GeoWaermeWende - Empowering Low-Temperature District Heating and Cooling Networks with Comprehensive Geospatial Monitoring, Multi-Purpose Simulation Approaches, and User-Centric Planning Tools

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1 ABSTRACT

Planning low-temperature district heating and cooling networks (LTDHCN) still poses many challenges. It requires research, especially in the scalability of the networks and the connected energy producers and heat sources. In the project GeoWaermeWende (project number 03EN3059), a passive, existing LTDHCN is monitored. For this purpose, a monitoring concept will be developed to collect relevant operating parameters at different network locations, which will be compiled and processed in a database. In addition, various tools are developed for planning LTDHCN. With the help of the measurement data, individual simulation models are validated, which provide the basis for a holistic district model consisting of all relevant components. Analytical and numerical approaches enable a variety of promising analyses regarding the network dynamics under changing boundary conditions and the interaction of the network with the subsurface. All simulation tools are accessed via a geothermal network information system (GNIS). The GNIS is established as a spatial data infrastructure with a geoportal to facilitate web-based access to the data required for the analysis and simulation. The geoportal is also

to be used to configure and analyze the LTDHCN.

Keywords: GeoWaermeWende, LTDHCN, Thermal Network Simulation, Shallow Geothermal Energy, GIS, Geoportal

2 INTRODUCTION

The urgency for a rapid and decisive energy transition is increasingly apparent in the context of the escalating climate change. The need for action intensifies as the impacts of rising global temperatures on ecosystems and societies are evident. The building sector is responsible for a significant part of the total greenhouse gas emissions, highly emphasizing effort towards its decarbonization. Therefore, an urgent need to increase the usage of renewable energy sources as an alternative to fossil fuels in the building sector is evident.

Shallow geothermal energy is becoming increasingly recognized as a renewable energy source that can provide reliable energy for space heating, domestic hot water (DHW), and space cooling. Its base-load capability underscores its reliability, addressing concerns often associated with other renewable sources. Recently, Germany has been taking legislative steps to emphasize the importance of local heat planning and the transition to renewable energy sources in municipalities. The upcoming *Second Amendment of the Building Energy Act* is expected to have significant implications for implementing and expanding heating networks, including LTDHCN, in Germany. To make the most use of this technology's potential, building new and transforming existing heating networks is essential. In particular, LTDHCN offer an efficient way to utilize geothermal energy and are a practical method of distributing heat throughout a residential district. The passivity of the system without a central circulation pump makes the system more robust and easier to scale. However, estimating and controlling the hydraulic conditions and the associated quality of mutual heat exchange can be quite difficult.

Although the benefits of LTDHCN are widely recognized, their implementation can be challenging, especially for existing heating networks with a higher temperature level or districts with no heating network. Considering the complexity of the technology, it is crucial to develop an intuitive and user-friendly planning tool. This tool would simplify the planning and configuration processes and encourage the broader implementation of LTDHCN, which is a fundamental step toward sustainability.

3 PROJECT DESCRIPTION

One core element of the project is the sensory equipment and the monitoring of the LTDHCN in the German city of Schifferstadt. The data collected in the monitoring process is used to validate simulation models, which represent a digital image of the actual model and are also used in planning new LTDHCN. This knowledge will be combined into a planning tool to support specialist planners in designing and analyzing new LTDHCN. In addition, an augmented reality app is being developed to visualize the heating network in Schifferstadt, making the technology accessible to a broader audience.

3.1 LTDHCN Schifferstadt

The LTDHCN in Schifferstadt is located in the Upper Rhine Plain in southwest Germany, a region with increased volcanic activity and the location of the Upper Rhine Aquifer. The geological conditions of this region give rise to many projects dealing with the extraction of geothermal heat.

In Schifferstadt, 41 residential buildings are thermally connected by an uninsulated heating network, as shown in Figure 1. The network consists of two meshes, each with a supply and a return loop. A geothermal borehole heat exchanger (BHE) field is connected in the district's northwest, consisting of 28 BHE with a drilling depth of about 95 meters each. The buildings are supplied by heat pumps that draw heat from the grid for heating purposes or feed heat back into the grid for cooling purposes. The heat pumps will collect analysis data since they are equipped with extensive sensor technology by their manufacturer to extract all relevant operation data. Additionally, various measuring points are planned at the maintenance building, the BHE, and at five positions inside the network. The sensors shall record the fluid's pressures, temperatures, and volume flows. All measurement data will be permanently stored in a database, processed, and made available for further use.

