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Integrated concept of local heat transition using geothermal heat production, aquifer storage and optimal scheduling of distribution network

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ABSTRACT

Germany's energy transition depends about 50 % on heat production. As the proportion of renewable energies are rapidly increasing for electric power supply, heat on the contrary, especially for buildings, is still mainly produced with fossil energy sources and only about 15 % covered by renewables. Therefore, the heat sector has a very high potential to reduce CO_2 emissions towards a CO_2 neutral energy production by 2040.The research centre KIT Campus North close to the city of Karlsruhe, south-western Germany, transits to a sustainable energy supply for its offices, laboratories and test facilities by 2030. In this integrated strategic framework, the major technology to support heat production can be geothermal energy, as the research centre is located on Germany's biggest known temperature anomaly, inside the Upper Rhine Graben (URG) area.

Currently, the existing second-generation district heating network's base load heat supply is produced by a combined heat and power plant. Peaks of heat consumption are covered by a boiler which is running on natural gas. Additionally, several research facilities are producing excess heat and feed it into the system on an irregular basis. The network consists of three main pipes, the southern, northern and central pipe, that are interconnected thus forming a complex mesh network. Furthermore, modernization of the 17 km simple length network through lowering of the supply temperatures which currently is 110 °C at 6 bar would necessitate changing the heat exchangers in more than 300 buildings, which is economically challenging.

First exploration results show high potential for geothermal heat production along two major fault systems in Permo-Triassic sandstone formations at about 3300 m depth. Thermal water of about 170 °C can cover a major portion of the campus' heat consumption even at moderate flow rates. By experience, moderate flow rates allow mitigation of induced seismicity. Major challenges of heat supply using geothermal energy are the seasonal differences in consumption reaching from base load of 2 MW in summer to peaks with more than 25 MW in winter. To overcome seasonal changes the use of an HT-ATES (high temperature aquifer thermal energy storage) system is planned. Excess geothermal heat production in summer can be stored in about 1350 m depth in a rim of a former oil field reservoir and producing water with temperatures about 120-130 °C in winter. Using simulations with optimized scheduling, we show that the heat supply transition of the research centre will significantly reduce CO_2 emissions.

1. INTRODUCTION

The energy transition in Germany has progressed strongly in recent years, especially in the area of electricity production (IEA, 2020). The heat transition contributes an important share of about 50% (UBA, 2022) to a successful energy transition but is currently with about 15% renewable sources far less represented than the electricity production by renewables. About half of the heat demand is generated at the municipal level and consists of building heating. As a result, heat demand in northern latitudes is highly subject to seasonal fluctuations. Geothermal heat production can make a decisive contribution to the heat transition, if natural conditions permit. In Germany, three main regions are used for deep geothermal energy: the North German Plain, the South German Molasse Basin and the Upper Rhine Graben. The latter is the subject of the heat supply discussed here and is of particular interest in the region north of the city of Karlsruhe due to the temperature anomaly with temperatures of up to 170°C at a depth of about 3000 meters (Baillieux et al., 2013). Heat production by deep geothermal energy is base-load capable and provides reliable heat all year round, but the production rate is kept constant to avoid large pressure changes in the reservoir, which is why there is a surplus in summer and undersupply in winter due to seasonality of heat demand. Therefore, an important part of an efficient heat supply by deep geothermal energy is a use of the surplus of the summer. We discuss here the possibility of storing the surplus heat in underground reservoirs and using it in the winter months when demand is high, using the example of the Kit Campus Nord research centre north of the city of Karlsruhe.

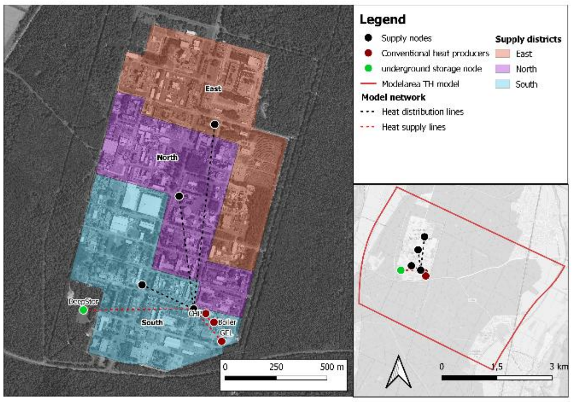

Figure 1: Location of the campus site and model set-up.

