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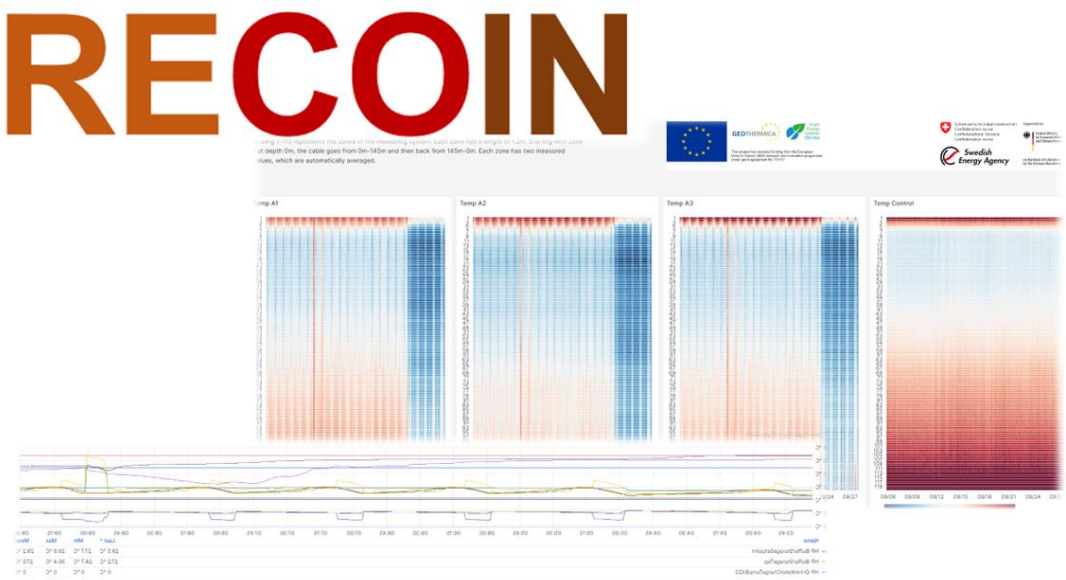
RECOIN

Real-time control and tuning of borehole heat exchanger fields for optimal integration in heating and cooling systems



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Zusammenfassung

Dieses internationale Projekt konzentriert sich auf die Verbesserung der Leistung von geothermischen Systemen durch die Entwicklung und Anwendung fortschrittlicher Überwachungs-, Modellierungs- und Regelmethoden. Es werden Echtzeitdaten und maschinelles Lernen genutzt, um die Energieeffizienz zu optimieren und die Umweltauswirkungen zu reduzieren. Ein einzigartiges EWS-Feld in Lausen, Schweiz, wird als Grundlage für die Untersuchung und den Vergleich verschiedener Leistungsüberwachungsmethoden genutzt. Dieses Feld verfügt über mehrere Jahre Messdaten, die bisher nicht interpretiert oder in Modellen reproduziert wurden.

Um eine detaillierte thermische Profilierung des geothermischen Systems zu erstellen, werden Sensoren an wichtigen Punkten installiert. Ein halbanalytisches Modellierungstool wird entwickelt, das verschiedene hochmoderne Verfahren zur BHE-Feldsimulation kombiniert und auch Echtzeit-Modellaktualisierungen ermöglicht.

Das vollständig trainierte Modell wird zur Vorhersage der Langzeitleistung des BHE-Feldes verwendet und dient dazu, den Wert verschiedener Datenquellen und Messauflösungen zu bewerten. Es wird auch eine datenbasierte Routine entwickelt, die für die Anwendung in einem nichtlinearen Model Predictive Control (MPC)-System geeignet ist. Als Innovation wird ein datenbasierter Emulator entwickelt, der maschinelles Lernen verwendet, um den "Modell"-Teil der MPC-Einheit zu repräsentieren. Dies macht das System effizienter und robuster.

Durch computerbasierte Simulationen werden Regelziele und -beschränkungen identifiziert, wobei sowohl kurzfristige als auch langfristige Leistungsschwankungen berücksichtigt werden. Ein Ziel besteht darin, den Primärenergieverbrauch zu minimieren, was gleichzeitig als Maßstab für die Reduzierung von CO2-Emissionen und Gesamtkosteneinsparungen dient.

Schließlich wird ein innovatives Regelgerät entwickelt, das mit dem emulatorbasierten Steueralgorithmus ausgestattet ist und beim Projekstandort Lausen getestet wird. Das Konzept wird auch an BHE-Feldern in Schweden und Deutschland demonstriert.

In diesem Zwischenbericht werden die Arbeiten am Projektstandort Lausen zusammengefasst. Diese fokussieren sich auf die Erstellung und Installation eines Monitoring- und Regelsystems.

Das Monitoringsystem wurde im Sommer 2023 installiert und erfasst über 1000 Datenpunkte mit einer Abtastrate von 30 Sekunden. Die Datenpunkte werden in einer zentralen Datenbank gespeichert und dienen dem internationalen Projektteam als Grundlage für die Modell- und Reglerentwicklung.

Résumé

Ce projet international se concentre sur l'amélioration des performances des systèmes géothermiques grâce au développement et à l'application de méthodes avancées de surveillance, de modélisation et de contrôle. Il utilise des données en temps réel et l'apprentissage automatique afin d'optimiser l'efficacité énergétique et de réduire l'impact environnemental. Un champ unique de champ de sondes géothermiques verticale à Lausen, en Suisse, est utilisé comme base pour étudier et comparer différentes méthodes de surveillance de la performance. Ce champ dispose de plusieurs années de données de mesure qui n'ont pas encore été interprétées ou reproduites dans des modèles.

Afin d'établir un profil thermique détaillé du système géothermique, des capteurs seront installés à des points clés. Un outil de modélisation semi-analytique sera développé, combinant différentes méthodes de pointe pour la simulation de champ BHE et permettant également des mises à jour de modèles en temps réel.

Le modèle entièrement entraîné est utilisé pour prédire les performances à long terme du champ BHE et sert à évaluer la valeur de différentes sources de données et résolutions de mesure. Une routine basée sur les données sera également développée pour être utilisée dans un système de contrôle

prédictif de modèle (MPC) non linéaire. En guise d'innovation, un émulateur basé sur les données est développé, qui utilise l'apprentissage automatique pour représenter la partie "modèle" de l'unité MPC. Cela rend le système plus efficace et plus robuste.

Des simulations informatisées permettent d'identifier les objectifs et les contraintes des règles, en tenant compte des variations de performance à court et à long terme. L'un des objectifs est de minimiser la consommation d'énergie primaire, ce qui sert également de référence pour la réduction des émissions de CO2 et les économies de coûts globales.

Enfin, un dispositif de contrôle innovant, équipé de l'algorithme de contrôle basé sur l'émulateur, sera développé et testé sur le site du projet de Lausen. Le concept sera également démontré sur des champs BHE en Suède et en Allemagne.

Ce rapport intermédiaire résume les travaux effectués sur le site de projet de Lausen. Ceux-ci se concentrent sur la création et l'installation d'un système de monitoring et de régulation.

Le système de monitoring a été installé en été 2023 et enregistre plus de 1000 points de données avec une taux d'acquisition de 30 secondes. Les points de données sont enregistrés dans une base de données centrale et servent de base à l'équipe internationale du projet pour le développement de modèles et de régulateurs.

Summary

This international project focuses on improving the performance of geothermal systems by developing and applying advanced monitoring, modeling, and control methods. Real-time data and machine learning will be used to optimize energy efficiency and reduce environmental impact. A unique BHE field in Lausen, Switzerland, is used as the basis for studying and comparing different performance monitoring methods. This field has several years of measured data that have not previously been interpreted or reproduced in models.

Sensors will be installed at key points to provide detailed thermal profiling of the geothermal system. A semi-analytical modeling tool will be developed that combines several state-of-the-art BHE field simulation techniques and also allows real-time model updates.

The fully trained model is used to predict the long-term performance of the BHE field and is used to evaluate the value of different data sources and measurement resolutions. A data-based routine suitable for use in a nonlinear Model Predictive Control (MPC) system is also developed. As an innovation, a data-based emulator is developed that uses machine learning to represent the "model" part of the MPC unit. This makes the system more efficient and robust.

Computer-based simulations are used to identify control objectives and constraints, taking into account both short-term and long-term performance variations. One goal is to minimize primary energy consumption, which also serves as a metric for reducing CO2 emissions and overall cost savings.

Finally, an innovative control device equipped with the emulator-based control algorithm will be developed and tested at the Lausen project site. The concept will also be demonstrated at BHE fields in Sweden and Germany.

This interim report summarizes the work at the Lausen project site. These focus on the creation and installation of a monitoring and control system.

The monitoring system was installed in the summer of 2023 and collects over 1000 data points with a sampling rate of 30 seconds. The data points are stored in a central database and serve the international project team as a basis for model and controller development.

Contents

Abbreviations

PIE	PI Electronics AG. Swiss project leader
GEX	Geo Explorers AG. Swiss project partner
MLU	Martin Luther University Halle-Wittenberg. Project leader
BHE	Borehole heat exchanger

1 Introduction

1.1 Background information and current situation

Context: The shallow ground is an attractive energy source for several reasons: Geothermal energy is available everywhere and, by drilling boreholes to depths of 100 m and more, substantial volumes of the ground can be accessed. In comparison to the use of air by competing air-source heat pumps, energy density is orders of magnitude higher in the ground and the subsurface temperature is much less variable. However, heat transport in the ground is also much slower, dominated by conduction that is sometimes accompanied by forced convection (i.e., advection) through groundwater flow. The slow thermal transport processes in the ground are crucial when operating BHEs, which are the ground elements of ground-source heat pump systems for energy supply and storage for decades. Imbalanced energy extraction or injection causes slowly evolving **thermal anomalies which grow in size and intensity**, often associated with gradual deterioration of entire system performance. This also means that thermal regeneration is equally slow, with recovery times in the same range as the system operation time and longer[1]. Regulations on thermal anomalies in the ground thus are commonly precautionary, allowing only small induced ground temperature changes and restricting the lateral expansion of thermal anomalies[2]. This is not only due to the long time that would be needed for thermal regeneration, but it is also for saving soil and groundwater ecosystems, and for limiting the ground volume used per installation. Neighbor conflicts due to potentially interfering adjacent systems have to be avoided[3]. Especially in Central European cities and cold climates, caution is growing with respect to thermal overuse of urban ground and new solutions are demanded for **better description and control of shallow geothermal development**[4].

