK 5697 6116
Project partners	Grundfos, ReMoni, TEGnology, Silkeborg Forsyning, Kredsløb A/S
Submission date	05 April 2024

2. Summary

Project summary:

Today, real-time measurements of temperature, flow and pressure are limited to a few locations in the district heating (DH) network since access to the buried pipes is very limited. However, there is a strong need among DH companies for a commercial kit that is robust, low cost, and easy to install to support the sparse existing measurements and smart heat meter data in the transition towards new data-driven operation opportunities.

The purpose of this project was to develop an advanced and efficient system for DH distribution network measurement points combining thermoelectric generators (TEG), solar cells, clamp-on sensor technology, and a novel mesh network of gateways and repeater units for wireless data transmission.

Two solutions were presented, both having the advantage of being independent of cabling for power and data transmission:

- The first solution harvests solar energy to power gateways in lampposts near DH pits where sensors are installed.
- The second solution exploits TEG and LoRaWan without equipment installed in the street.

Two utilities demonstrated the technology in real environments, indicating promising potential for energy- and cost savings. Furthermore, the measurement system achieved a high degree of accuracy down to ±0,3 °C and could be installed in less than one hour.

In the future, the commercial partners will seek to integrate the developed technology into products and especially investigate the use of DH manhole covers made of composite material or other solutions for robust and continuous data transmission, which was identified as the key challenge. With this challenge solved, it is expected that the technology will help DH utilities to benefit significantly from implementation of pit measurement points through a whole range of suggested application scenarios.

Projektresumé:

I dag er realtidsmålinger af temperatur, flow og tryk begrænset til nogle få steder i fjernvarmenettet, da adgangen til de nedgravede rør er meget begrænset. Der er dog stort behov blandt fjernvarmeforsyninger for et kommercielt kit, der er robust, billigt og nemt at installere for at understøtte de få nuværende målepunkter og varmemålerdata i overgangen til nye datadrevne driftsmuligheder.

Formålet med dette projekt var at udvikle et avanceret og effektivt system til IoT-fjernvarmemålepunkter i distributionsledningsnettet, der kombinerer termoelektriske generatorer (TEG), solceller, clamp-on sensorteknologi og et innovativt netværk af gateways og repeater-enheder til trådløs datatransmission.

To parallelle løsninger blev præsenteret, som begge har den fordel at de er uafhængige af kabling til strøm og datatransmission:

- Den første løsning høster solenergi til strømforsyning af gateways i lygtepæle i nærheden af fjernvarmebrønde, hvor sensorerne er installeret.
- Den anden løsning udnytter TEG og LoRaWan uden behov for installation af udstyr i gadeniveau.

De to medvirkende forsyningsselskaber demonstrerede teknologien i deres netværk, hvilket indikerede et lovende potentiale for energi- og omkostningsbesparelser. Desuden opnåede målesystemet en høj grad af nøjagtighed ned til ±0,3 °C og kunne installeres på mindre end en time.

I den kommende tid vil de kommercielle partnere forsøge at integrere den udviklede teknologi i produkter og især undersøge brugen af særlige brønddæksler lavet af kompositmateriale eller andre løsninger til robust og kontinuerlig datatransmission, hvilket blev identificeret som den vigtigste udfordring der stadig er tilbage ved projektets udgang. Når denne udfordring er løst, forventes det, at teknologien vil hjælpe fjernvarmeforsyninger i deres bestræbelser mod højere energieffektivitet, reducerede varmetab til jord mm. gennem en lang række foreslåede anvendelsesscenarier.

3. Project objectives

The overall objective was to develop all parts of an advanced, flexible, and robust system for district heating (DH) grid measurements in DH pipe networks. The technology focused on installing new measurement systems in existing pits (manholes), but also other accessible locations.

The goal was pursued through a united approach combining power harvesting modules (TEG – ThermoElectric Generator), solar cells, clamp-on sensor technology, as well as development of a novel self-healing mesh network for data transmission from DH network locations to the cloud. The concept aimed to cover all elements of the total IoT solution, including cloud integration and development and implementation of algorithms for online sensor performance surveillance.

The solution strived towards:

- Low cost – for scalability and enabling future grid monitoring by “sensor networks”.

- Easy use – plug'n'play installation in DH pits and minimal maintenance when installed.
- Wireless technology – independence of both external power supply and cables for data transmission.
- High-accuracy temperature measurements – evaluated and minimized measurement uncertainty for current and future high-accuracy applications.

During the project, two complementing solutions were developed:

1. A battery/solar-driven solution aiming at continuous high-frequency data transmission capable of providing real-time temperature- and pressure data for the DH control system.
2. A TEG-driven solution for continuous lower-frequency applications.

A "sensor module" with attached temperature sensor pocket, pressure transmitter, and ventilation valves was developed, and can be applied with both solutions above.

The battery/solar-driven solution in combination with the sensor module was demonstrated in real environment at 10 pits in the networks of Silkeborg Forsyning and Kredsløb. Integration with other utility data and network models was carried out to identify energy optimization potentials and evaluate more application possibilities. The TEG-driven solution was demonstrated to a limited extend in the DH network of Svebølle Viskinge Fjern-varme by a prototype installation in one pit.

4. Project implementation

The project was organized in work packages (WP's) addressing development of the measurement system (WP1), transmission system (WP2), Grundfos- and ReMoni cloud integration (WP3), implementation and validation (WP4) and demonstration in DH networks (WP5).

Besides half-annual general project meetings, the progress was facilitated by three dedicated workshops in the first year of the project.

Very early after the kick-off meeting, a **first workshop** in November 2021 was held at Lisbjerg Forbrænding (Kredsløb) focussing on user specifications and requirements posed by the utilities. Here, the utilities detailed their wishes, requirements, and scope of their planned use cases in the project. It was for example concluded that the solution should aim at a real-time data transmission frequency of 1-2 minutes resolution, and the business cases of development scenarios compared to existing Differential Pressure (DP) cells and other solutions were investigated. Also, the utilities gave input to the technical developers at ReMoni, Grundfos and Danish Technological Institute about typical conditions in DH pits and the prioritized measurement parameters. It was concluded that pressure and temperature were in highest demand, and that the flow measurement was third. After the workshop, a site visit in the network at a current DP cell was made – see Figure 1.

The collected information on user requirements was followed up by a **second workshop** in December 2021 where the technical staff discussed the technical aspects of a sketched solution, and which direction the development should follow. The development of the battery/solar cell powered solution (1) was detailed and planned, but it was also concluded that the partners needed more information on

1. The actual conditions and design of DH pits in general for optimal adaption
2. A deeper investigation of potential ultra-low power modems to potentially enable a solution powered by TEG alone.

Figure 1 Site-visit in Lisbjerg (supplied by Kredsløb) in relation to the first workshop on specifications and requirements.

Regarding point 2, it was found that typical TEG-elements could deliver 20 mW at best case temperature differences of 50 °C between pipe and air, however the modem typically require 1 W while active, and the gap was not realistic to be closed in case of 1–2-minute data transmission from a pit. It could be done, but the solution would require installation of many TEG-modules rendering the installation cumbersome, space consuming and too expensive. Another path focussing on optimization of an ultra-low-power modem with superior (low) power consumption was also investigated, but unfortunately not realizable in the project lifetime. Hence, it was decided to divide the development in two tracks focussing on a main solution (battery/solar driven) and a parallel solution using TEG for complementary purposes.

Regarding point 1, Danish Technological Institute followed up by conducting an extensive collection of observations from pits by access to the networks and help by the staff at Silkeborg Forsyning and Kredsløb. These activities led to an overview of types and their prevalence among DH pits – see Figure 2.