The district heating system of KIT Campus North supplies over 300 buildings with 70 to 80 GWh heat per year of which the KIT facilities use about half while the rest is used by other institutions situated on the premise. It consists of a mesh network of pipes with a simple length of 17 km, and one central point where the hot water is injected into the three main supply pipes, "north", "east", and "south". Figure 1 shows an approximation of which area of Campus North is mainly supplied by which main pipe. Due to domestic water heating regulations (DVGW 2004, DIN V 18599), the return temperatures must stay above 60 °C. The system pressure lies between 6 and 7 bar, and the supply temperatures are max. 110 °C. The system is controlled mainly through volume control meaning if a drop in pressure (and/or temperature) is detected, the delivery rate of the pumps is increased thus more hot water is supplied to the network.

The hot water for the district heating system is currently supplied by the following systems:

- A combined heat and power plant (CHP) with a gas engine which supplies the base load of about 2 MW,
- the gas engine test lab (GEL), a testing facility with two gas engines used for experiments which are therefore not controllable, and
- a heating plant with three boilers with a total heating power of 49 MW which run on natural gas but can also use domestic fuel oil as fuel.

Since the heat production is completely based on the burning of fossil fuels, it has a huge impact on the CO2 emissions of KIT. With respect to the aim of reaching “Net Zero“ by the year 2030 (BNN 2021), a transition of the current heat production towards a renewable, less CO2 emitting heat source seems unavoidable.

1.1 Related Work

Geothermal heat generation is often proposed as a sustainable replacement to fossil fuels in district heating system since it is renewable, simple, safe and sustainable (Mock et al. 19997, Ozgener et al. 2006). Schmidt et al. (2018) show that the integration of aquifer thermal storage for seasonal load shifting into district heating systems has a lot of potential in bridging the gap between production and consumption that easily leads to inefficiencies (Guelpa and Verda 2019). There are several ways to model a district heating system found in literature. Component modelling approaches model each aspect of the district heating system, the heat sources, the demand of the end users and the distribution network separately. Hereby different approaches might be used for the components, e.g., the demand side might be modelled using historical data, deterministic methods, or predictive time series (Talebi et al. 2016). On the other hand, holistic models of district heating system look at the whole district heating system as one physical or black-box model. While physical models represent all components as physical equations, black-box models disregard the design of individual components and model the whole system, e.g., with the help of artificial neural networks (Yabanova, I., and Keçebas 2013).

1.2 Contribution to the Field

With the present work, we address the interdisciplinary research area of combining an existing district heating system with a geothermal heat plant. Additionally, we create a physics-based model of the geothermal high-temperature aquifer storage (HT-ATES) into our model of the existing district heating system as described in chapters 4. We use the geothermal storage to enable seasonal load shifting and optimize the scheduling of the generators of the district heating system model. Therefore, we answer the following **research questions**:

(1) What impact has the inclusion of geothermal heat production into an existing second-generation district heating system?

(2) What additional benefits does the inclusion of a geothermal storage bring?

(3) What is the impact on the CO2 emissions of the system?

1.3 Structure of this work

To answer the research questions, the remainder of this paper is organized as follows: In chapter 2 we present our geothermal model of HT-ATES followed by the district heating system model in chapter 3. We then use both models in chapter 4 to simulate different scenarios and present the simulation results. Finally, the simulation results are discussed and contextualized in chapter 5.

2. GEOTHERMAL STORAGE MODEL (HT-ATES MODEL)

In this chapter, we present the modelling of the geothermal storage system. The site of the geothermal storage boreholes is located in the southwest of Campus North as shown in Figure 1.

To simulate the high-temperature aquifer storage, we use a numerical thermo-hydraulic model of the aquifer, the confining cap rocks and the relevant fault systems. The basic hydraulic and thermal model parameters are taken from Stricker et al. (2020), permeabilites has been varried according to a min/max expectation of the subsurface parameters. The model geometry is based on a detailed 3-D geological model.

2.1 Geological setting

KIT Campus North is located on the eastern side of the Upper Rhine Graben, which formed as a rift valley during the Tertiary. The graben has been successively filled with marine and partly fluviatile sediments, which thickness can be more than 2 km in the study area (Böcker et al., 2017). The highest thicknesses are related to marls and sandy marls, occasionally intercalated by sandstone horizons. Petroleum has been produced from some of the sandstone layers over a period of 3 decades in the past, several reservoir horizons are located below the North Campus at depths of 800 m (Niederoedern-Formation), 1000 m (Cyrena Marls, Upper Froidefontaine-Formation) as well as the Meletta Sandstones (Lower Froidefontaine-Formation). The deepest of the reservoirs is to be used for high-temperature storage and lies at a depth of about 1300-1400 m.