BHE field simulation and planning: Understanding the thermal processes in shallow ground is fundamental to regulations and urban subsurface energy plans, and it is crucial for optimal design and operation of ground-source heat pump systems. Therefore, there are continuously improving computer-based **simulation and model-based planning tools** available. These enable prediction of ground temperature evolution and of geothermal system performance over the entire lifetime. A plethora of different models to simulate BHEs individually or as element of a BHE field exists, and a complete picture of all available alternatives cannot be provided here. Instead, focus is set on those ones closely related to the planned research of this project. Eskilson (1987)[5] introduced the so-called g-functions, which represent dimensionless response functions of heat step impulses, determined initially by means of simulations with radially symmetric two-dimensional numerical models. By superimposing g-functions, transient heat extraction or injection at a BHE is simulated and borehole wall temperature depending on heat rate per borehole length is determined. Multiple BHE fields are characterized by g-functions derived for given geometries or based on superimposed single BHE g-functions. Planning software such as Earth Energy Designer (EED)[6] utilizes a library of g-functions to determine required BHE properties and to suggest the best choice from a finite set of variants. To this day, the number of available g-functions and related computation procedures is growing continuously, considering further geometries and variable conditions. A premise for development of g-functions is always a physical model for validation.

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There are two major categories of **process-based BHE modeling** techniques, namely numerical and analytical. Numerical model platforms commonly offer an enormous flexibility[7,8], on the expense of a relatively high computational demand. This demand, including the data hunger and the time-effort to build and calibrate numerical models, limit their applicability in practice. Therefore, numerical solutions have been combined with analytical models, or pure (semi-)analytical models such as line-source based solutions or thermal capacity and resistance models have been proposed[9,10]. Analytical models are appealing due to their computational efficiency, their easy handling, and thus their suitability especially for simultaneous simulation of multiple BHEs. Using spatial and temporal superpositioning (following Duhamel's theorem), they are considered particularly desirable for variably spaced BHE fields[11].

During recent years, substantial advancements have been presented and available line-source solutions are able to account for the effect of horizontal groundwater flow[12,13], to efficiently resolve short-term heat exchange with the ambient ground[14]_ENREF_29, to account for layered heterogeneity of the ground[15], vertical temperature variation[16], geothermal and ground heat flux[10,17], inclined boreholes[18], as well as for parallel, serial, and hybrid application of BHEs for simultaneous heat injection and extraction[19]. Available models are computationally efficient, have specific strengths but are of limited capacity especially for addressing several complexities at the same time. For example, there is no line-source model available that can account for (layered) ground heterogeneity, while also considering complex axial BHE effects (e.g., accelerated ground heat flux in urban environments) and short-term ground heat transport. As short-term heat exchange influences the proximity of the BHE and as it is mainly controlled by the properties of the borehole (pipes, grout), ground heterogeneity may play a minor role. In practice, however, boreholes are not perfect cylinders. If backfilled, grout thickness and thermal properties may vary with depth and thus artificial heterogeneity may be introduced when implementing the BHE. The consequences of these may be overestimated by short-term tests, whereas the role of ground heterogeneity will only become apparent during long-term operation.

Analytical solutions commonly presume a specific constant heat extraction rate along the borehole wall, which may vary in a BHE field[20]. This is a convenient but simplifying assumption, which is also inconsistent with the original condition for Eskilson's g-functions. Here, the temperature along the borehole wall was assumed to be constant, given that the inlet temperature is the same for all BHEs,

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[8] Boockmeyer, A. & Bauer, S. (2016) Efficient simulation of multiple borehole heat exchanger storage sites. *Environmental Earth Sciences* 75.
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[18] Lazzarotto, A. (2016) A methodology for the calculation of response functions for geothermal fields with arbitrarily oriented boreholes–Part 1. *Renewable Energy* 86.
[19] Belzile, P., Lamarche, L. & Rousse, D.R. (2016) Semi-analytical model for geothermal borefields with independent inlet conditions. *Geothermics* 60.
[20] de Paly, M., Hecht-Méndez, J., Beck, M., Blum, P., Zell, A. & Bayer, P. (2012) Optimization of energy extraction for closed shallow geothermal systems using linear programming. *Geothermics* 43.

which is more realistic for common parallel BHE arrangement. Several authors[11,18,21,22] recently presented procedures (iterative, using Laplace transforms, etc.) to adjust the specific heat extraction rate per borehole or borehole segment to converge to a constant borehole wall temperature. This is especially relevant for thermal interaction within borehole fields, where the assumption of a constant specific heat extraction rate may lead to overestimation of Eskilson's g-functions[20,23], and thus of the temperatures experienced in the field.

Uncertainties in simulation and prediction: In fact, despite the efforts to improve modeling techniques, their predictive capabilities are not only determined by the conceptual maturity, but by the accuracy of the estimated model parameters, many of which are related to the subsurface. The ground, however, represents a highly variable, hidden environment. There are some in-situ investigation techniques available such as the thermal response test (TRT)[24], borehole samples may be inspected and even hydraulic tests may be carried out, but the exact **ground properties** commonly remain unknown. Validation of BHE models thus is a key issue in current research[25,26]. Current BHE design guidelines neglect the spatial **heterogeneity** of the ground and instead treat it as a preferably homogenized medium (e.g., VDI 4640[27]). This may be justified in some cases, especially in case of moderate thermal and hydraulic parameter heterogeneity. This may however be critical when heterogeneity is significant. As an example, Beck et al. (2010)[28] simulated and optimized a BHE field in a hydraulically heterogeneous aquifer (Fig. 1). This synthetic example represents a crude and arbitrary simplification of conditions in reality, as vertical heterogeneity is ignored here, and layered heterogeneity is more common in natural systems than in horizontal direction. Still, it nicely illustrates the influence of heterogeneity, in case of **groundwater flow,** on the evolution of ground temperature. Apparently, a complex picture of superimposing thermal anomalies evolves, and description is hardly feasible without perfect insight into the ground conditions. Perfect insight however is impossible, and this means dealing with **uncertainty** that can be mitigated by investigation. As detailed ground investigation is costly, safety factors may be applied instead by, for example, (slight) increase of required total borehole length. However, this adds to the total system costs. Even if expected or mean

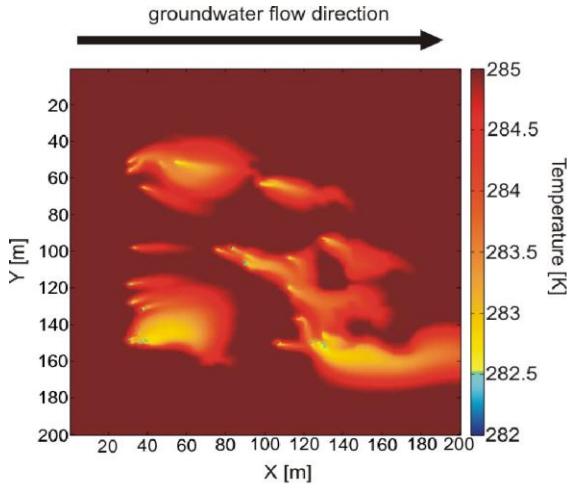

Figure 1: Top view of ground(water) temperature anomalies evolving from a BHE field simulated by two-dimensional numerical model. This arbitrary example assumes hydraulic heterogeneity and a square lattice field of 6 x 6 BHEs with 10 m distance, positioned in the center of the figure. Further details can be found in Beck et al. (2010).

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[22] Laferrière, A., Cimmino, M., Picard, D. & Helsen, L. (2020) Development and validation of a full-time-scale semi-analytical model for the short- and long-term simulation of vertical geothermal bore fields. *Geothermics* 86.
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ground properties are considered sufficient for technological design, these still may be difficult to acquire; also, average parameter values are uncertain or only representative for the immediate surrounding of the borehole (e.g., derived from TRTs). Finally, the uncertain ground properties are not the only critical aspects of proper ground-source heat pump operation. Commonly, only rough predictions of the seasonal energy requirements are possible, which among other factors, increase the uncertainty of entire ground-source heat pump system performance. This can be especially relevant when large-scale BHE fields are operated that rely on well-described conditions and which induce large-scale thermal anomalies.

This is where this project is offering a new strategy. Our idea is to exploit not only information available before starting the heat pump but especially *during* the operation phase. In fact, the insight from **ground temperature monitoring during operation**, even if done just at the outlet of the BHE tubes, is the most immediate insight into the ground thermal conditions relevant for the geothermal system. This can be interpreted as conducting a continued TRT. Moreover, observations can be made over long time periods. In contrast to numerous related studies on optimal heating energy supply[29,30], the focus of this project is on **optimal control based on an improved understanding of the physical conditions in the ground and learning of the observed heat/cold demand evolution**. Ultimately, optimal performance conditions are achieved by controlling individual BHEs in the field as well as by integrated control of further heat/cold sources in an energy network. Recent scientific work revealed the opportunities of optimal design and control for practical BHE application, which has been addressed from different perspectives.

Design optimization and control techniques: As pointed out by Cimmino & Bernier (2014)[31], BHE field **design optimization** is rarely seen in design tools that are utilized during the planning phase. Common practice is to identify the best variant (BHEs geometric arrangement, depth of boreholes) from a given set of alternatives[6], or to conduct sensitivity analyses to determine optimal configurations[31]. Especially the combination of simulation with mathematical optimization or control algorithms is a nearly unexplored field. In recent work, with a focus on the optimal system in the ground with lowest thermal impact, mathematically optimized BHE positioning and individual BHE heat transfer (i.e., load) control strategies were proposed[20,28,30,32,33,34,35,36]. Current reviews summarize the state of the art in this field[37,38]. When control or “co-design”, i.e., design and control, is the purpose, only few techniques have been presented and major objectives include optimizing the expected share of geothermal heat or cold, and of another source (e.g., gas fired boiler) or storage medium in so-

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called hybrid systems[39,40]. Atam & Helsen (2016b)[41] conclude that "*co-design has a huge potential to give better results for the overall design and control problem. However, both its formulation and its solution may be very hard, if not impossible, for complex systems*."