Based on the collected information from on-site visits, complemented by information from a visit at the storage hall for pipes and network components at Kredsløb, a **third workshop** was held concentrating on a strategy for developing a mounting system for sensors in the pit. It was concluded that the system should focus on category 2 in Figure 2. These pits contain pre-insulated (encapsulated) valves, and the reasons for choosing these pits as target was that they appear in large numbers and are very similar: Sensors can be conveniently mounted on top of vertical pipes with direct line of sight to the medium in the main pipe below. The vertical pipes usually end by a 2-inch thread above a security valve such that no further cutting is required. In this type of pit, however, flow cannot be measured by the envisioned clamp-on flow sensor, but the utilities prioritized temperature and pressure measurements. For this reason, the system was prepared for future attachment of a clamp-on flow sensor, and the flow sensor was tested in the laboratory rather than in DH networks during the project.

The main expected risks associated with the development of the envisioned solution included that the solar powered network gateways were not allowed to be installed in some locations and that some pits could be flooded in extreme weather conditions, damaging the sensors and electronics. Indeed, both issues were encountered. The solar powered gateways placed in lampposts during the demonstration were allowed, based on discussions with the utility and municipality, but the partners experienced that several people, living in the affected areas, contacted the team, asking for explanations. It was emphasized that clear information should be found on the units, and so this was added to the gateways during the demonstration activities. Flooding of pits was seen in several instances and at both utilities. Hence, this issue is to be regarded not only in relation to extreme weather conditions but is a general condition that a future solution must be able to tackle. Since the equipment is "low cost" it could be easily replaced if flooding occurs, however in the end of the project a design is anticipated that is immune to water by encapsulation of the vital parts such that all components can withstand flooding.

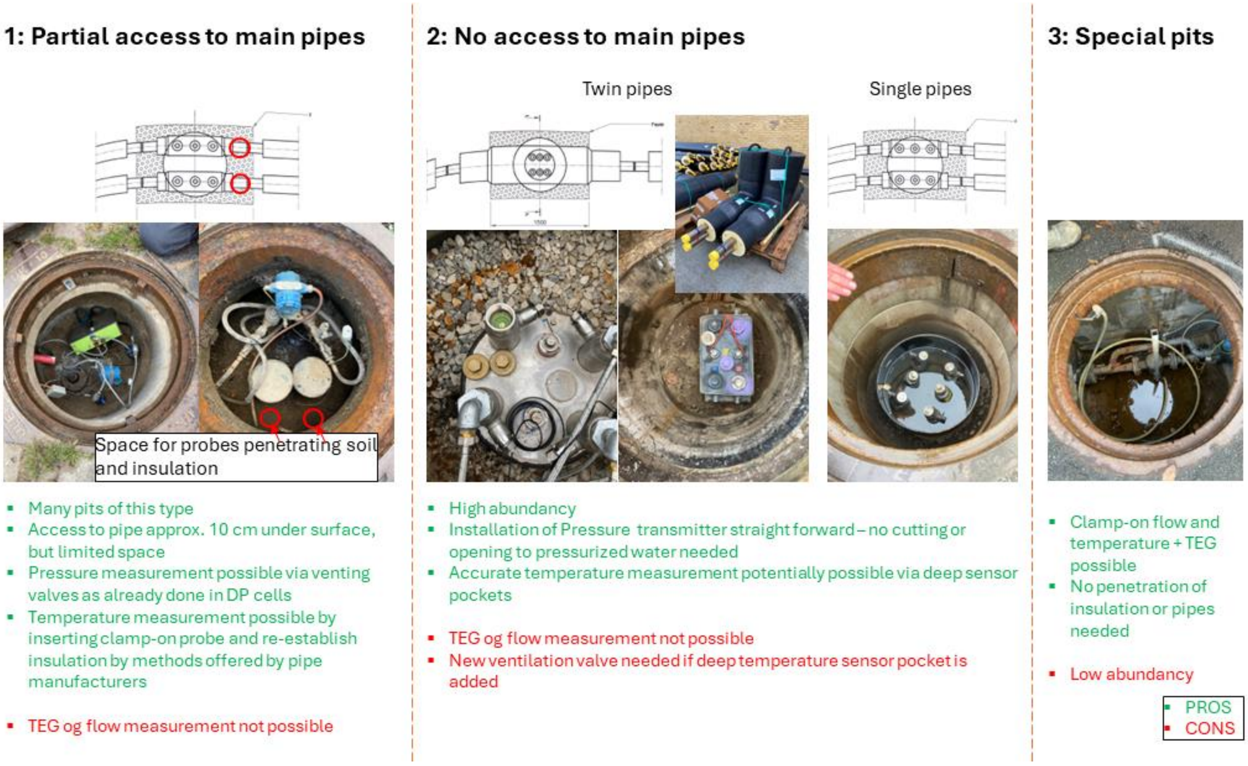

Figure 2 Identified types of pits in the DH networks of Silkeborg and Aarhus and comments on their respective advantages and disadvantages for installation of sensors.

Figure 3 Special lids with integrated composite material investigated by Kredsløb for data transmission above the ground.

A special challenge was the transmission of wireless signal from the pit to above the ground to reach solar powered gateways or repeater units. This issue was not only surprisingly difficult to overcome, but identified as the main challenge which still needs to be tackled completely. It initiated dedicated activities investigating transmission angles and positions of the sender in the pit, but also activities not foreseen about the use of alternative lids made of composite material which allow better transmission of the wireless signal in contrast to the solid metal lids encountered at almost all existing pits. Kredsløb investigated the use of these lids and showed that the signal could be enhanced by a factor of 3-4 while the lid could still be placed on roads with traffic up to 40 tons. At the end of the project, this solution seemed to hold potential, but the consequence for scalability of the solution will have to be investigated since the acquisition of specially made lids adds significant costs to the hardware part of the overall solution.

Due to the specific challenge of sending data wirelessly from the pit to gateways located in the street, the demonstration activities aiming to demonstrate value and potential use of the new measurement data was modified accordingly. Instead of demonstrating the potential with real-time data, an off-line solution was developed to complement the main solar cell powered gateway solution, such that data could be effectively and robustly recorded within the lifetime of the project (see description of this solution in section 5.1).

Figure 4 On-site installation in real environment was an iterative process where different versions were mounted, tested, and debugged. Service vans and staff from Kredsløb (left) and Silkeborg Forsyning (right).

Different prototypes of the developed solution (of which the final one is presented in the next section) were installed and debugged in an iterative process consisting of on-site work in the networks of both utilities, assisted by staff from the utilities (see photos of the service vans on Figure 4). This included testing how far the staff could handle the equipment and installation on their own, checking data connections, revealing shortcomings in the installation process not thought of before (length of wires, space conditions in the pit, etc.), feasibility of installation of gateways in the street and challenges such as flooding or options to depressurize the water during mounting of deep sensor pockets. A detailed list of these practical observations was compiled in the delivery report D6 [3], aiming to guide further developments and optimizations of the solution.

5. Project results

Overall, the technological objectives were obtained, but with some key challenges identified during the process that still need to be tackled. As described in the previous section, the main challenge is to establish a robust connection between the pit module and gateway in nearby light mast within 15 meters from the pit. A second development point is to achieve the final dimensioning of solar panels for the solar powered gateway system. This should in principle be straightforward, but could not be completed and demonstrated fully within the project, since work on data connection had to be prioritized, ensuring that data would be available for the utility demonstrations in the last phase of the project.

5.1 Technological results

Pit Module: The pit module in the primary solution consists of two parts: 1) The electronics and wiring for data logging and transmission and 2) a pre-mounted sensor module to be mounted directly by sealing one single thread. These parts and how to combine them is shown on Figure 5. The system contains two sensor modules, one for supply- and return pipes, respectively, but uses the same data logger and transmitter unit. Note that an extra temperature probe has been added which can be used to monitor the air temperature in the pit or serve other purposes. The details have been described in the delivery report D5 [2].