2.2 Hydraulic and thermal parameters and boundary conditions

Analysis of porosity and permeability obtained from a nearby deep well indicates an average permeability of about 2.5E-14 m², locally permeabilities higher than 7E-14 m² were measured for the reservoir horizon. The thickness of the reservoir is between 7 m and 10 m. Because of this range, 2 scenarios were considered that cover both, lower and upper bound. The lower bound allows lower production rates, therefore only 5 l/s were applied for these permeabilities, 10 l/s for the upper value range. The fine sandstone has a porosity of about 15 %. Hydrostatic conditions are assumed for the initial pressure distribution in the reservoir with a density of saline fluid of about 1060 kg/m³. The flow boundary conditions are defined as fixed pressure boundaries at the upper and lower model surfaces. Thermal boundary conditions consist of fixed temperature boundaries at top and bottom, where the lower temperature value is calculated according to geothermal gradient, and the temperature of the upper model boundary corresponds to the long-term air temperature of the region. Production and injection wells are implemented as horizontal well sections of about 100 m in the model as well boundary conditions. The injection temperature is 140°C at the hot well and 60 °C at the cold well.

2.3 Simulation set-up

We used Comsol Multiphysics 6.0 software (COMSOL, 2022). The initial temperature and pressure field is set using a steady-state solution. To simulate the storage capacity in long-term operation, 10 years of storage operation with a pumping capacity of 5 and 10 l/s are preceded by the actual simulations in order to heat up the high-temperature storage using transient simulation.

3. DISTRICT HEATING SYSTEM MODEL

In this section we describe the existing district heating system at Campus North as well as the data-driven model we use for simulations.

3.1 Setting at Campus North

The district heating system at KIT Campus North consists of a mesh network of pipes with a simple length of 17 km, and one central point where the hot water is injected into the three main supply pipes, "north", "east", and "south". The system is controlled mainly through volume control meaning if a drop in pressure (and/or temperature) is detected, the delivery rate of the pumps is increased thus more hot water is supplied to the network. The hot water for the district heating system is currently supplied by a combined heat and power plant (CHP) using natural gas, the gas engine test lab (GEL) with two gas engines, and a heating plant with three boilers. The boilers run on natural gas but can also use domestic fuel oil as fuel. The specifications of the existing systems are shown in Table 1.

Table 1: Specifications of existing heat generators.

	CHP	GEL1	GEL2	Boiler
Fuel type	Natural gas	Natural gas	Natural gas	Natural gas
Electrical output (MW)	2.00	4.50	4.50	-
Thermal output (MW)	1.93	3.67	3.67	49.00
Total efficiency (%)	84.7	87.7	87.7	-
$C0_2$ emissions (g/kWh)	160*	180**	180**	290*

*Approx. based on the anual report of KIT (2020).
**Based on carbon factors provided by the U.S. EPA (2020).

Since parts of the district heating system are 30 years old, we only know where the pipes are located as well as their approx. lengths, but we unfortunately do not have the information about the exact type of pipes (incl. material, insulation, internal friction, etc.) that are installed. This information however is crucial to a flow-based simulation of the grid since in a mesh network the direction of flows is nontrivial to determine (Vesterlund et al. 2016) and might change over time depending on supply and demand. Furthermore, for loss calculations information about the pipe insulation are needed. Hence, we use a data-driven approach to create a holistic model the district heating network as a black-box which is described by the measured time series of the temperatures, mass flows, and heat at the three main supply pipes as described in the following section. The advantage of this approach is that we do not have to use estimations due to insufficient data availability, and instead base our simulation on the real measurements of the supply side.

3.2 PyPSA model

We use Python for Power System Analysis (PyPSA) (Brown et al. 2018) to model the district heating system. PyPSA is a free Python toolbox for modelling modern energy networks (electricity, heat, gas, etc.) including generators, storage units, loads, as well as sector couplings and can, among other things, calculate optimal unit commitment. We use PyPSA because it is designed to scale well with large networks and long-time series.

Models in PyPSA are based on graphs and consists of buses (nodes) and links (edges). All other components e.g., generators and loads, connect directly to busses. Figure 2 shows a representation of our PyPSA model which consists of four buses and three links.