Available **control techniques** of a full hybrid borehole energy storage system[42] or single BHEs integrated in a heating/cooling system[43] are based on predefined, often over-simplified ground heat transfer models. The models are deterministic representations without any uncertainty in BHE performance and in the description of the ground thermal regime. There has been a special emphasis on capacity control of multi-stage/on-off heat pump operation[44,45], in particular for small-scale systems. Less focus is set on efficient solution procedures such as dynamic programing, applied for different weather scenarios[42], or on **model predictive control (MPC)**[43]. MPC is an advanced control method, which consists of calculating the optimized values of the manipulated variables at the current time slot subject to the process and input-output constraints, while keeping future time slots in account. This is achieved by calculating an optimal sequence of control steps ("control moves") over a finite time horizon, but only implementing the first control move, followed by optimizing again, repeatedly, as the time horizon is advanced by one step at each computation. MPC has recently been shown to offer improved building energy performance, compared to other techniques such as standard rule-based control laws in a broad range of applications.

Ikeda et al. (2017)[46] stress the lack of control techniques that account for the thermal conditions and response of the ground. They simulate a BHE field by infinite line sources and apply a heuristic optimization technique, a variant of differential evolution[20], to derive an optimal deterministic control strategy for a hybrid system. A crucial issue is the nonlinearity (and sometimes non-convexity) of the formulated problem, which is difficult to solve by standard dynamic programing or related techniques (such as nonlinear MPC). Recently, it has been demonstrated based on a theoretical study, that model-based BTES control can save up to 20% of CO_2 emissions when applied to an energy network supplying the Empa research campus in Dübendorf, Switzerland[9]. Thus far, however, no versatile methodology has been presented that offers **adaptive BHE control under realistic ground conditions**, that is, when ground thermal conditions and thus the thermal response of the ground is *uncertain*. The performance of model-based controllers depends mainly on the accuracy of the models. A mismatch between the model and the actual process can deteriorate the performance of the model-based controller. Combining the method of **moving horizon estimation (MHE)** with MPC is a powerful method to address model inaccuracy. MHE can provide robust output feedback to MPC, estimating unknown states or parameters by minimizing discrepancy between previous model predictions and actual measurement outputs. Just recently, Cupeiro Figueroa et al. (2021)[47] opened a new door by a virtual study based on a real BHE field in Brussels. They revealed the suitability of both MHE as well as alternative data assimilation methods such as the time-varying Kalman filter to presenting the mean temperature of a BHE field simulated by a linear model. Clearly, the logical next

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[42] De Ridder, F., Diehl, M., Mulder, G., Desmedt, J. & Van Bael, J. (2011) An optimal control algorithm for borehole thermal energy storage systems. *Energy and Buildings* 43.
[43] Atam, E., Patteeuw, D., Antonov, S.P. & Helsen, L. (2016) Optimal control approaches for analysis of energy use minimization of hybrid ground-coupled heat pump systems. *IEEE Transactions on Control Systems Technology* 24.
[44] Cervera-Vázquez, J., Cazorla-Marin, A., Montagud, C. & Corberán, J.M. (2017) Optimal control and operation of a GSHP system for heating and cooling in an office building.
[45] Madani, H., Claesson, J. & Lundqvist, P. (2011) Capacity control in ground source heat pump systems part II: Comparative analysis between on/off controlled and variable capacity systems. *International journal of refrigeration* 34.
[46] Ikeda, S., Choi, W. & Ooka, R. (2017) Optimization method for multiple heat source operation including ground source heat pump considering dynamic variation in ground temperature. *Applied Energy* 193.
[47] Cupeiro Figueroa, I., Cimmino, M., Drgoňa, J. & Helsen, L. (2021) Fluid temperature predictions of geothermal borefields using load estimations via state observers. *Journal of Building Performance Simulation* 14.

step is considering conditions with realistic ground thermal behavior, including optimal control and predictive uncertainty in long-term load evolution (i.e., the heat/cold demand).

For control applications involving BHE fields, it is crucial to have simple models in the state-space form which predict the borefield outlet temperature[43]. As ideal complement to adaptive system control in practice, online-learning of data-driven models (emulators) such as artificial neural networks (ANNs) has been proposed for BHE simulation[48,49] and predictive control[50], which however commonly have first been trained with deterministic process-based models that may deviate to some extent from the conditions in the field. Therefore, such data-driven models may be beneficial but can hardly replace calibrated process-based models to characterize evolution of system performance in the long-term project phase (i.e., they cannot extrapolate). Being black boxes, they offer limited insight into the true physical processes in the ground. However, accurate prediction of (at least) BHE field outlet temperature is important for performance optimization, to prevent thermal build-up during summer periods and depletion of the borefield or to prevent freezing of the circulating fluid during winter periods[43].

In essence, the theoretical work of the last decade reveals the potential (i) of single ground-source heat pump control (e.g., for minimization of total electricity consumption), (ii) of multiple BHE field control (e.g., for prevention of local thermal extremes in ground and maximization of seasonal performance factor), and (iii) of hybrid applications with BHEs combined with supplementary energy source (e.g., for maximization of total renewable energy use in network and total CO_2 emission savings). MPC is revealed to be favorable considering that it has the ability of anticipating future events (to minimize predictive uncertainty), and it also can take control actions accordingly. In contrast to these promising findings, field application is scarce and only reported for very few cases or for specific components. For instance, with respect to (i), single ground-source heat pump control was implemented for an office building in Valencia[44]. Regarding (ii), in current practice, BHE operation in a larger field is sometimes executed based on zonal sections that are loaded or unloaded separately. To the best of our knowledge, control of such configurations in practice however is not strategic, predictive and/or integrative. Clearly, **no prototype or market-ready control devices exist for adaptive BHE field operation** under uncertainty and its optimal integration in a heating/cooling system or network.

[48] Pasquier, P., Zarrella, A. & Labib, R. (2018) Application of artificial neural networks to near-instant construction of short-term g-functions. *Applied Thermal Engineering* 143.
[49] Shoji, Y., Katsura, T. & Nagano, K. (2022) MICS-ANN model: An artificial neural network model for fast computation of G-function in moving infinite cylindrical source model. *Geothermics* 100.
[50] Gang, W., Wang, J. & Wang, S. (2014) Performance analysis of hybrid ground source heat pump systems based on ANN predictive control. *Applied Energy* 136.

The *scientific challenges* are (i) to identify a suitable layout and level of detail needed for a BHE field **monitoring system** and the **most decisive parameters for optimal control in practice**; (ii) to develop a new model-predictive **real-time control algorithm**; (iii) to elaborate a **simulation framework** that is sufficiently flexible for representing complex thermal ground conditions, while being able to depict short-term operational temperature fluctuations as observed during monitoring; (iv) to develop a data-based **emulator** that relies on concepts from the field of deep learning to replace process-based simulation as proxy and facilitate efficient real-time control in practice.

The *technical challenges* are (i) to develop the **control device hardware and software** as a reliable and autarkic technology; (ii) to **implement and validate the control device** in a BHE field and realize ideal interaction with temperature/flow monitoring and regulation points; (iii) to achieve a **versatile technological design** of the monitoring and control device that is transferable and easily configurable for a broad range of other BHE fields; (iv) to establish the **basis for combined BHE field and heat pump operation control** for full heating/cooling system optimization.

The *commercial challenges* are (i) to develop a control device that – together with the monitoring system – is **robust and sufficiently cheap** to justify general application to any BHE field; (ii) to **more than compensate additional costs for the control device** by revealing transparent long-term economic advantages; (iii) to develop a device that can be implemented in **new and as retrofit in existing fields**.

1.2 Purpose of the project

The focus of this project is on multiple **borehole heat exchanger (BHE) fields**, which are implemented for heat and cold supply, or as **borehole thermal energy storage systems** (BTES). A BHE is considered a well-known geothermal technology, which is planned in practice based on standardized procedures. There exist decades of experience with proper design concepts for estimating suitable borehole lengths and coupling the ground devices to an above-ground heat pump system. In contrast to the standardized design and installation phase, little attention is given to the operation phase. This is due to the common workflow of geothermal system application in practice: geothermal system designers, drilling and installation engineers, and/or HVAC planners are engaged to implement a technology based on the expected conditions in the subsurface, the expected heat and cold loads, as well as to a presumed static seasonal operation mode and user behavior. However, no matter how well this is accomplished, *expected* conditions often deviate significantly from the real conditions. Therefore, BHE field **design and operation can hardly be optimal in practice**. Uncertainties may be dealt with by (empirical) safety factors, which mean additional costs that ultimately compromise the market competitiveness in comparison to alternative heating and cooling devices. Moreover, as the optimal system for a given site is not known, the owners of a BHE field cannot judge its improvement potential.

In fact, no need is even seen for improvement after commissioning of a system. However, consequences of **suboptimal BHE functioning** by, e.g., overexploitation of available ground heat become apparent mainly at later stages long after the planning phase, after years of cumulating thermal deficits. Then, the BHE field is cost-inefficient, remediation of failed systems at later stages of operation becomes challenging, expensive and inconvenient. What is more, failed cases hamper the **reputation** of BHEs as robust and reliable devices.

The current status of the planned control procedure is that theoretical simulations and coupled-simulation and optimization have already been carried out to reach technology concept formulation according to TRL 3. In this project, the target at finalization will be **TRL 7**. During the course of RECOIN, the simulation, emulation and control elements and hardware devices will be developed and validated in the computer lab (TRL 5). The monitoring concept will be configured, extended, tested and demonstrated in relevant environment, i.e., at a field site in Switzerland (TRL 5–7). The full control system will be validated and demonstrated in relevant environment as well as in operational environment by application to field cases with BHE fields in Switzerland, Sweden and Germany (TRL 6–7).

1.3 Objectives

The overall aim of RECOIN is to develop a new procedure and device for automated control and adjustment of the optimal operating parameters of BHE fields during long-term operation in practice. The underlying hypothesis is, that BHE systems can be planned and in particular operated in a more efficient and transparent way than dimensioned and realized so far. Theoretical studies revealed substantial improvement potentials (savings of CO_2 emissions and primary energy consumption), which have not been realized in field application. A crucial gap is the development of a versatile control device that is implemented in a BHE field and demonstrates the benefit of continued (individual/zonal/hybrid) BHE tuning for overall technico-economic system optimization.