Solar-driven gateway: In the transmission system, the solar driven gateway displayed on Figure 6 was developed and mounted in the network supplied by Silkeborg Forsyning. A solar panel supplies a pack of lithium battery cells for temporary energy storage, and the unit contains a modem sending to ReMoni's data platform ReCalc via the tele network. As sketched on Figure 6 left, the transmission system is also expected to make use of less energy requiring repeater units without a modem, however this unit was not developed and tested in the project lifetime. From the ReCalc platform, data is transferred to Grundfos' cloud platform, iGRID.

Once the transmission between pit and light mast is established, for example via alternative lids (see Figure 3) and the solar panels have been finally dimensioned, the system should perform continuous real-time transmission every minute, only limited by the battery in the pit module (Figure 5) which is expected to have a lifetime of 15 years based on specifications and the calculated power consumption.

The installation procedure in Figure 5d, could be carried out by the utility staff alone using the prototypes, and the time spent was down to 35 minutes showing that measurement points can be installed and/or moved to other pits effectively.

Offline datalogger: In cases where it is not possible to install a repeater unit or gateway on nearby lampposts, an alternative solution was also developed, based exclusively on equipment placed in the pit. This solution can be used if there are poor transmission conditions out of the well, and it was used in the demonstration phase to make sure that the utilities received full and intact datasets for their analysis of application and energy saving potentials.

The system is shown in Figure 7. In addition to the basic pit module, a data collector unit is placed in the well together with a connected rechargeable battery pack. The device collects the wireless signal from the sensor box and stores data over a limited period, while there is power on the battery. The data collector is then transported home together with the battery, after which the system can be recharged and data transferred to ReMoni's data platform, ReCalc. The data transfer takes place automatically when the data collector is connected to power and contacts a device that can transfer data to the cloud via a wireless network.

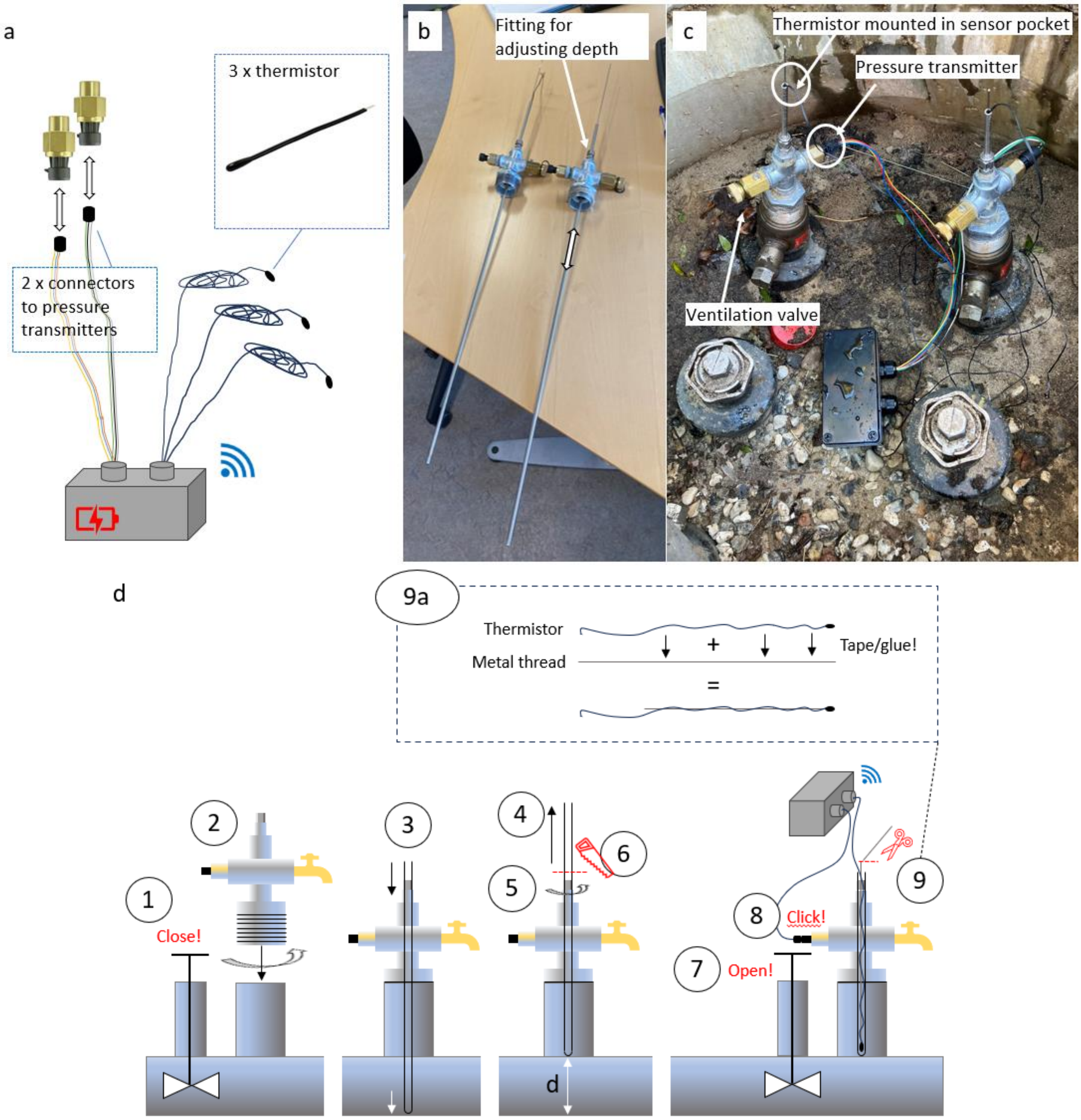

Figure 5 The final pit module consisting of the sensors and electronics, including the antenna for data transmission out of the pit (a), the sensor module ready for installation (b) and as installed (c). (d) shows the mounting procedure.