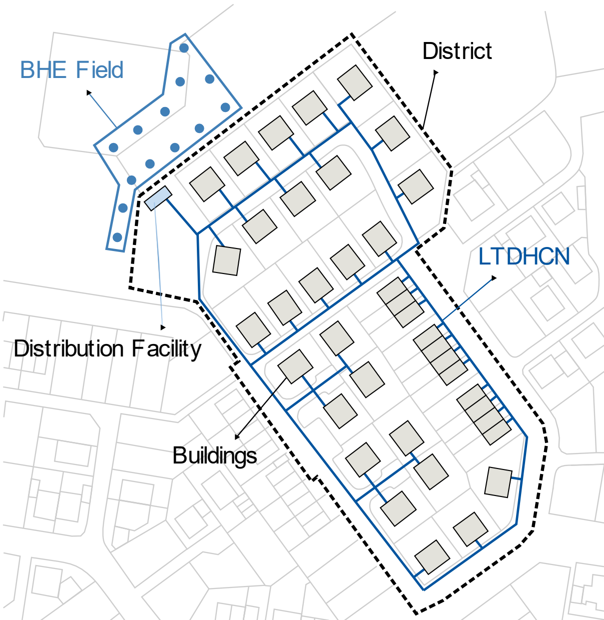

Figure 1: Schematic Floorplan of the LTDHCN in Schifferstadt

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3.2 Concept of the Overall Planning Tool

The entire planning tool is developed to enable web-based access by any interested party without installing additional software. This reduces barriers to using the tool and allows for quick results to be achieved. Depending on the planning stage, the requirements for the tools to be used and the level of detail of the results differ. Figure 2 shows the preliminary functional relationship of the different tools in the project.

The network information system (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**) compiles general data relevant to the planning of heating networks and passes it on to the system configurator (see Section **Fehler! Verweisquelle konnte nicht gefunden werden.**). System-specific parameters are defined there and passed on to the tools for modeling buildings, heat pumps, pipe networks, and underground. Both the simplified (blue) and the detailed models (red) will be triggered from the system configurator.

3.3 Geothermal Network Information System (GNIS)

The goal of the geothermal network information system (GNIS) adapted from a former project GeTIS ([1], [2]) is the establishment of a project-related spatial data infrastructure with a geoportal for web-based access to the data required in the analysis and simulation tools for the execution of these tools and, finally, for visualization of the obtained results.

The planning, dimensioning, and operational optimization of LTDHCN require various data.