Subordinate objectives are:

This collaborative project will further develop the **theoretical basis**, build up the **hardware and devices** and establish the **design concept** for optimal integration of controlled modern BHE fields in heating and cooling networks as well as for being used in BTES or hybrid systems. We can rely on substantial progress in recent theoretical science as well as in own pioneering, award-receiving recent work that has initiated the proposed new strategy of **real-time control of shallow geothermal systems**. Considering the crucial uncertainties that exist when implementing BHE fields for long-term application of decades, it is remarkable that the potential of continued learning during operation and tailored monitoring has not been tapped in practice, yet. Clearly, expenditures need to be minimized since, especially during early times of operation, likely technological deficits are commonly not apparent. Furthermore, available scientific works are focused on individual technological components, they represent theoretical applications with virtual realities of no uncertainty, and they do not address at all the complexities related to the technical realization of the proposed control system. There is a clear benefit from individual BHE or zonal control, which becomes apparent when BHE fields are simulated with uniform operation modes, especially in complex environments with ground heterogeneity and groundwater flow. This also becomes apparent when comparing predicted heat and cold transfer of BHE fields with those that are executed in practice. Now, GEOTHERMICA opens the door to build up on the complementary international expertise from geologists, energy and information engineers and data acquisition specialists for **getting it into practice**. This step calls for several methodological and technological innovations that are addressed in this project.

RECOIN will execute a **complex analysis for achieving a simple solution**: A fundamental principle of this project is to capture and understand the complexity of the performance of a real BHE field in detail in order to be able to identify those few key elements that are necessary for control application to any BHE field in practice. By carefully resolving the thermal conditions evolving in the subsurface, the processes that are relevant for long-term performance will be understood. By rigorous virtual testing of emulator and control algorithms based on long-term evolving real conditions (resembling the concept of a “digital twin”), those few control targets will be identified that are most beneficial in

practice. By learning from small-scale field validation and demonstration with a prototype, the crucial step towards market maturity of the control system will be achieved. Ultimately, by the planned monitoring and computer-based assessment, a control system device can be developed that will be installed causing moderate expenditures during BHE field construction and which ensures long-term security of optimal BHE field integration in a heating/cooling system/network. We expect that moderate additional expenditures are reasonable, as the entire control system is made of ordinary elements such as a control device, temperature sensors and flow-regulating valves. Moreover, instead of “full” monitoring and control, RECOIN will identify a level that is desirable.

Clearly, there is still a long path to standardized application of such system, as there exists no concept of efficient control. RECOIN will develop the prototype and pave the path for efficient, failure-free control by identifying the elementary and most cost-efficient targets of monitoring and control. Individual BHE control and zonal control (of BHE groups) will be examined, and the practical basis will be established for integrating BHE control into the control system of an energy supply network. **BHE fields can then be optimally regulated together with multiple energy source and buffer elements such as in hybrid applications with temporal heat storage and solar energy sources** that could be strategically used for recharging an exhausted BHE field during summer periods[34].

We are not aware of a competitive or similar project dedicated to BHE-field controller development. In the related field of research, however, the theoretical potential has been identified. The number of articles that have been produced on this topic shows that there is great interest in this application and there is a shared view of the potential. Yet, the application of MPC for BHE-field control is not used in practice as most of the available heat pumps are operated using rule-based strategies, and to the best of our knowledge **no real-time and MPC-based control systems are under development**

In contrast to related theoretical work, a major innovative aspect of the project is the combination of the application of the **real-time MPC methodology to BHE-field zoned or individual control** and the ability of the **emulator** (that feeds the MPC) to adapt to the incoming measurement data. These features combined together provide flexibility and robustness in the optimization of the operation of the field, yielding great potential for performance improvement. The most remarkable step forward by this project will be the development and demonstration of a prototype of the entire control-system together with an attuned monitoring layout. The theoretical, manufacturing and experimental activities covered by the Swiss subproject will be key to this innovation.

The market gap identified in RECOIN is a versatile MPC controller, which is implemented/retrofitted at a BHE field and provides continuous adjustments for an overall technical-economic optimization of the system. Thus, the developed component consists of an interaction between software, algorithms and control technology, enabling the automated monitoring and simultaneously adapted management of the probes. Both a **software environment and the complementary hardware device are being developed** and the project innovation focuses on both domains. On the software side, model tools will be merged and utilized for an application in the controller. So far, algorithms are not applicable to practical applications (operational phase of BHE), but limited to the pre-planning stage. Smart control of BHE fields as in-situ operation optimization brings new challenges to those necessary tools. Within the software, these have to be adapted for dynamic and continuous operation and mapped with interfaces. Key parameter derivation is another key innovation here, given the computing costs involved. A flexible counterpart for the resulting software has to be designed from scratch in the hardware development, since such a device is not available yet. This is the second innovation focus involving various challenges, including special sensor technologies, computational capacity requirements and unfavorable conditions at the operating locations. In parallel, subsequent availability for series production must also be considered, in that flexibility with regard to dimensioning and boundary conditions is required.

In summary, the innovative elements of RECOIN are listed below:

This list of major innovations outlines individual steps that are required to **achieve the full controller implementation**. While the controller device represents the ultimate novelty of the project, some innovations result from adoption of existing complementary methods to our field of research and development. These are, in particular, machine learning and MPC algorithms, where no new theoretical developments are foreseen rather than achieving a step forward by being utilized for the proposed novel application theme. A major hurdle will be the complications from transferring recent developments from the perfect *theoretical world*, which has been considered by most previous fundamental research work, into practice, which involves not only uncertainty in all system parameters and in prediction, but also technical challenges (such as device implementation, real-data collection and processing) not envisioned so far.

A direct commercialization within the project is not foreseen, as it focuses on **prototype development**, **testing, validation, and refinement**. Within this project, starting with a prototype tested at several locations, a later broad market availability is guaranteed with only a few more activities. Hardware and software are designed as a composite and may finally be commercialized together. This will be accomplished in a follow-up project by the consortium. During RECOIN, the essential codes developed for the emulator and the real-time control will also be made **available as open libraries** for being further developed and tested by colleagues. Furthermore, decoupling the software as a sub-component of larger systems synchronized with heat pump control will be possible, which is considered most beneficial for integrated large-scale heating/cooling optimization.

The key targets and planned accomplishments of RECOIN are summarized as follows:

The role of the **Swiss subproject** is the fundamental development of a novel control device (main task by national project leader PIE) as well as monitoring at the **BHE field at *Lausen*** (CH). At this unique site, detailed hydrogeological insight exists, performance of the ground-source heat pump as well as the subsurface thermal conditions of the small 3-BHE field site have been monitored (depth-resolving by distributed thermal sensing by fiber optics/DTS, temperature sensors, etc.) for more than five years by GEX. The Swiss partners will be focused on establishing the experimental proof of concept of the control technique based on the developed new device and prototype validation according to TRL 3-6. By providing the monitoring basis for the theoretical assessment of the subsurface thermal regime, and of the performance of a realistic BHE field (GEX), all model- and controller-based developments will be supported. Based on this, during the present project, the monitoring system is expanded (temperature loggers at BHE outlets, full-year DTS coverage, etc.). By manufacturing and first-time experimental testing of a novel control device (PIE), the fundamental work will be carried out for subsequent prototype field installation and application by the partners at small scale field sites. The Lausen site will serve as reference for deriving a recipe of optimized, cost efficient monitoring design, while also representing the major reference site for the control system developments of this project. This can only be derived by comparing different information levels, and thus detailed site monitoring at Lausen is needed. In contrast, based on the findings of Lausen, the monitoring systems of the two further application sites (*Wisdome*, Stockholm; *Food Campus*, Berlin) will be simplified, tuned and adjusted to the site-specific conditions.

2 Description of facility

2.1 Project locations

3 test objects are available for the development and evaluation of the new control system. These are different in size, use and technical implementation of the heating system. The objects are located in Switzerland, Germany and Sweden. For this report, the focus is on the Swiss object.

2.1.1 Apartment house, Lausen Switzerland

Figure 2 – Lausen view front building

The apartment house, built in 2016, comprises a total of 8 residential units and is heated using a heat pump along with three 145-meter deep bore hole heat exchangers (BHE). In addition to the three active BHE, a fourth monitoring borehole was created for the purpose of monitoring the ground. This property is part of the project “GEO4D-Lausen”[51] , which is supported by the Federal Office of Energy.

[51] App 1: annual report GEO4D-Lausen - https://www.aramis.admin.ch/Texte/?ProjectID=35865

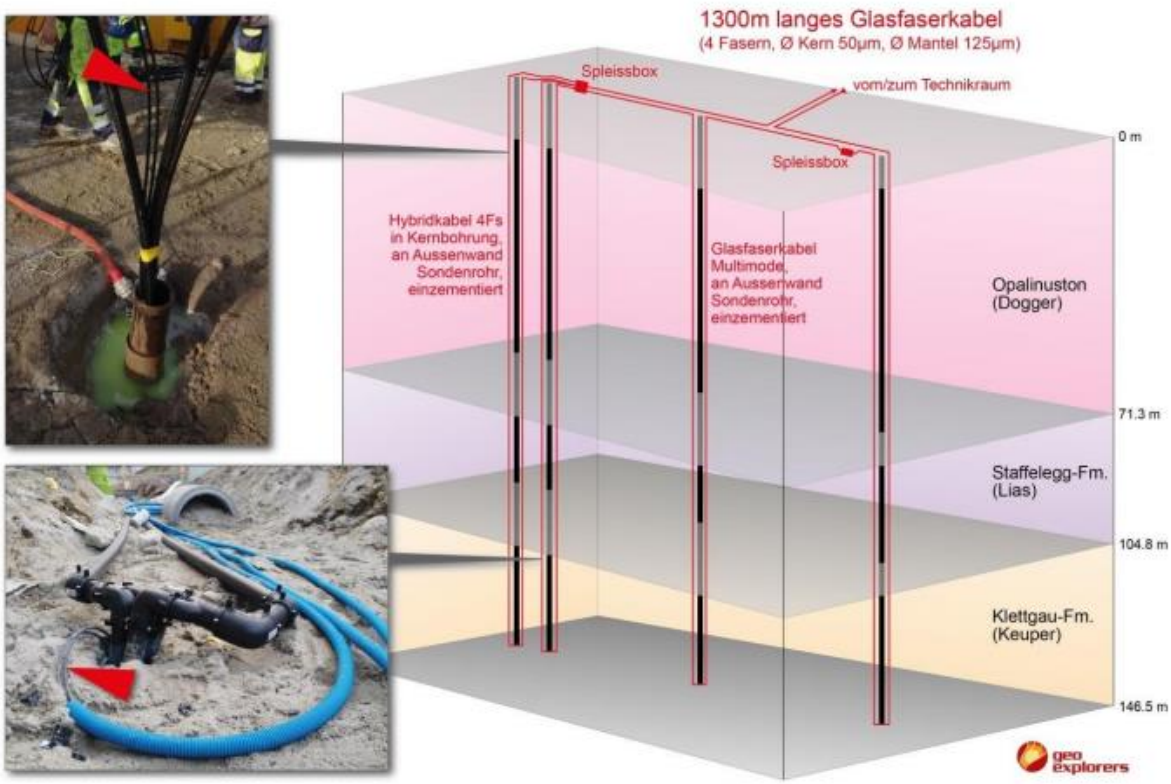

Figure 3 – Extract annual report project "GEO4D-Lausen"