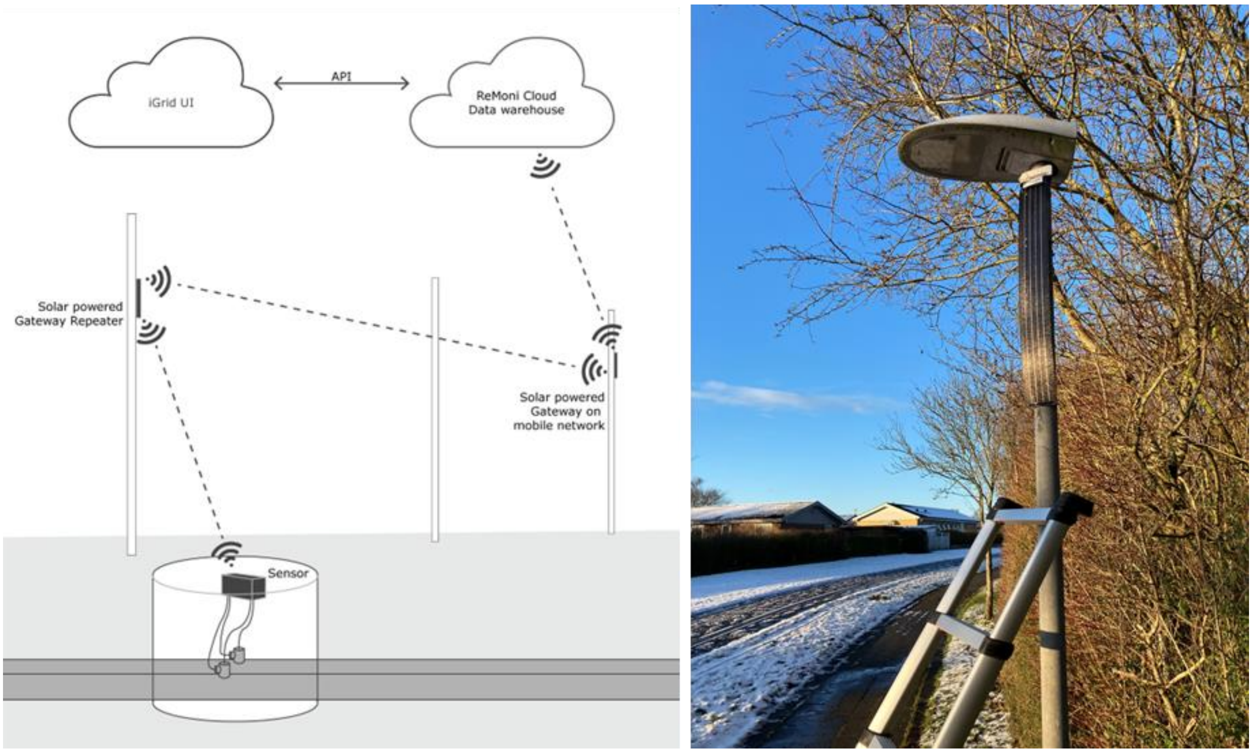

Figure 6 The solar cell-driven units for transmission of the signal from pit to cloud.

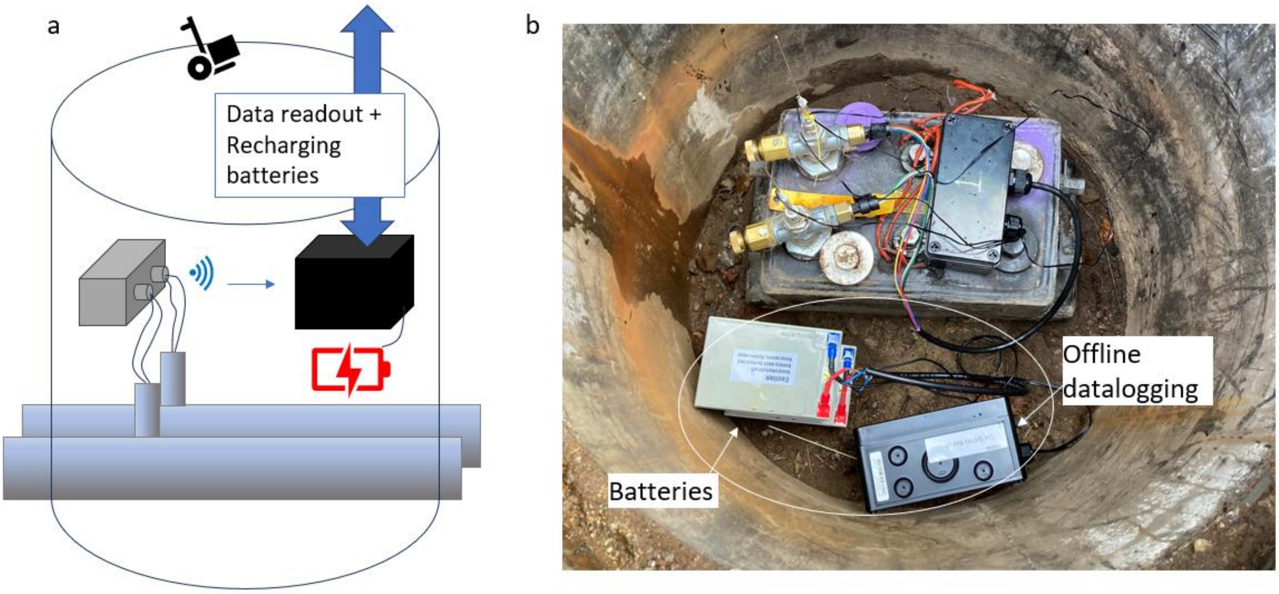

Figure 7 The offline data collection system developed for data logging from pit measurement points over shorter periods of 8-10 days.

TEG-based solution: A solution based on a TEG-powered sending unit in the pit rather than solar cell driven gateways outside the pit, is relevant in parallel for other purposes than the primary focus of enabling control of the DH network based on pit data (pressure and temperature). According to the utilities, data-driven control requires a time resolution of 1 minute, while it was found that a less frequent reading in real-time with a frequency of 5 minutes could be realized with the TEG as a power source and used for other purposes.

The prepared TEG-based solution is shown in Figure 8. As can be seen in comparison with the primary solution, the starting point is the same setup adapted to the same type of pre-insulated valves. The main differences are that a central sensor readout and transmitter unit is now supplied exclusively with a TEG unit located on the hottest pipe (supply side). The transmitter uses the LoRaWan network and transmits signal and data all the way up into the cloud without intermediaries in lampposts or repeater units. This again gives the cable-free advantage, but on the other hand, data can only be sent every 5 minutes if the system is to run continuously.

An exhaustive list of the differences between the TEG- and solar-driven based solutions is given in the internal delivery report D5 [2].

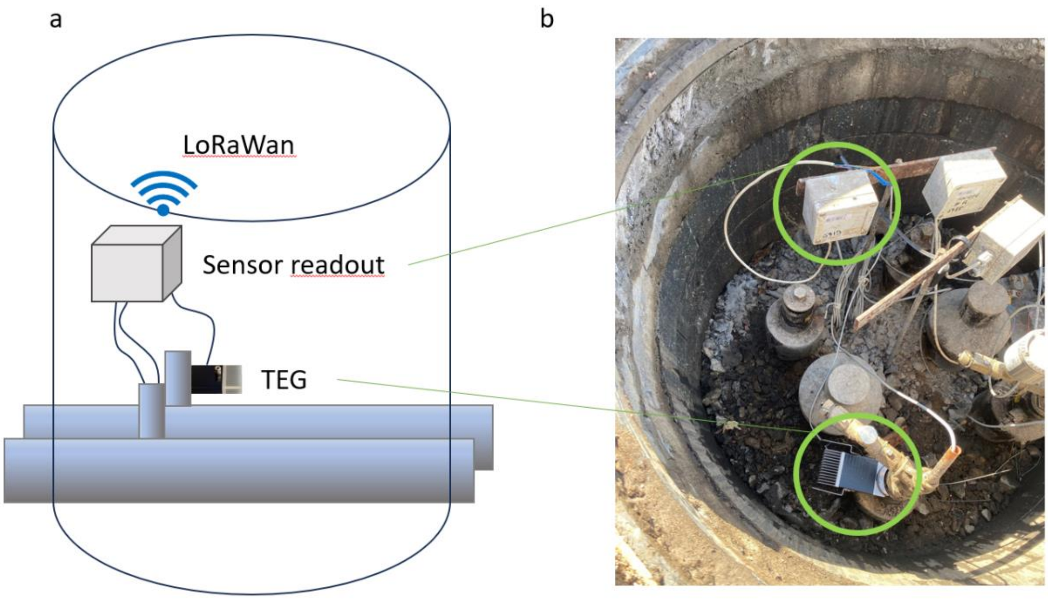

Figure 8 Sketch of the TEG-based solution (a) and photo from the test pit where it was mounted.

Validation and accuracy: An important feature of the pit module is that it is validated by laboratory experiments performed at DTI (described in reference [1]). The uncertainty of the temperature measurement was quantified, and the sensor module with deep sensor pockets enhances the accuracy compared to other solutions on the market. Also, the laboratory test gave knowledge about the magnitude of drift of sensors to be expected and guidance on what will be required of maintenance.