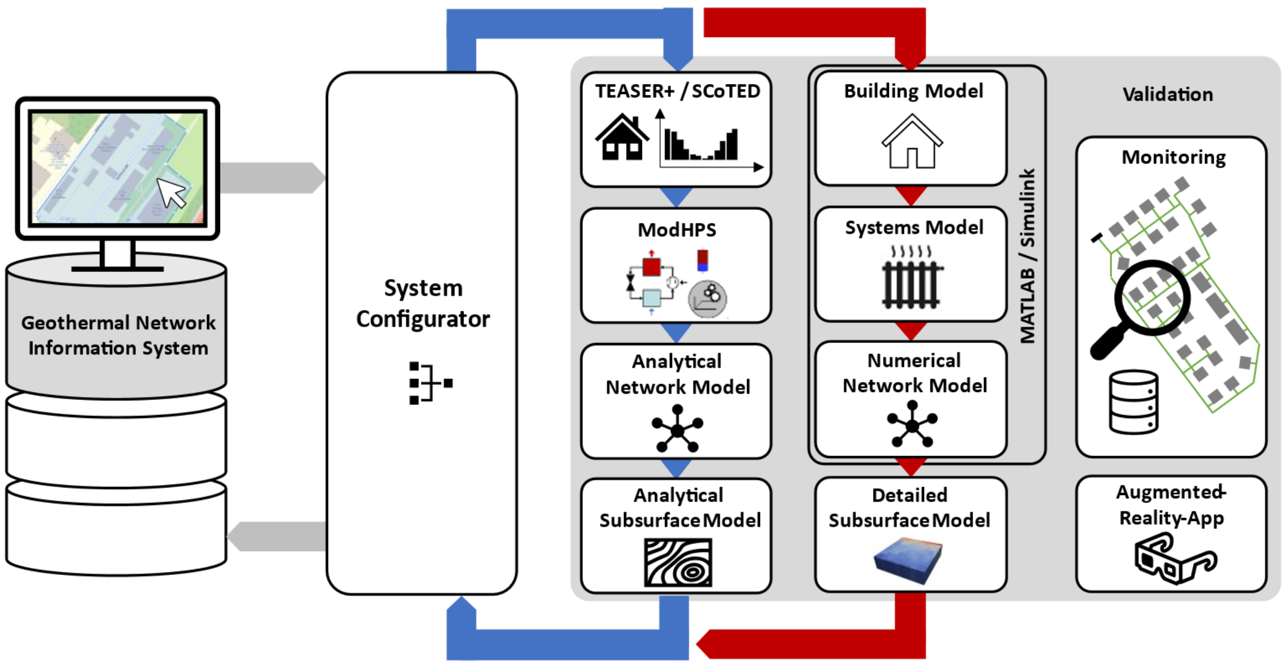

Figure 2: Conceptual flow chart of the toolchain to be developed

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An essential part of the spatial data infrastructure of the GNIS is the aggregation of hydrogeological data of the subsurface with data regarding the LTDHCN and semantic data of its environment. For this purpose, existing maps, subsurface and city models are linked with monitoring data and made available via the geoportal, as demonstrated in Figure 3. As far as possible, this data is connected to the GNIS via standardized interfaces of the Open Geospatial Consortium (OGC), such as the specified geodata services, also called OpenGIS Web Services (OWS). In this way, the data can be integrated into the GNIS but do not have to be transferred to a project-based, own database as a secondary dataset and are kept up to date automatically. Furthermore, it increases the interoperability and, thus, the scalability of the GNIS and improves the possibilities of further system development. The various analysis and simulation tools (see Section 0) can be connected to the geoportal via purpose-built interfaces based on the OpenGIS Web Processing Service (WPS) [3].

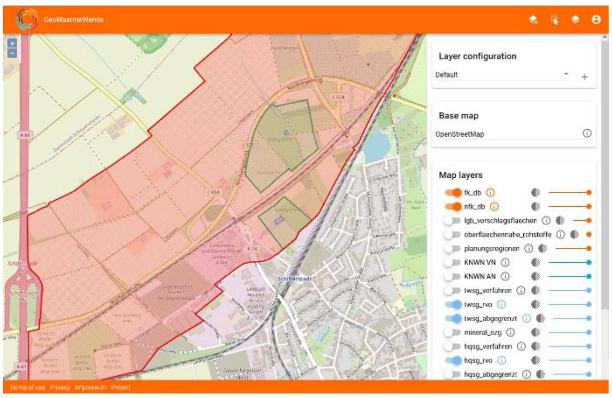

Figure 3: The Geoportal in GeoWaermeWende

This also includes interfaces for integrating georeferenced LTDHCN and the monitoring database. Furthermore, it is intended to incorporate planning and approval-relevant requirements and valuable information from real-world experience in the planning process of LTDHCN.

To fulfill the diverse demands, the GNIS is designed as a distributed geoinformation system (GIS) according to service-oriented architecture (SOA) principles. Corresponding to this principle, individual services are implemented and orchestrated to unite a large and powerful system that allows for flexible adaptation to new or changed requirements.

3.4 System Configuration

Following the digital geothermal site analyses and the data aggregation in the geothermal information system, the heat and cold generation systems and the LTDHCN must be designed. For a user-friendly design of the heat pumps, buffer, DHW storage tanks, and the network topology, the web-based system configurator GeoWPSys+Web [4] is used. GeoWPSys+Web gives automated system suggestions of available devices and provides default values for most design parameters. In GeoWaermeWende, the system configurator will be extended with functionalities for dimensioning and planning the LTDHCN routes. The resulting heat network configurator shall execute the calculation tools described in the following to determine or check design parameters automatically.

3.5 Calculation & Simulation

3.5.1 Simplified Approaches

Hourly load curves for heating, domestic hot water, and cooling are required to dimension a LTDHCN and the systems involved and input data for several models within the toolchain described here.

With the help of the open-source program TEASER+ [5], generic low-order Modelica building models can be parameterized, suitable for large-scale simulations of many buildings due to their low complexity. TEASER+ uses a database of archetypes, i.e., buildings with standard construction and usage profiles based on age and type, to scale building geometry based on net floor area, height, and number of floors or derives it from CityGML data, merging this with archetype data to create a reduced-order model. The models are refinable through additional parameters, with updated archetypes recently incorporated to better match the actual buildings in Schifferstadt.

Alternatively, the analytical tool SCoTED [6] can generate heating load curves by leveraging standard heating loads or annual energy consumptions of buildings, along with hourly weather data. Unlike TEASER+, SCoTED also produces domestic hot water consumption curves.