2.1.2 Wisdome, Stockholm Sweden

Wisdome Stockholm is a new building part of Tekniska Museet that is planned to be a new arena for learning and experience through immersive projections, unique content and labs for deeper understanding. Including and presenting our control system as part of the museum will be an ideal case of public outreach and for reaching non-professional recipients. Here, public audience can learn about the developments of RECOIN. The BHE field site is under construction, and it is expected to be finished during 2023. Cooling and heating of the entire building will be supplied by means of geothermal heat pumps. The site will be equipped with monitoring tools measuring energy flows exchanged starting from the geothermal side of the system, passing through the heat pumps and going all the way to the energy delivered to the building. Additionally, a selected borehole will be equipped with fiber optic cables (DTS) for detailed in-situ measurements along the borehole depth, comparable to the Lausen site.

2.1.3 Food Campus, Berlin Germany

The Food Campus covers a 14,000 m² large construction site. It will offer a floor area of 40,000 m² and divisible production areas and laboratories for both emerging and established companies from the food industry. Thus, it represents a highly visible center of sustainable food research and is highly interested in integrating and showcasing modern concepts of renewable energy integration. A key objective of the innovative energy concept at the site is to cover heating and cooling demands by renewable energies, predominantly shallow geothermal energy. A BHE field of up to 166 boreholes will be installed in 2023-2024 to a maximum depth of 45 meters each. Given the heterogeneous utilization of energy, the hydrogeological and geothermal conditions, this location provides perfect conditions for testing the monitoring and control system developed in RECOIN. There, partners will be able to comprehensively test the project's innovation in one subsection (10-20 BHEs) of the BHE field.

2.2 Overview Lausen

This chapter shows an overview of the local situation in Lausen.

The boreholes (*Figure 4* in red) are located in front of the main entrance. “KB” (*Figure 4* in violet) is the control hole. The hydraulic distribution is located in a shaft (*Figure 4* green dot). From this shaft, two pipes lead to the technical room where the heating pump is installed (*Figure 4* “WP”).

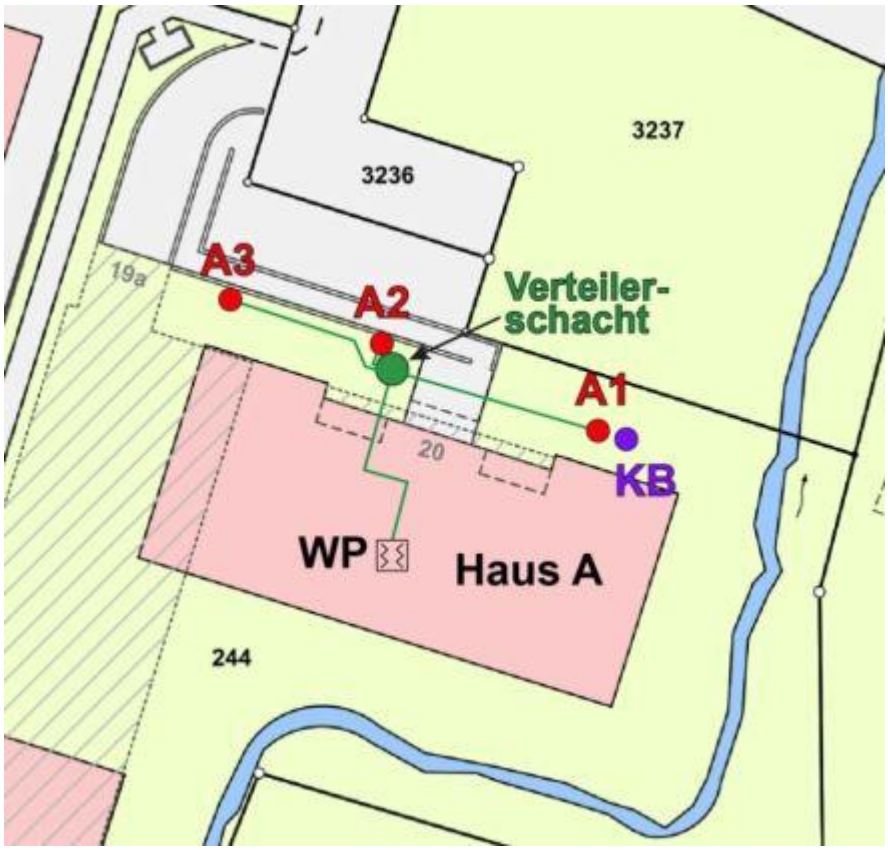

Figure 4 – Overview BHE

Figure 5 Figure 6 will show the heating pump and the DTS System to measure the temperature in backfill of the BHE.

Figure 5 – Heating pump

Figure 6 – DTS System (BHE temperature measurement system)

Figure 7 – Control hole (Figure 4 violet)

Figure 8 – Manhole (Figure 4 green)

2.3 Installed Sensors Lausen

The following describes which data points are recorded at the Lausen installation site. In total, over 1000 data points are periodically recorded and stored.

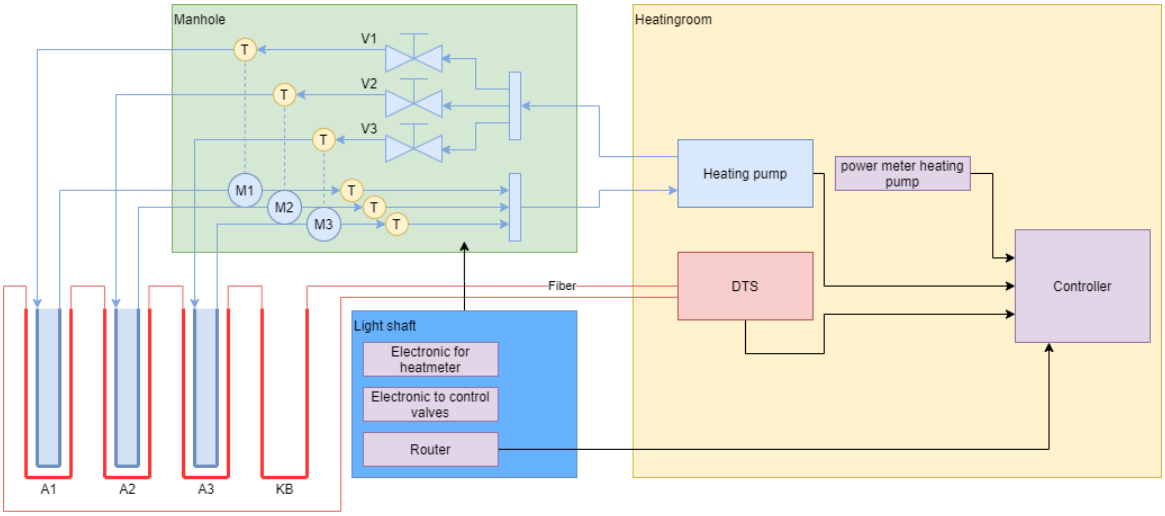

Figure 9 – Schematic overview sensors

The data acquisition includes the energies and temperatures per BHE (chapter 2.3.1). This is ensured with three energy meters in the manhole (chapter 2.3.5). With the bus integration of the heat pump (chapter 2.3.4), all relevant data points of the heat pump can be queried. The additionally installed energy meter records the electrical power of the heat pump (chapter 2.3.2). The temperatures of the BHE backfill are recorded with the DTS system (chapter 2.3.3). This measures the BHE temperature every 1.2m via a 1300m long optical cable. The flow rates of the individual BHE can be regulated via the three additionally installed actuators (chapter 2.3.5).

2.3.1 Heatmeter for boreholes

A product from the Micronics company was used for the heat meters. This allows subsequent installation of the meters on a pipe. The meters consist of an electronic unit, ultrasonic sensors and two temperature sensors.

The meters have a ModbusRTU interface. This was connected to the LTE router, which acts as a gateway ModbusRTU to ModbusTCP. This allows the values of the energy meter to be read via TCP/IP.

One disadvantage of the sensors used is that they cannot detect heat and cold energy simultaneously ex works. For this reason, the cooling energy (in the case of freecolling operation) is calculated from the volume flow and the temperature difference in the controller itself.