The completed laboratory tests showed that the Sensor Power measurement system measured temperatures in DH water very close to the reference values in the test. At 75 °C, the largest observed error was only -0,13 °C when using the developed sensor pocket and -0,28 °C for mounting as a clamp-on on the metal pipe under the insulation. In addition, various effects were investigated in the physical system for their impact on the temperature measurement: Variations in flow rate, repeatability of the installation, finding the optimal vertical location in the pipe, investigating possible installation faults, thermal paste in the sensor pocket, dynamic temperature, penetration of water into the sensor pocket, and ambient temperature conditions in the well.

The dominant uncertainty contributions come from the drift of the thermistors and their specified uncertainty if not calibrated before use, whereas it was found that the mentioned physical factors did not contribute significantly to the overall measurement uncertainty. If the selected epoxy-coated NTC thermistor is used without calibration, the system achieves a temperature determination of ±1.55 °C incl. the drift indicated by a separate stress test, however this scenario is based on a procedure where the worst outliers are sorted out by a pre-stress treatment and comparison at 0 °C. The best uncertainty among the investigated possibilities (±0,31 °C) is achieved with calibrated, glass-coated thermistors.

Initially, observations at high flow (> 45 m^3/h) indicated an advantage in raising the tip of the sensor pocket up to the location at the level of the main pipe ceiling to avoid destructive vibrations. The difference between the location in the middle of the flow and just retracted in the vertical pipe was determined at 75 °C to be only 0,1 °C and is covered by the measurement uncertainty without contributing appreciably to it.

The stress test that simulated the harsh conditions with high humidity and temperature clearly showed that the tested glass-coated thermistors have a superior stability compared to the epoxy-coated ones. This could point to an advantage in moving forward to using the glass type, which, if calibrated, could be included in the DH Sensor Power solution with an uncertainty contribution for drift of less than 0.2 °C. Alternatively, a hermetic closure of the sensor pocket at the top could be added, possibly in combination with a reduced temperature range up to, for example, 75 °C, which in many cases would be able to cover applications within low-temperature 4th generation DH. A new stress test at lower humidity and temperature should then be carried out.

Altogether, the results of laboratory tests validate the temperature measurements and quantified the uncertainty. Importantly, they also led to recommendations regarding future development: The effect of calibrating or selecting NTC probes before use, change to the glass-coated type as well as to display the resulting uncertainty on temperature measurement on the data platform to end users.

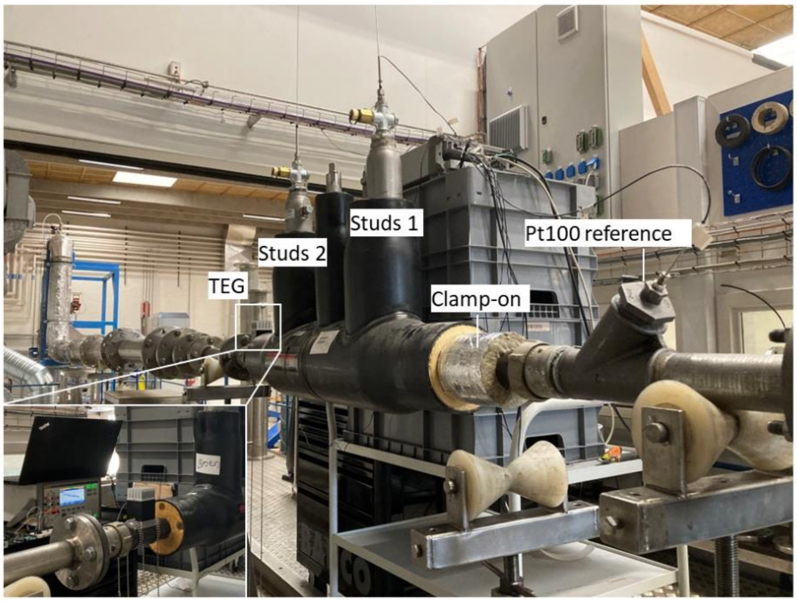

Figure 9 Laboratory setup in the national water flow laboratory at Danish Technological Institute, Aarhus.

Measurement campaigns: Due to the extra work and tests in the network on data connectivity, including several prototypes of the system, the project experienced a delay. This caused very late access to synchronized data from actual “sensor networks” consisting of 5 pit measurement points in each local area hosted by the two utilities, respectively. Originally, the project planned for deep analysis of data from these correlated measurement points to develop algorithms for sensor surveillance (detection of drift and faults on individual sensors by comparison to its neighbours) and overall improvement of the uncertainty on the measured and calculated temperature and pressure by taking several pit points into account in a network model. Also, these algorithms could be supplemented by data from plants, pumping stations or consumer heat meters. Fortunately, Danish Technological Institute has the opportunity to develop this methodology in direct continuation after the project end by bringing the Sensor Power solution and equipment into play in the European metrology project FunSNM (started 2023) where DTI is partner and responsible for a sensor network methodology use case focussing on DH network models.

On the other hand, valid minute-resolved data from both utility networks over periods of 5-10 days from all 10 pits were acquired. This made analysis of potential value and application scenarios possible. The analysis results were collected in the delivery report D6 [3]. This work represents a preliminary overview of the data due to the delay in the project, but more information from these data could be extracted in future analysis. Kredsløb analysed the application potentials and value from the utility point of view (see section 5.2) and data from both demonstration areas were compared to simulation results by Termis network models showing potential for improvement of the models.

The high level of detail and insight in the dynamics of the network that is made possible by the sensor network is evident on the example on Figure 10. As shown in the figure, this type of data makes it possible to extract both temperature (and heat) loss and transport time for the district heating water between all pit measurement points. At the same time, the transport time is again correlated with the pressure loss between the same pits (not shown here). This type of analysis has potential within several applications, including evaluation of the heat loss and current insulation capacity of the pipelines between the respective pits, and thus also the possibility of indicating a loss in insulation degree or a rupture that has occurred, which typically results in wet foam and degradation of the insulation degree.

The relationship between the transport time, the pressure loss and the heat loss again provides the opportunity to evaluate the operation of the individual NTC thermistors (or other types of temperature probes used). Since the temperature loss through the system will depend partly on the flow and transport time and partly on the soil temperature, which fluctuates more or less equally in the area, heavy drift for some sensors could be detectable via monitoring algorithms. This is a very relevant development area, as sensor drift and possible damage is a risk due to the harsh environment in the DH pits and the utilities' emphasis on the importance of a measurement system with the least possible need for maintenance.