The simplified heat pump system model ModHPS [7] used the hourly load curves created with the previously described tools to represent the decentralized distributed heat pumps at the district level. ModHPS is an open-source black-box characteristic curve model with control mechanisms and storage balances for buffer and DHW storage tanks. It can be used for individual buildings or entire city districts and coupled bidirectionally to subsurface models.

3.5.2 Automated determination of the number of storeys in buildings

Building parameters such as the average floor height, the total floor area, the window-to-wall ratio, and the number of storeys critically influence building energy simulations [8]. Accurate physical building parameters are vital for these simulations [9], yet they are difficult to obtain on a large scale. Even though machine learning, artificial intelligence, and image processing algorithms have been utilized in energy simulations, their applications have been restricted to individual buildings. Thus, they cannot scale on an urban level [10]. This is why developing algorithms to extract building parameters on an individual and a large level is important.

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The recent surge in oblique aerial imagery, especially in German cities, is promising since these images make building facades visible, enabling the extraction of facade information. The growing usage of 3D city models, like CityGML data, aids in energy simulations by providing standardized 3D representations of urban objects.

CityGML data provides a standardized 3D representation of city objects, i.e., buildings, in different levels of detail [11]. Depending on the level of detail, CityGML data can include building parameters such as the number of storeys. However, this information is highly inconsistent and dependent on the data provider. Nevertheless, other important information, such as the 3D coordinates of the building, is already available in CityGML data (Figure 5). Combining this information with oblique aerial imagery (Figure 4) is a basis for an automatic approach to determining the number of building floors. The process begins by selecting an appropriate oblique image

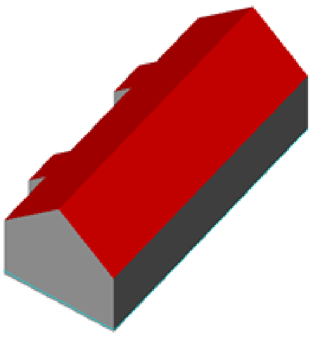

Figure 5: CityGML example viewed using FZK Viewer

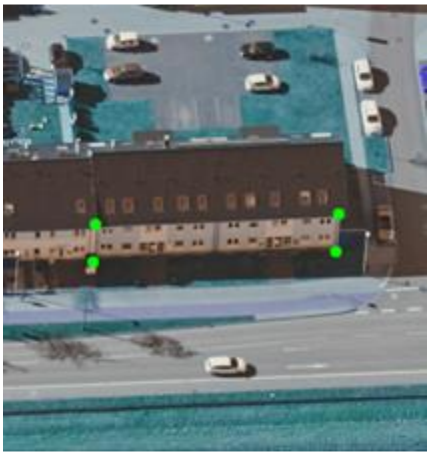

Figure 4: The corresponding facade in oblique aerial images (source: city of Soest, NRW Germany)

where a building's facade is clear. Utilizing 3D coordinates, the facade's location is pinpointed in the image, followed by facade rectification. Subsequent image processing identifies the edges representing windows on the facade. By analyzing the frequency of vertical edge pixels in each row of the image, it becomes feasible to calculate the building's number of floors based on the count of maxima in the frequency image.

3.5.3 Analytical ground and fluid models

A key to the adequate design of LTDHCN is to ensure sufficient and appropriate fluid temperatures within the network. Generally, the efficiency of a heat pump depends on both the temperature difference it needs to produce and the absolute fluid temperatures, showing a negative correlation with the former and a positive correlation with the latter. Furthermore, there is the need to assess the induced temperature changes in the

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subsurface to ensure the system's sustainability and conform to regulatory demands.

Therefore, the temperature of the fluids and the surrounding ground, need to be determined effectively. The chosen analytical approach divides the modeling area into two regions: The subsurface surrounding the heat exchangers (HE) and the area inside the heat exchanger. In this context, any system component with significant heat fluxes is considered a heat exchanger. That includes borehole heat exchangers (BHE) and the connecting network pipes.

The subsurface temperatures are determined through the construction of g-functions. Different boundary conditions are used for different system components: A constant temperature is commonly a boundary condition on the surface for borehole heat exchangers (BHE), modeled after [12]. Connecting pipes installed close to the surface are modeled using a time-dependent surface temperature boundary condition [13]. This allows the incorporation of daily and seasonal temperature cycles in areas above the neutral zone. Other types of heat exchangers can be integrated if a suitable g-function formulation is available.