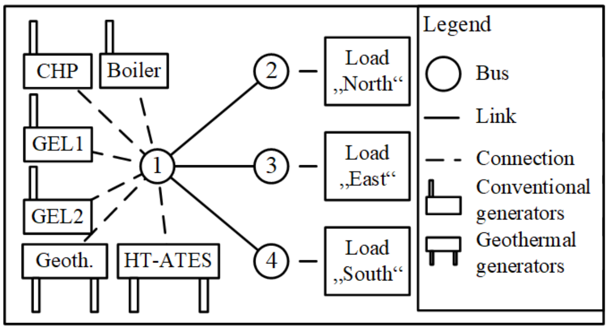

Figure 2: PyPSA model of the district heating system.

Bus 1 represents the heat supply distribution and is connected to the six generators. While the CHP and the boilers are represented as generators which are controllable with a constant maximum power, GEL1 and GEL2 are represented as generators whose power output is set to a time series of measurements since they are used for experiments and thus not controllable. The geothermal heat plant is represented by a generator with a time-varying maximum power output of 9 MW reduced by the power needed to refill the geothermal storage. Lastly, the geothermal storage HT-ATES is also represented by a generator whose maximum power output varies over time and is provided by the geothermal storage model. Bus 2, bus 3, and bus 4 represent the three main supply pipes and are connected to the loads of the north, east, and south pipe, respectively. Furthermore, they are all individually connected to Bus 1 thus representing the distribution of the supplied heat onto the three main supply pipes.

We are aware that this model contains a lot of simplifications. For instance, the conversion losses caused by heat exchangers of the heat provided by the geothermal heat plant as well as HT-ATES are neglected. Since in the present work, we only look at the district heating systems thermal side, we also do no take the coupled electricity side into account, e.g., we partially disregard the electrical power the pumps of the geothermal heat production would need. Furthermore, ramp constraints, minimum up and down times as well as the electricity produced by the conventional generators are not accounted for in our simulations.

4. SIMULATION

In this section we describe the simulation setup and compare different scenarios and their influence on the CO_2 emissions.

4.1 Simulation setup

Our simulation consists of two steps: First, we simulate the geothermal model with COMSOL, then we use the simulated thermal power HT-ATES supplies as input for the PyPSA simulation, as shown in Figure 3.

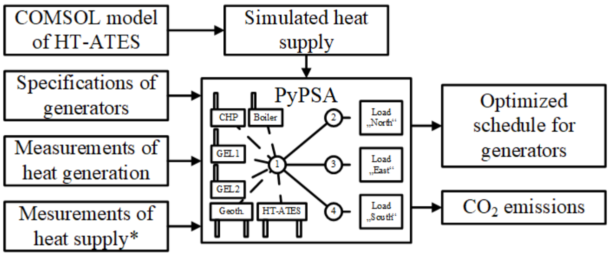

Figure 3: Simulation setup.

For the simulations done with PyPSA, we use historical measurements from 01[st] July 2017 to 30[th] June 2018. Figure 4 shows the heat demand of the three main pipes as well as the heat supplied by GEL1 and GEL2 during the simulation period.

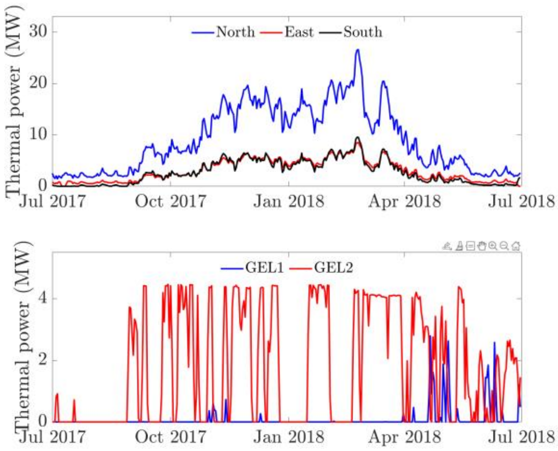

Figure 4: Heat demand and heat supplied by GEL1 and GEL2 during simulation period.

The total heat demand during the simulation period equals 79.7 GWh of which the heat supplied by GEL1 and GEL2 combined amounts to 16.2 GWh resulting in a total of 2916 t CO2 emissions. Since GEL1 and GEL2 are not controllable, they will not be displayed in the upcoming figures of simulation results, but their emissions are counted as part of the total emissions.