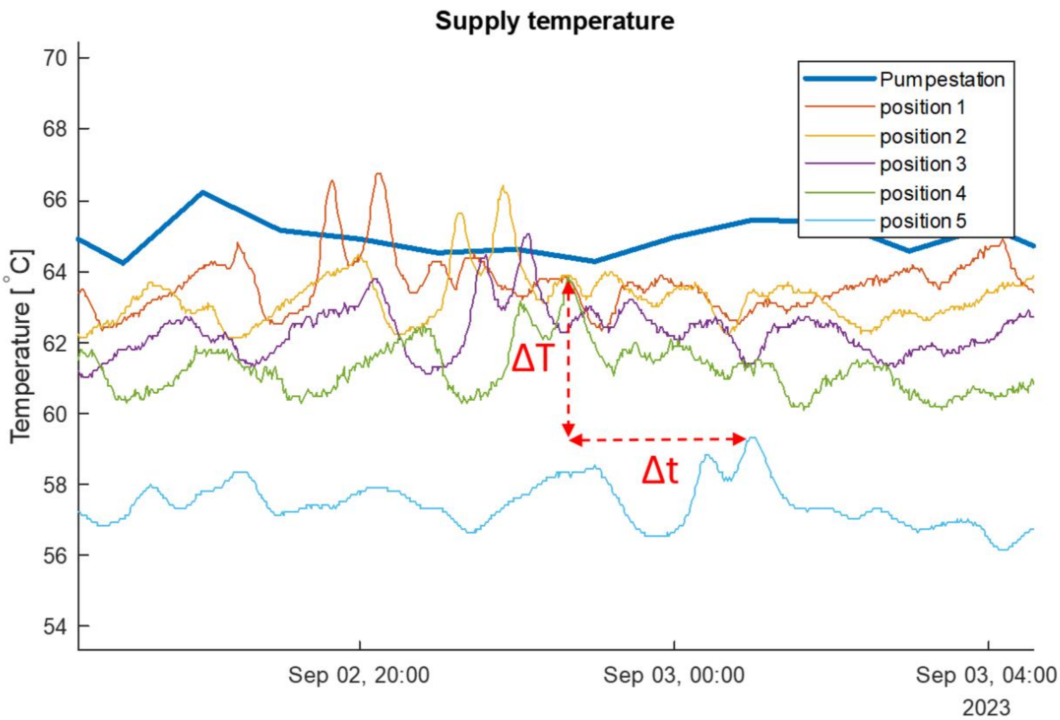

Figure 10 Visualization of pulse propagation through the network passing by the 5 pit measurement points in Silkeborg. The positions refer to the distance to the nearest pumping station upstream. Data points from the pumping station before the first pit (position 1) are hourly averages whereas the pit data is minutely resolved and corrected by the preliminary calibration at DTI before installation.

5.2 Commercial results

The commercial introduction of the solution to the market is still awaiting, but tasks have been carried out in the project to prepare for this. The commercial results include both software/data platforms, the hardware components as well as the demonstrated user cases for both solutions (solar- and TEG-driven). The partners that are expected to utilize the commercial results are Grundfos, ReMoni and TEGnology.

The software and data platforms hosted by both Grundfos and ReMoni have integrated the data from pit measurement points during the project and offer API's that third parties can use to extract data without interacting on the user interfaces at iGRID and ReCalc. The user interfaces displaying data from the same pit measurement point are shown in Figure 11. An account with login and password secures the data, and access can be granted to end users by registering with their email address. This procedure was used in the demonstration activities in the project. However, future applications are anticipated to be based on automatic API calls to the databases of both ReCalc and iGRID to ingest measurement data directly into the SRO system of utilities or into other software systems hosted by digital service companies exploiting the data.

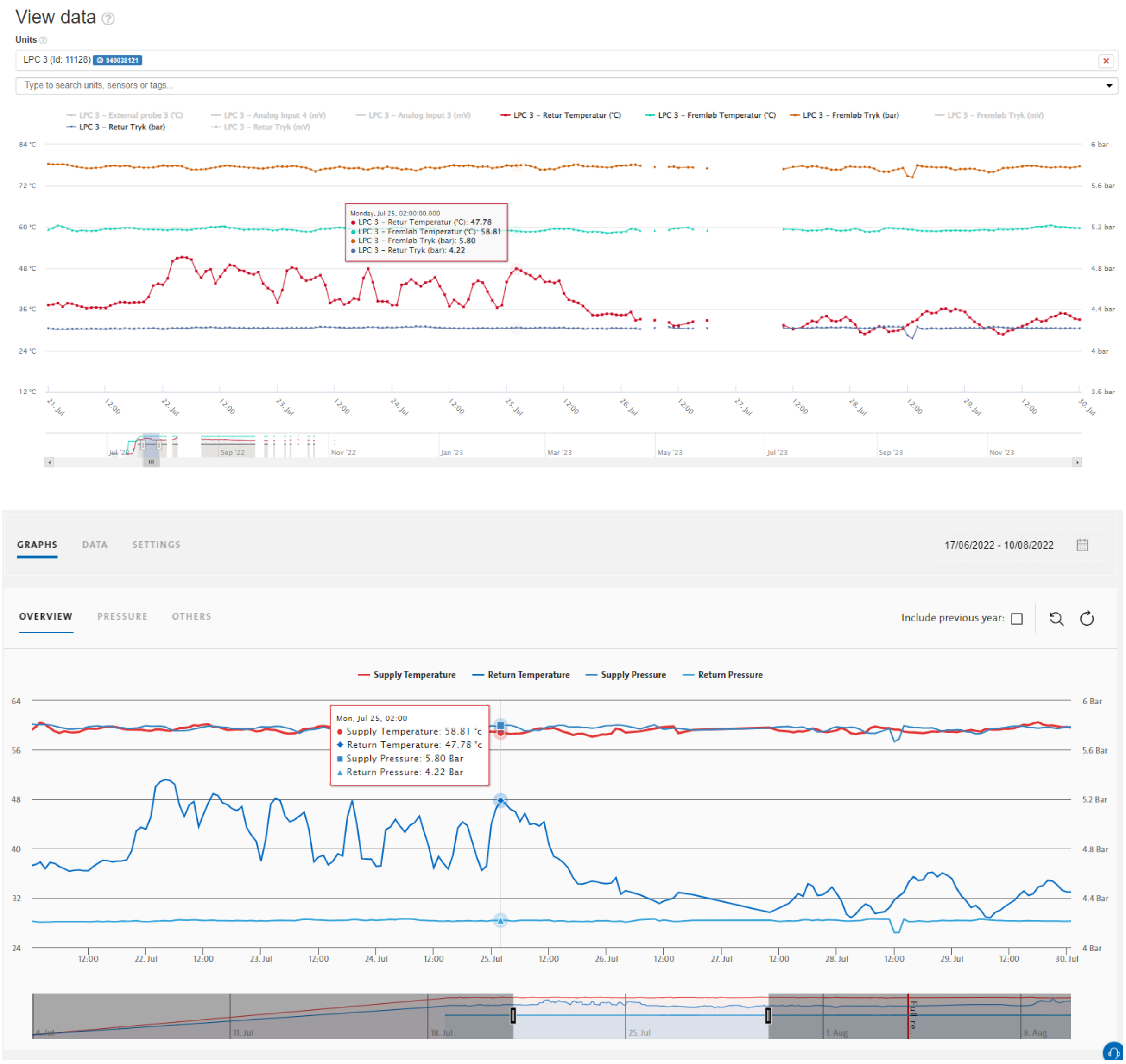

Figure 11 User interfaces on the data platforms by ReMoni (upper screen shot) and Grundfos (lower screen shot).

The following technical elements could be commercialized in relation to the software- and data platform solutions:

- The prototype of the laboratory validated sensor module for easy installation on pre-insulated valves.
- The pit data logger- and transmitter system, prepared for 3 NTC probes, 2 pressure transmitters and one future clamp-on flow sensor.
- The prototype solar-powered gateway system intended for light posts or other locations in the street.
- The demonstrated TEG-system for pit measurement points using the LoRaWan network.

In addition, the commercialization will benefit from the practical experience with installation and knowledge about actual conditions on-site at the pit locations. Also, the initiated work exploiting composite material lids to solve the issue on data transmission out of the pit could be used.

Target group: The primary target group is DH utilities which will be able to apply the pit measurement data for various energy optimization and security of supply purposes, as described in the next section. The solution is targeted the approximately 400 Danish DH suppliers in the first run, but in the next step there is a grand potential on the international market. For utilities abroad, some factors are still unknown, including the actual design of pits. Although pit design is unknown, it is anticipated to be similar to the Danish constructions since the manufacturers of pre-insulated valves are international market players. Another point is that the partners need to confirm that solar gateways can indeed be installed in streets abroad according to local regulations.

Although DH utilities constitute the target group that is expected to make value out of the products, the solution will also be promoted towards digital service providers working in the field of DH such as Gradyent, Kamstrup, Utilifeed or consulting engineers such as NIRAS and COWI, who already showed interest in the project. The first group could use pit measurements in their modelling of DH networks to calibrate the models and improve accuracy and reliability of real-time simulations, and consulting engineers are keen to apply pit measurement points in integrated solutions when advising DH utility customers about network design and renovations.