After obtaining the g-functions for all system components, the temperature at the HE wall can be determined through

$$T_b = T_0 + \Delta T \qquad (1)$$

where T_b and T_0 are the borehole and undisturbed ground temperature. For time-varying loads, the incremental load steps can be considered such that

$$\Delta T = \frac{1}{2\pi\lambda} \sum_{l=1}^{k} (q_l - q_{l-1}) \cdot g_{k-l+1} \qquad (2)$$

where q is the thermal load, λ is the soil thermal conductivity and the g-function is a function of the characteristic time, radius, and buried depth of the BHE. This can be efficiently evaluated by computing the convolution of the load increment and g-function arrays [14].

T_b is linked to the circulating fluid temperature through the thermal resistance R_{th}, which encapsulates the heat transfer processes inside the HE. It is defined such that

$$\overline{T_f} = q \cdot R_{th} + T_b \qquad (3)$$

where $\overline{T_f}$ is the average fluid temperature inside the HE.

Using R_{th} as a coupling parameter between HE and surrounding ground is advantageous due to its facilitation of a linear equation for complex heat transfer dynamics. This linearity, evident in Equations 1 and 3, aids in developing a linear system of equations for the system.

System components are interconnected by equating the inlet and outlet fluid temperatures of successive HEs, as demonstrated in

$$T_{f,i,m} = T_{f,o,n} \quad (4)$$

These relations serve as constraints besides the total required heat load from the ground. The resulting system is expressed as a sparse matrix, which can be solved using SciPy's *sparse* algorithm [15], an approach validated by Düber et al. on systems involving BHE and corresponding pipes ([16], [17]).

The approach allows the incorporation of heat pump models such as ModHPS for additional fluid temperature and flow rate constraints, which are usually neglected in the conventional planning of such systems. The calculation times depend on the system complexity but should be in the minutes. This enables iterative or optimization algorithms to design the system for adequate fluid temperatures automatically.

3.5.4 Numerical Methods

The modeling and simulation of the hydraulic network, heat pumps, and buildings will be conducted in the SimScape [18] environment for detailed planning. SimScape is an extension of the Simulink software developed by Mathworks. It extends Simulink with graphical modeling of multiphysics systems in which individual sub-models can be interconnected via bidirectional signals. SimScape incorporates an extensive model library of individual components and provides examples of how these components can be implemented in complex systems. Therefore, it is suitable for modeling the changing flow direction in heat networks and the thermal interaction of the network with the subsurface. Although the CARNOT-toolbox [19] has proved unsuitable for use as the central platform in initial application trials, parts of it are nevertheless used for some subsystems of the numerical simulation model, such as for integrating weather data or calculating solar radiation.

Since the supply and return pipes of the network are usually located next to each other, a configurable double-pipe model is being developed to serve as a basic building block for a pipe section of any size. This allows the thermal interaction of the two conductors to be implemented within the model and the model structure to be simplified. The network is then composed of many double-pipe elements connected by T joints. In addition to the heat transfer, the pressure losses of the fluid are also calculated in this model.

The utilization of reduced-order models (ROM) is planned for the buildings, which are parameterized with the previously mentioned tool TEASER+. These models are based on the modeling approach of VDI 6007 [20] and an adaptation of Lauster et al. [21]. This guideline describes a calculation method based on the fundamental approach of considering the thermal zone as an electrical circuit. Each wall layer consists of a pair of resistances representing the thermal conductivity of the material and a capacitance representing the heat storage capacity. Several wall layers can be combined to form a wall element. The volume of air the walls enclose is assumed to be a homogeneous zone, resulting in an additional heat capacity. This air volume is extended by supply and exhaust air openings, which enables the implementation of ventilation flows. Heating and cooling effects and internal gains can be modeled via ideal sources and sinks and will be replaced in the further course of the project by modeling the system technology.

4 CONCLUSION

A comprehensive collection of activities has been defined in the project GeoWaermeWende, covering many theoretical, experimental, and modeling aspects of planning and operating a LTDHCN. The project addresses many areas of the subject of geothermally fed LTDHCN, such as gathering and processing georeferenced data relevant to system design and approval procedures, basic and applied understanding of hydraulic and thermodynamic behavior of heating networks, analytical and numerical modeling and validation, as well as involving the public and presenting scientific findings. Initial results over the first months of GeoWaermeWende have been encouraging and offer fresh insights. This wealth of new knowledge is expected to help municipalities, planning authorities, and other parties implement LTDHCN technology broadly.

5 ACKNOWLEDGEMENTS

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