Figure 10 – Heatmeter in the manhole

Figure 11 – Heatmeter

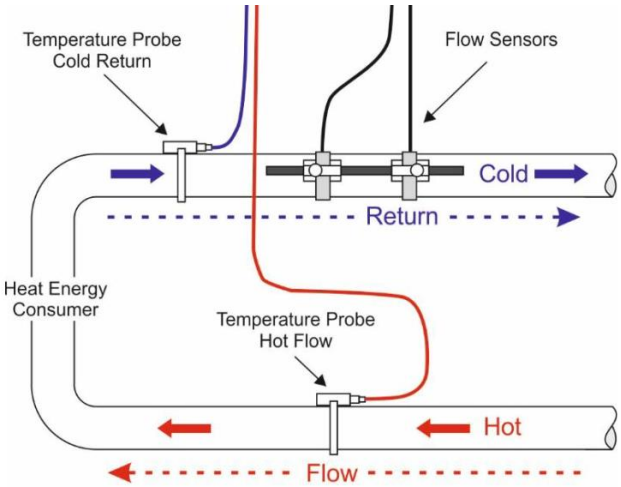

Figure 12 – Heatmeterr installation

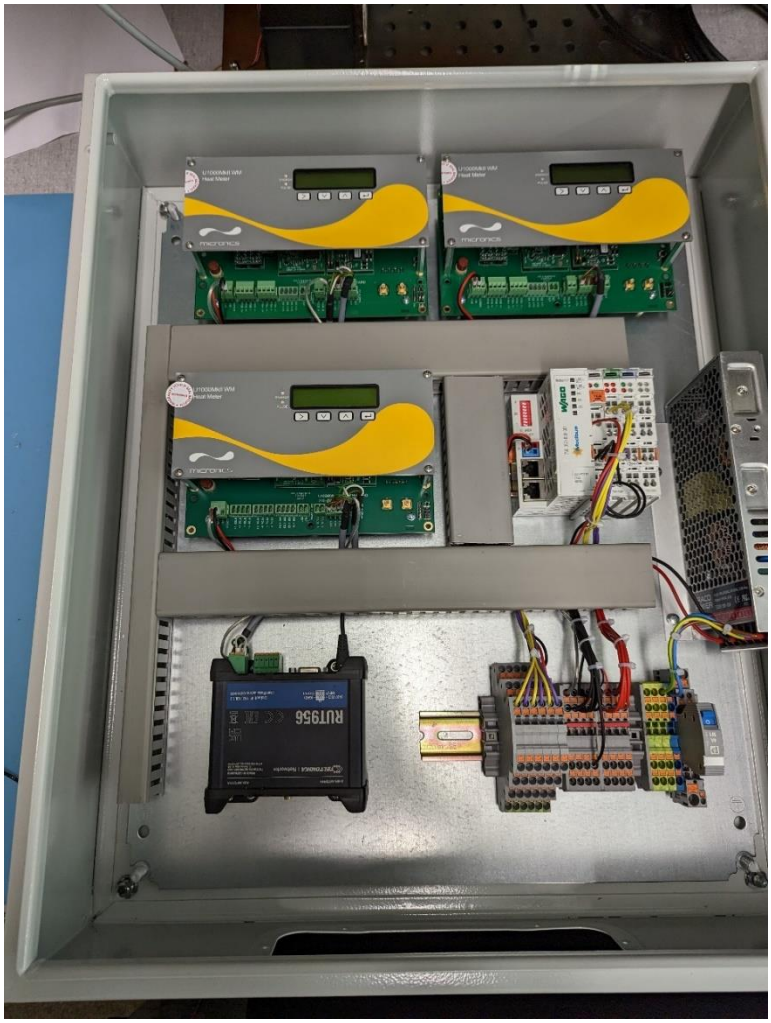

Figure 13 – Outer unit with electronic for heatmeter, LTE router and fieldbus coupler

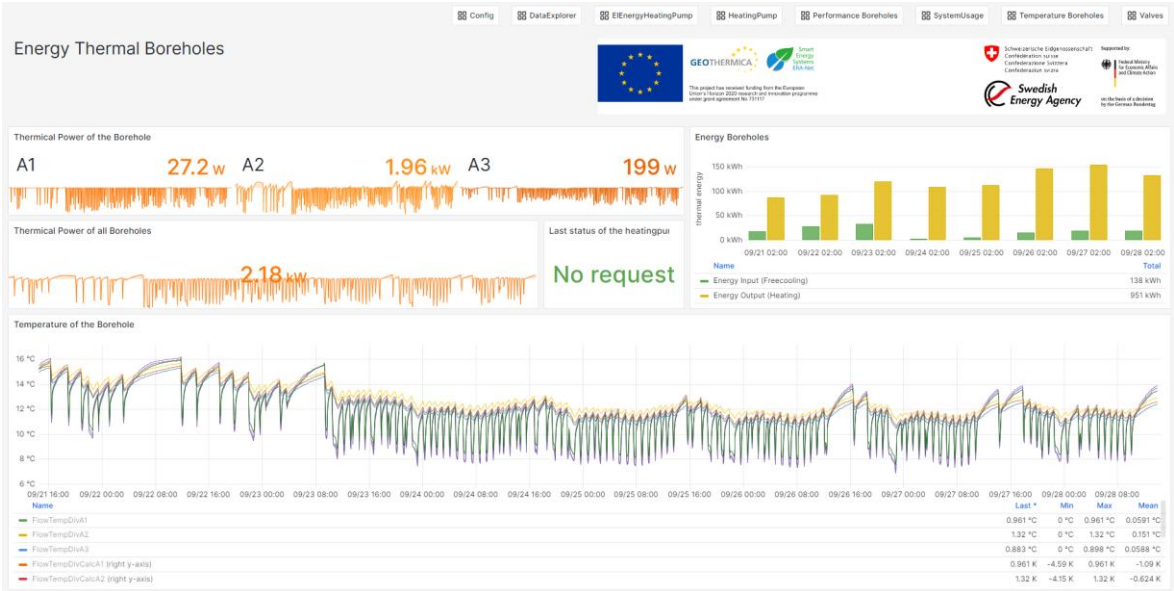

Figure 14 – Example dashboard heating meter BHE

2.3.2 Powermeter for heating pump

This energy meter is used to record the electrical energy of the heat pump. Here, care was taken to ensure that the meter could be installed outside the electrical distribution board. This was necessary because otherwise a fire protection wall of the building would have to be breached.

The meter is queried via ModbusTCP and supplies current, voltage and energy of all 3 phases as value.

Figure 15 – Powermeter for heating pump

Figure 16 – Powermeter for heating pump mounting place

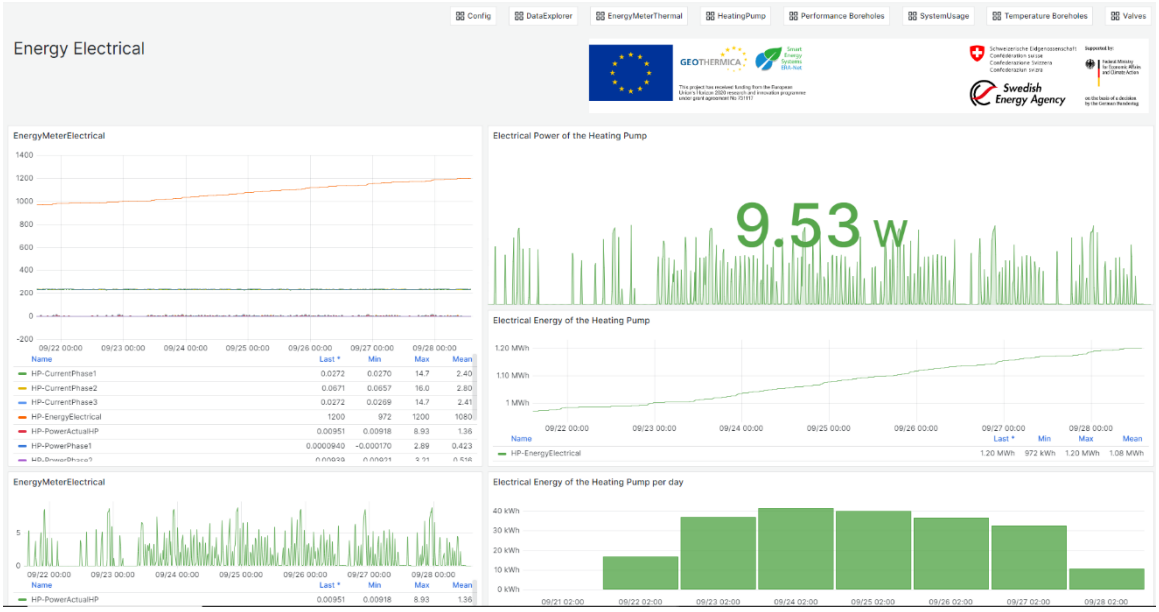

Figure 17 – Example dashboard power meter heating pump

2.3.3 Integration of the DTS System

The DTS system records the temperatures of the backfill of the three BHE and the control borehole every 20min. The data are recorded at intervals of 1.2m of the total 1300m long cable. For the use of the ModbusTCP interface, a license was purchased from the manufacturer.

Figure 18 – DTS System

Figure 19 – Example dashboard DTS

2.3.4 Integration of the heating pump

A ModbusRTU communication module was bought for the heat pump. This allows access to the various heat pump data. In addition to temperatures, the current operating status and pump activities are also visible.

Figure 20 – Communication modul heating pump

Figure 21 – Example dashboard heating pump

2.3.5 Valves for the boreholes

Belimo actuators were installed to control the fluid flow. Since the existing valves are used, a support had to be built and installed. Furthermore, the space available is very limited. This made the installation even more difficult. The actuators are controlled by a 2-10V signal, which is generated by a fieldbus coupler in the outer unit.

Figure 22 – Valves in the manhole

2.3.6 Mounting and interventions in the building

Due to the retrofit installation of the sensors, a unit with electronics had to be installed outside the technical room, near the manhole. The external unit (Figure 24) contains the electronics for the heat meters and the control of the actuators for the valves. Furthermore, an LTE router is installed for an internet connection. For the power supply and the communication with the electronics in the technical room, a power cable and an Ethernet cable were routed around the house (Figure 25).

In order to eliminate the risk of a defect in the heating system, it was decided to reduce the intervention in the system to a minimum. For this reason, ultrasonic energy meters and the existing shut-off valves were used. This meant that the hydraulic system did not have to be opened. In addition, the demounting is massively simplified.