User value: The user value was analyzed carefully using different approaches:

- Dedicated interviews with the Manager for Strategic Operation and colleagues at Kredsløb.
- Meetings and dialogue with consulting engineers in DH at COWI.
- Detailed analysis based on demonstration data from Kolt, Aarhus, performed by a hydraulic specialist at Kredsløb.
- Continuous evaluation, comments, and design of user cases throughout the project by both utilities.

In Tabel 1, a summary of the identified application scenarios for the Sensor Power pit measurement points is given. Overall, the utilities emphasize that the most important case is reduction of temperature and pressure levels closer to the critical values while still securing the supply. However, it is seen that many other applications are of interest to the utilities and could result in energy- and cost savings as well as other advantages.

Tabel 1 Identified applications, need and user values for the DH Sensor Power Pit Measurement Points (PMP's)

Application scenario	Need	Value
Integration of waste heat	Utilities can use additional PMP's to surveil surplus heat customers/suppliers. What do they deliver and how does it affect the network? Also, surplus heat can affect the dynamics of critical points	- Better follow-up on contracts where the waste heat prosumer is obliged in relation to how much heat is delivered and at what temperature. - Can form the basis for adjusting the price or closing the agreement

	which are monitored for pumping control. There may therefore be a need to be able to move the measuring point.	
Easy relocation of PMP's	Surplus heat or changing seasons, consumer behavior, construction in the network or similar can affect the dynamics of critical points that the pumps control according to. This causes a need to be able to move the measuring point which is not possible with today's wired DP-cells.	- Temperature and pressure optimization - Security of supply
Pumping and temperature control depending on several monitored PMP's	PMP's make it possible to keep several set points in different places in the network at the same time (typically up to 9 pcs.)	- Temperature and pressure optimization - Security of supply
Control depending on alternating PMP's	There may be differences in which critical locations are found in the network in winter vs. summer, e.g. in places where the pressure is not high in the summer and where a measuring point is not critical any longer -> better with more or movable measuring points.	- Temperature and pressure optimization - Security of supply
Documentation of actual conditions in the DH network	Need to be able to deliver and document the required differential pressure to the customers	- Security of supply - Analysis of unexpected system behaviour - Facilitated dialogue with consumers
Network models	PMP's (possibly only temporary) allow for better models by virtue of model calibration	- More reliable model results and accurate simulations
Network models	PMP's can be set up if a model fails (may be due to lack of knowledge about real pipe diameter, condition, valve that was not fully closed or open, etc.) -> verification with movable PMP	- Verification of network models and registered pipe data
Revealing inappropriate conditions in the network	Direct measurement of unexpectedly high local pressure drops and heat losses	- Information for Asset Management purposes - Efficient and targeted renovation
Renovation	The PMP's can form a better basis for dimensioning both new areas and existing areas in connection with renovation	- Reduction of pipe dimensions, heat losses and need for use of bypasses.

Bypass control and design	Utilization of the PMP's for better management forced circulation to avoid still water, as the measured and hitherto poorly known return temperature can reveal inappropriately high activity in the circulation	- Energy and cost savings

User value analysis by Kredsløb: In continuation of the qualitative list given in the table, Kredsløb performed calculations of their potential cost savings in the demonstration area [4]. For example, better bypass control is anticipated to lower the return temperature by 0,5 degrees on average, resulting in a saving of approx. 67.2 MWh in heat loss and 7.3 MWh in pump energy. These figures come from a simulation for the exchanger area 145 Kolt. If the heat price is set to DKK 300/MWh and the electricity price to DKK 1200/MWh, this will give a total saving of approx. DKK 28,920 per year. The exchange area 145 Kolt is approx. 2.43% of the heat supply, so if it is assumed that the savings can be scaled linearly with the heat supply, the annual savings will be approx. 1.2 million. This is not a direct saving of the PMP's, but it can be used as a tool to achieve this saving.

PMP data can also be used to investigate deviations in models, for example in relation to pressure. This is also of great value as it is important to have models that match reality, but it is difficult to quantify direct cost savings. Comparison between PMP data and Termis simulations from both Silkeborg Forsyning and Kredsløb indicated that models could benefit significantly from calibration or adjustments by integrating PMP data (explained in delivery report D6 [3]).

The pumping lift can be reduced in large parts of the year where with the current pump control there is more differential pressure than necessary. If it is assumed that the lift can be reduced using PMP's by 0,1 bar on average over the year, there will be a saving of approx. 8.2 MWh in pump current, which is approx. DKK 9,840 per year for the exchange area 145 Kolt. For Kredsløb's entire supply area, this corresponds to DKK 405,000 annually.

For the temperature, the measurements can be used to create a more precise temperature control than is currently used, however this will also require control algorithms that handle several feedback points from the PMP's. The calculation for Kredsløbs overall supply area yields approximately 150.000 kr. per year, but the utility is already operating at low temperatures and hence this potential could be much more significant for other utilities.

Finally, there is a saving of + 100.000 kr. related to avoiding future construction of wired DP cells or traditional wired PMP if the solution reaches absolute robustness and stability.

Based on these examples, it was concluded in the analysis that there is good potential for integrating PMP's, both permanent and intermittent (moveable) ones. To achieve the savings, the following requirements were underlines:

- Low price
- Low maintenance
- Precise measurements
- Easy installation

If these requirements are met, it was evaluated that there is a significant potential for use for PMP's in the DH network.

Dissemination: Dissemination of the project activities and results has been carried out or are planned as follows:

Articles:

- Fjernvarmen Nr. 1, januar 2022, "*Onlinemåling i fjernvarmenettet skal optimere drift og mindske energispild*"
- Energy Supply, 11. april 2022, "*Online-målinger i fjernvarmenettet skal optimere driften*" (online)
- Dagens Byggeri, 1. feb. 2022, "*Online fjernvarme-måling skal forbedre CO2-regnskabet og mindske varmeregningen*" (link)
- Nyhedsmagasinet Elektronik, online 1. feb. 2022 (link)
- Fagmagasinet Maskinmesteren, "*IoT måleløsninger på vej til fjernvarmenettet*", in draft and expected april-may 2024
- Scientific paper: "*Development of traceable temperature measurement points in district heating pipe networks*", will be submitted with deadline 8. April 2024 to the IMEKO 2024 XXIV World Congress

Conferences and workshops:

- Oral presentation at Metrologidagen, november 2023, at FORCE Technology, Brøndby
- Presentation at workshop in relation to the final conference of the "IEA DHC Annex TS4: Digitalisation of District Heating and Cooling Optimised Operation and Maintenance of District Heating and Cooling systems via Digital Process Management", Berlin 20. – 21. November 2023.
- Presentation at "Åbent Hus" at the Danish Technological Institute, 12. marts 2024.
- Planned (accepted by program committee): Oral presentation at the IMEKO 2024 XXIV World Congress 26. – 29. august 2024

Web pages:

- Information about the project was published on a project website in the domain of Danish Technological Institute (link)

6. Utilisation of project results

The project results are expected to lead to the following outcomes:

- **ReMoni** will exploit the technical developments and hardware prototypes of the data loggers and transmission components that ReMoni has developed under the project. Once a market channel with sufficient volume is identified, ReMoni will prepare the components for commercialization including finding solutions to data transmission issues and finalizing the hardware and design aimed at production. The collaboration with Grundfos will create synergies and connection between the digital iGRID products and ReMoni products. In this way, it is possible that ReMoni will be subcontractor as part of overall solutions offered by Grundfos, or other players in the DH market.
  Furthermore, ReMoni will consider using the results and experiences from the projects in solutions targeting the water supply sector, for example by integrating the tested clamp-on flow sensor into the measurement point.
  Work will continue with clamp-on temperature and flow, and the experience from the project will be used on what is needed technically to move forward. Another relevant scenario that ReMoni will investigate is a case where sensors are placed on pipelines where there is no well in advance and in combination with a cabinet for cable extraction and transmission. ReMoni is also open to using TEG

to power sensors and will exploit the collaboration with TEGnology. Overall, it is an advantage if hardware can become cheap if the unit numbers become high enough, and therefore market channels are looked for, with a large enough volume to stand optimal when entering the commercialization phase.

- **TEGnology:** The project has opened and emphasized TEGnology's attention towards DH which is now a main focus – heat is available for TEG and TEGnology has established collaborators and attention about their solutions in the DH field through the project. For TEGnology, the utilization will focus on identification of situations where TEG is necessary, in other words where TEG is better than batteries. Better use cases will lead to better business models, and the use case and demonstration of the TEG-driven pit measurement point will be exploited in this manner. TEGnology will seek collaboration with industrial partners and use project contacts from external stakeholders that contacted the project consortium during the project, for example to investigate the use of TEG in prefabricated valve solutions.

  Grundfos: Currently, Grundfos sees too many uncontrollable uncertainties to be able to prioritize and allocate the needed resources for taking the "EUDP Sensor Power products" to market immediately. This is related to their current PMP on the market since the new solution needs to be differentiated enough. However, Grundfos learned new aspects that can be of value to the current portfolio of iGRID solutions:
  - In terms of data transmission and signal coverage, it is normally a challenge to ensure a perfect, stable connection due to the dense metal covers of the pits. In this project, covers or lids of composite material were utilized at the test sites, and they showed a significant improvement of signal strength. This solution can also be used in combination with the current iGRID PMP product and existing installations among customers to ensure a more stable connection.
  - In terms of battery solutions, Grundfos learned from the discussions in the project and has become aware of possibilities. These solutions could become relevant, since it is not always possible to get the required differential temperature to run the thermal electric generator (TEG) in DH and never possible in district cooling.
- **The Danish Technological Institute** will exploit the results in several ways:
  - Consultancy and support targeted DH utilities and industry about exploiting the grid measurement points in future applications.
  - Exploitation of the technical results and obtained expertise about DH grid measurements in future R&D activities, including international cooperations.
  - Dissemination of the obtained knowhow to the scientific community for a wider impact of the technical results. In particular, DTI will take over and exploit the demonstration hardware in a European joint initiative within the Horizon Europe programme on sensor network analysis (the FunSNM project). Here, a use case on a fundamental metrological approach to the DH case is planned with international partners, and two of the commercial partners in the DH Sensor Power group has already joined the stakeholder group.
- **Silkeborg Forsyning and Kredsløb** will seek to exploit more measurement points in the optimization of network operation. The utilities will await the introduction of the solution on the market, however the use of composite material lids to improve current solutions such as the existing Grundfos pit measurement point will continue. The performed analyses of energy- and cost saving potentials will be discussed internally and evaluated for possible implementation of optimization initiatives.

Competition and possible sales barriers: The DH Sensor Power solution seen as a the whole unified "IoT package" has a good position on the market by differentiating on several parameters, including superior accuracy on temperature measurement, ease of installation and price. The main competitive product is still the existing pit measurement point offered by Grundfos. Hence, the primary sales barriers for the new solution consist of achieving the originally expected remarkable cheaper PMP and that a superior data connection can be established. Both points are related to finally settling down on the right solution of combining the developed components with composite material lids or other antenna solutions. This will be key to leverage the vision of true scalability and enabling a multitude of PMP's in the future utility networks.

According to new feedback from the market DH utilities request help to make use of data, and for this reason they are also interested in buying measurement points as a part of a bigger solution where Grundfos or other service providers optimizes pressure, temperature and/or flows with a measurable ROI, for example through larger decentralized mixing loops. Therefore, it might be fruitful or even needed in cases to integrate the sale of PMP's into overall optimization solutions.

Contribution to energy policy objectives: The project results will help energy efficiency initiatives within DH, which is a key sector in the overall ambitions to reach a sustainable energy system. Besides this, focus on energy efficiency improvements is a central sales argument for the involved partners, and several other Danish manufacturers of products for DH and heat installations.

The project supports the aim of reducing greenhouse gas emissions in Denmark by 70 % compared to the 1990-level before 2030. When DH utilities mature over the next years, the utilization of data from pit measure points will contribute to the reduction of greenhouse gas emissions by:

- Optimized control and operation of Danish DH systems reducing heat losses and pumping power.
- Security of supply by enabling measurements at critical supply points in the grid, and the possibility to move them when necessary.
- Increasing the reliability of network model results to help better renovation and construction activities as well as daily network operation.
- Documentation of conditions and dynamic parameters in the network will be easier and more trustworthy with direct and validated measurements. This will save time spent on such activities at the DH utilities and in the end offer consumers better DH prices and make DH attractive.
- The scalable measurement points will facilitate better follow-up on delivered temperatures by customers delivering surplus heat back into the system and overall make it more attractive to integrate waste heat seen from the utility point of view. In the same way, the scalable measurement points will help the operation of networks around geothermal heat sources.
- Pit measurement points hold potential for asset management in terms of evaluation of actual heat losses in the distribution grid and need for maintenance/renovation. Also, the data from pit measurement points has potential to reveal leakage, especially if the clamp-on flow sensor can be attached to the solution in the future.

On a longer time scale, validated data of high quality is a prerequisite for current trends in big data analysis using large amounts of data in combination with artificial intelligence and machine learning to develop algorithms that can analyze and forecast the state in the energy system. This opens new opportunities, as also highlighted EUDP's strategy 2020-2030, and major Danish companies already integrate such developments in their DH products in combination with innovative business models.

In addition to the energy efficiency possibilities within DH, the components and solutions developed in the project will be able to be used in building installations and in industrial processes with the same purpose of optimizing energy efficiency.

7. Project conclusion and perspective

The project developed wireless IoT solutions for measurement of temperature and pressure in district heating (DH) distribution networks suitable for locations where power, data transmission and compromised access to the pipes underground represent serious challenges.

The two presented solutions – driven by battery/solar cells and TermoElectric Generators (TEG), respectively – are adapted to a highly abundant and appropriate type of DH pit consisting of buried pre-insulated valves with existing opening handles for installation of sensors. The solution for temperature measurement was guided and validated by laboratory-tests and attained a very high degree of accuracy compared to other solutions on the market. The solutions were iteratively tested in real environment in the DH networks of the two participating utilities in Silkeborg and Aarhus resulting in valuable practical experiences to guide the development. Finally, the two utilities performed user cases involving sensor networks consisting of 5 pit measurement points in each demonstration area, and the user cases indicated promising potential of using the solutions for energy- and cost savings, better security of supply, as well as other advantages.

The next step is to resolve the outstanding issue about data transmission from the pit to above ground level, which was identified as the key challenge. The project already proposed a way forward using alternative lids made of composite material which can be penetrated by the wireless signal, but other solutions will be considered as well.

Overall, the partners received lots of feedback from external stakeholders that reacted on various of the dissemination activities, emphasizing that the topic is of current interest. After the project, the partners will continue maturing the technology and seek to penetrate the DH market to push for more use of DH grid measurements points for future benefits of both utilities, DH consumers and the environment.

8. References:

[1] Internal delivery report D1, “Laboratorietests”

[2] Internal delivery report D5, “Beskrivelse af den overordnede DH Sensor Power-løsning”

[3] Internal delivery report D6, “Implementering og analyse af anvendelsespotentialer”

[4] Report: ”Evaluering af målepunkter i område 145 – Kolt”, Lasse Olsen, Kredsløb