Figure 23 – Schematic overview cabel (red) and lightsaft (blue)

Figure 24 – Outer unit with the electronic for communication and heatmeter

Figure 25 – Cable routing 1

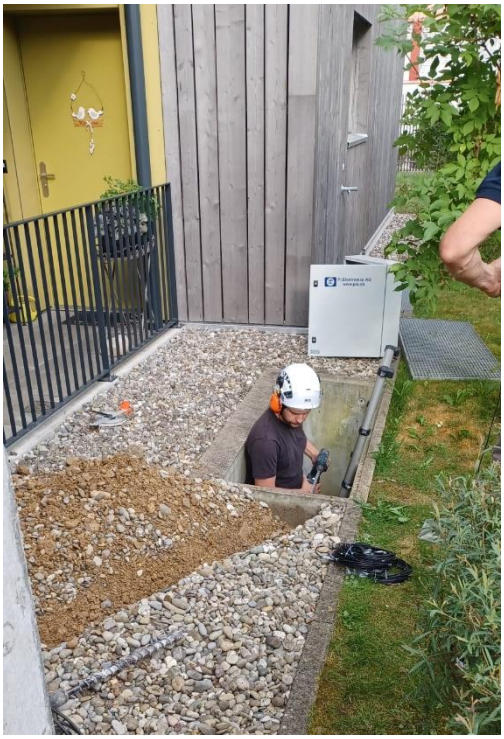

Figure 26 – Cable routing 2

Figure 27 – Cable routing 3

Figure 28 – Cable routing 4

2.4 Design and building of the controller

The controller was developed to cover a wide range of interfaces and installation situations. As a form factor, a 19" rack insert was chosen, which allows the installation in server cabinets as well as a stand-alone device. For Lausen, the controller was mounted in a 19" desktop housing.

Specifically, the controller has 5 Ethernet ports, 4 of which are connected via a switch and can be used to connect measuring devices. One Ethernet port serves as a service interface and is connected to a separate network card.

There are also 4 serial ports, either RS485 or RS232. Beside USB and HDMI connectors the controller offers a 24V DC output with 100W power. This is intended for extensions.

For commissioning or interaction on site, a touch panel was installed. Via the web interface configuration adjustments can be made easily on site.

Figure 29 – Controller front view

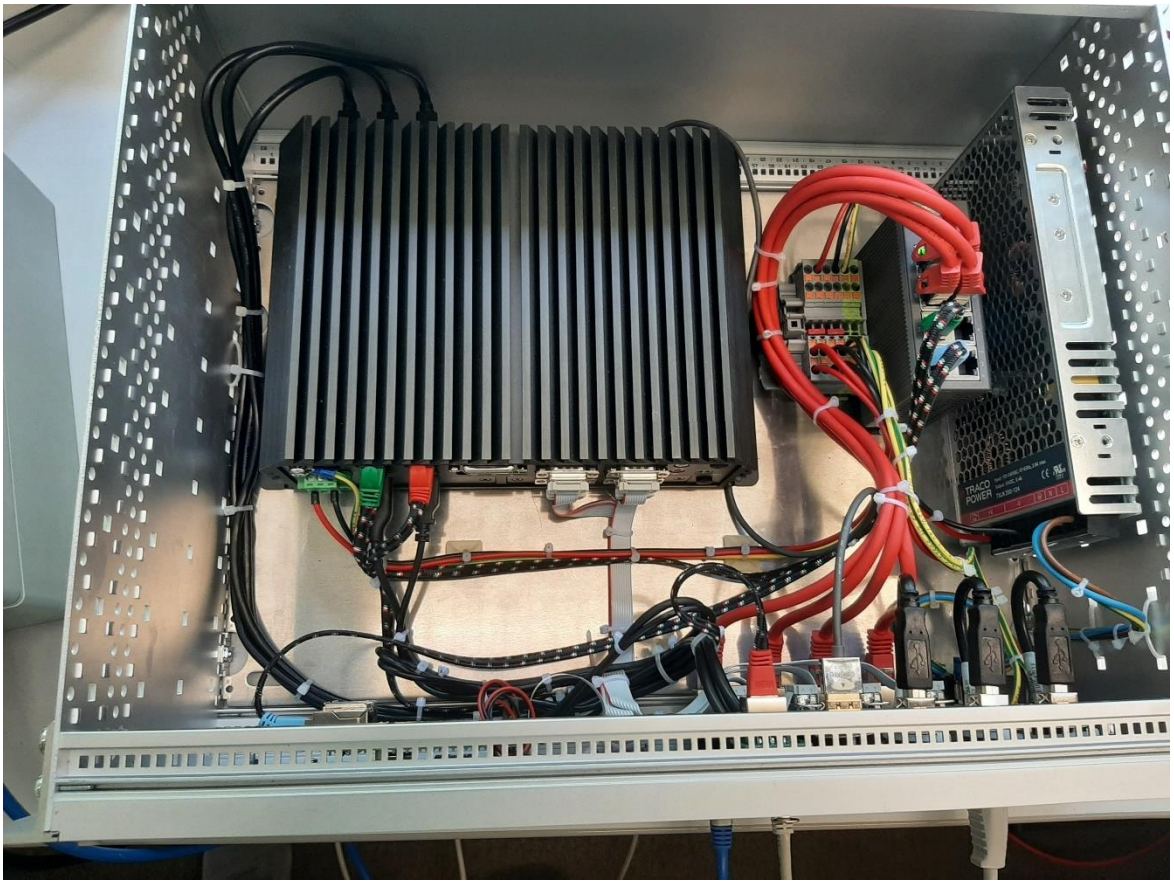

Figure 30 – Controller inside

Figure 31 – Controller in Lausen

The controller itself consists of a COTS industrial PC. The model offers particularly long availability of the components. Besides the large number of interfaces, two SDD mass storage devices are installed in RAID 1. This massively reduces the risk of data loss.

The necessary computing power for the MPC control and the calculations for the modelling should be covered by the installed CPU and the available RAM. The operating system is WIN 10 IoT which is preferred for such purposes.

The system-relevant data is also stored and visualized in a dashboard.

Figure 32 – Example Dashoard SystemUsage

2.5 Design of the Software

This chapter describes the software architecture.

For this project, a product from PI Electronics AG, called Silana was extended and supplemented. The application is written in the graphical programming language LabVIEW from NI (National Instruments). The concept is that the application has a maximum of flexibility. Thus the software can be used for all test objects.

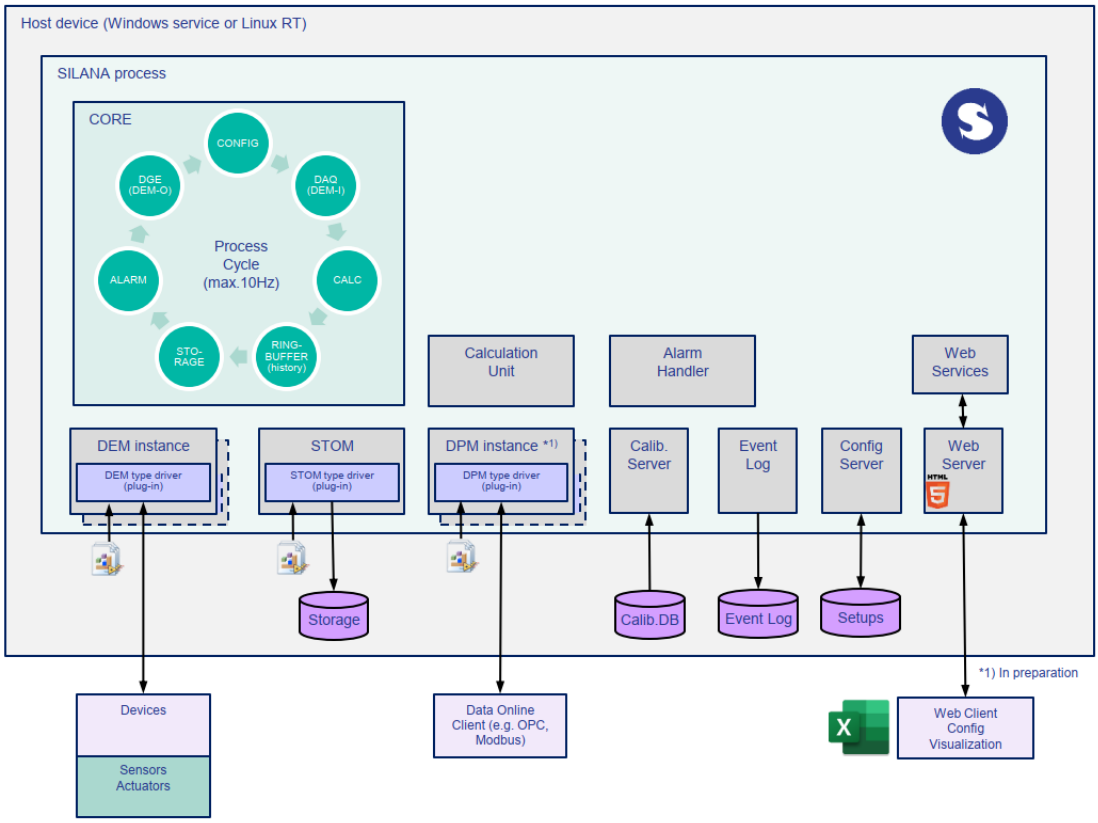

Figure 33 – Overview software architecture

An overview of the architecture is shown in *Figure 33*. The software essentially consists of a core module and generic drivers. The core module is responsible for processing the data. Depending on the configuration, different drivers are loaded for acquisition or storage. These modules are called DEM, Data Endpoint Module, or STOM, Data storage modules.

The advantage of this architecture is the flexibility of the application. The installations for the various project locations differ only in the site specific device drivers used. The core application remains the same in all cases.

The configuration of the complete software can be done in MS Excel. The upload to the software is carried out through a web interface of the core application. This has several advantages. On the one hand, the configuration can be done offline. This is especially helpful if the application is already in

operation and an interruption of the data acquisition / control should be kept as low as possible. On the other hand, large configurations can be created quickly using the Excel formulas.

2.5.1 Example Data Endpoint Modul ModbusTCP

The functionality of such a driver is to be illustrated here. With this DEM devices with a ModbusTCP interface can be integrated. The driver was developed in such a way that all devices with such an interface can be integrated without additional programming effort. At the Lausen project site, this is used for several devices such as the DTS system, control of the valves or the acquisition of the electrical power of the heat pump. The same driver is then called three times in parallel by the core application. The parallel instances differ only in the configuration.

DriverType	*Description*	*Setup*	*SampleRate*	*RingbufferLength*				
MODBUS_TCP	ModbusMaster	Ip=192.168.80.4 Port=502 Timeout=2000 Decode=LittleEndian ExtendedMode=False	0.033333333	3600				
[Channels]								
IO	*Name*	*Description*	*Groups*	*Type*	*Unit*	*Calculation*	*Locator*	*Setup*
input	HP-EnergyElectrical	Consumed Energy over all phases	Device=HeatingPump; Unit=Energy; Phase=All		kWh	<R> / 1000	31163	Type=FLOAT32
input	HP-VoltagePhase1	Voltage on Phase 1	Device=HeatingPump; Unit=Voltage; Phase=L1		V		31021	Type=FLOAT32
input	HP-VoltagePhase2	Voltage on Phase 2	Device=HeatingPump; Unit=Voltage; Phase=L2		V		31041	Type=FLOAT32
input	HP-VoltagePhase3	Voltage on Phase 3	Device=HeatingPump; Unit=Voltage; Phase=L3		V		31061	Type=FLOAT32
input	HP-CurrentPhase1	Current on Phase 1	Device=HeatingPump; Unit=Current; Phase=L1		A		31023	Type=FLOAT32
input	HP-CurrentPhase2	Current on Phase 2	Device=HeatingPump; Unit=Current; Phase=L2		A		31043	Type=FLOAT32
input	HP-CurrentPhase3	Current on Phase 3	Device=HeatingPump; Unit=Current; Phase=L3		A		31063	Type=FLOAT32
input	HP-PowerPhase1	Power on Phase 1	Device=HeatingPump; Unit=Power; Phase=L1		kW	<R> / 1000	31025	Type=FLOAT32
input	HP-PowerPhase2	Power on Phase 2	Device=HeatingPump; Unit=Power; Phase=L2		kW	<R> / 1000	31045	Type=FLOAT32
input	HP-PowerPhase3	Power on Phase 3	Device=HeatingPump; Unit=Power; Phase=L3		kW	<R> / 1000	31065	Type=FLOAT32

Figure 34 – Example configuration DEM MobusTCP

Figure 34 shows the configuration of one of these Modbus devices. In the upper area the basic setup for the interface is defined. Among other things, an individual sampling rate for this device can also be stored here.

In the lower area the single data points, called channels, are defined. In addition to the obvious options, calculations can also be performed directly with the recorded data points.

2.5.2 Configuration of multiple DEM instances

As described, the configuration is done in Excel. If a new DEM is required, this can simply be created with a new table. The core application then generically opens the selected driver and creates a new instance running in parallel.

20	input	HP-CurrentPhase2	Current on Phase 2	Device=HeatingPump; Unit=Current; Phase=L2		A		31043	Type=FLOAT3
21	input	HP-CurrentPhase3	Current on Phase 3	Device=HeatingPump; Unit=Current; Phase=L3		A		31063	Type=FLOAT3
22	input	HP-PowerPhase1	Power on Phase 1	Device=HeatingPump; Unit=Power; Phase=L1		kW	<R> / 1000	31025	Type=FLOAT3
23	input	HP-PowerPhase2	Power on Phase 2	Device=HeatingPump; Unit=Power; Phase=L2		kW	<R> / 1000	31045	Type=FLOAT3
24	input	HP-PowerPhase3	Power on Phase 3	Device=HeatingPump; Unit=Power; Phase=L3		kW	<R> / 1000	31065	Type=FLOAT3
25									
26									

MAIN | CONST | CALC | _WeatherForecast | ElEnergyHeatingPump | HeatingPump | ThEnergyBoreholes | _TempBoreholesTestModbus | TempB

Figure 35 – Example configuration multiple instances

It cannot be mentioned strongly enough how essential such an architecture is for this project. Different sensors and actuators are used for control at all project sites. Creating a new software for each project would not only be a huge financial effort but would also have a negative impact on the functionality and reproducibility.

2.5.3 Integration of the MPC-algorithm

It is assumed that the MPC itself will be written in Python. The integration of this algorithm can then be done via the DEMs structure. The DEM opens the Python node and executes the script periodically. This offers far-reaching advantages.

2.6 Database and visualization concept

Due to the large number of data points and international collaboration for the development of the MPC scheme and models, a database is essential.

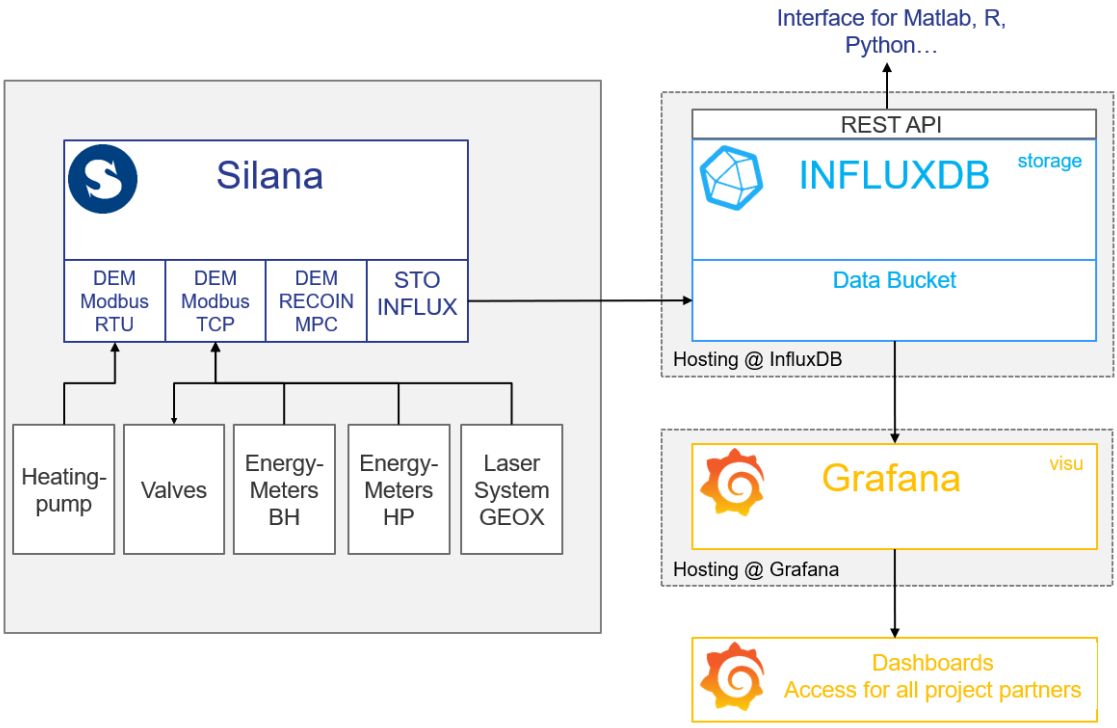

Figure 36 – Database concept

For data storage, a database driver was developed, specifically for the project. InfluxDB was evaluated as a suitable database technology (*Figure 36* in blue). This open source solution is especially suitable for the storage of time series data. The database can be self-hosted or hosted by a cloud provider.

The measurement data is collected by SILANA, processed and sent to InfluxDB via internet connection. As a back-up, all measurement data are stored again in csv files on the system. This means that there are no data gaps even in the event of a longer Internet interruption.

For the visualization of the measurement data, the open source solution Grafana (*Figure 36* in orange) is used. This allows the creation of user-defined dashboards. The data is obtained from the InfluxDB. As with the database, this solution can be self-hosted or operated as cloud hosting. The advantage of cloud hosting is better accessibility for all project participants. The concept was designed so that the different installations (Lausen, Stockholm and Berlin) are stored in the same database instance, but in separate thankbases. This allows easy comparison of the data.

3 Procedures and methodology

The test site Lausen is an ideal object for the development and verification of the MPC control due to the very extensive data basis.

The extensive number of sensors allows a detailed insight into the subsurface as well as into the heating system. Based on this database, the controllers as well as the underground model will be developed by project partners in Sweden and Germany.

In a next step, the controller will be integrated into the software and analyzed. The resulting knowledge will be used to further improve and simplify the algorithms. The iterative process will work towards a controller that is as simple and generally applicable as possible. This also means that an attempt is made to reduce the number of data points required for the controller.

From the 1000 data points with a high sampling rate at the beginning, it should be possible to operate the controller with a few at the end of the project.

3.1 Current state

At the moment, the site in Lausen is fully instrumented and the project is in monitoring campaign. As many data points as possible are being collected and stored.

The basis for the implementation of the software and hardware for the sites in Germany and Sweden has been created.

The detailed clarifications for the use of the system in the test facility in Sweden are in progress.

3.2 Reproducibility to other objects

From the beginning, care was taken to ensure that the software and the hardware developed could be used at all project sites.

In the software, this was ensured with the generic approach of the Data Enpoint modules. This means that different sites can be operated with the same software but with different configurations.

In the database concept, reproducibility was achieved with different databases and strict user rights. Thus, all three sites can be operated with the same technology. The only thing that changes is the login data for the database. These can be set in the configuration.

In the hardware, attention was paid to a uniform form factor. The controller can be mounted as a tabletop device or as a 19" rack version. In addition, care was taken to ensure that as many interfaces as possible were already implemented. This means that the same controller unit can be used for all three locations.

4 Activities and results

4.1 Timetable

02.06.2023	Controller hardware was completed
18.07.2023	Commissioning of the controller in Lausen. Mounting outer unit, heatmeter BHE and current measurement heat pump.
03.08.2023	Change the position of the ultrasonic sensors for the heating meter.
14.08.2023	Some Software updates. Core was not able to startup correctly after restart
17.08.2023	Work on the TCP connection between DTS and Silana

17.08.2023	Change the direction of the current transformer for the power meter of the heating pump
17.08.2023	Change communication settings on the heating pump. Now, heating pump is integrated into the system.
22.08.2023	Valve A1 was closed for the last weeks. Open by GEX.
29.08.2023	Add historical heating pump data (2016-2021) to database
05.09.2023	Update DEM ModbusTCP and ModbusRTU.
05.09.2023	Work on DTS system by GEX. Add zones to the config
05.09.2023	Integration of the DTS into the system
26.09.2023	Presentation of the system at the international project meeting in Baden, Switzerland.

4.2 Challenges

Especially the subsequent installation of the actuators on the existing manual valves was a challenge. This was because these valves were not developed for this application. Furthermore, the space available is very limited.

Moreover, there were several challenges regarding the integration of the different systems into the controller. For the DTS system, an additional license had to be obtained. Contrary to expectations, this was more time-consuming than expected. The manufacturer reacted only irregularly to our inquiries and thus several weeks of delay had to be accepted.

5 Appendix