4.2 Simulation results

First, we simulate the existing system without geothermal heat supply and HI-ATES to generate a baseline to compare against. As shown in Figure 5, this results in the CHP being used to satisfy the base load of approx. 2 MW and the boiler taking care of the peak loads especially during winter where the demand reaches over 25 MW. Overall, the CHP supplies only 16.6 GWh while the Boiler supplies 46.9 GWh heat, resulting in about 16258 t CO2 emissions excluding GEL1 and GEL 2.

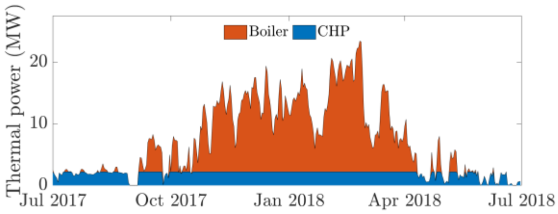

Figure 5: Simulation scenario 1 - Heat supplied by CHP and Boiler during.

In our second scenario, we include the geothermal heat plant which could constantly produce 9 MW thermal power, which is a very rough assumption of possible heat production using moderate flow rates at reservoir temperatures around 170 °C. This results in both, the CHP as well as the boiler, only being used during the heating period in winter from November until April, while the geothermal heat plant easily takes care of the rest of the year by itself, as shown in Figure 6. This reduces the CO2 emission by more than half but also results in about 40% of the available thermal power from the geothermal heating plant not being dispatched due to low demand in summer, meaning there is a big potential for seasonal load shifting.

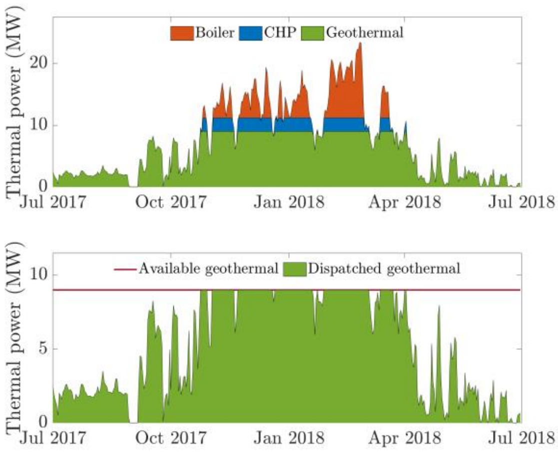

Figure 6: Simulation scenario 2 - Heat supplied by CHP, Boiler, and the geothermal heat plant as well as comparison of its available and dispatched thermal power.

To explore this potential, we compare two scenarios where we include die HT-ATES geothermal storage. First, we simulate a scenario with a pump rate of 10 l/s which signifies the best-case scenario for the geothermal storage if permeabilities are sufficient to keep the draw down in the wells less than 500 m. We use the geothermal storage as generator from 01st November 2017 until 31st March 2018. As shown in Figure 7, this results in a better usage of the available geothermal power and cuts the usage of the boilers nearly in half.

Lastly, we simulate a scenario with a pump rate of 5 l/s which corresponds to a more conservative scenario for the geothermal storage, linked to lower permeabilities of the reservoir. As shown in Figure 8, the lower pump rate lowers the effect the storage has during winter which gets compensated mostly by the boiler. Furthermore, the lower pump rate results in a decrease in the dispatch of thermal power from the geothermal heating plant during summer but allows for a bit more usage of geothermal power during autumn and spring. This shows that there is further optimization potential regarding the usage of the geothermal storage especially during those seasons.

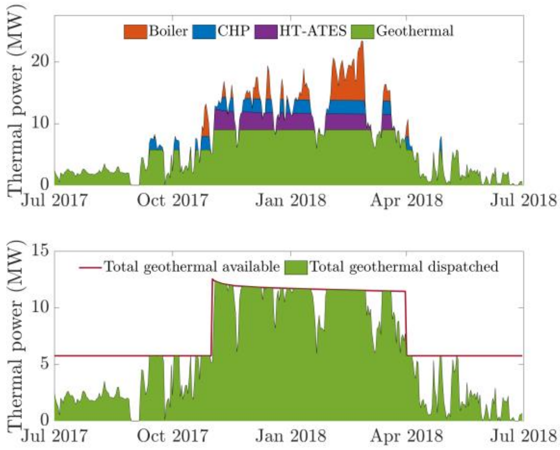

Figure 7: Simulation scenario 3 – Heat supplied by CHP, Boiler, geothermal heat plant, and HI-ATES with pump rate of 10l/s and comparison of available and dispatched thermal power from geothermal heat plant and HI-ATES combined.

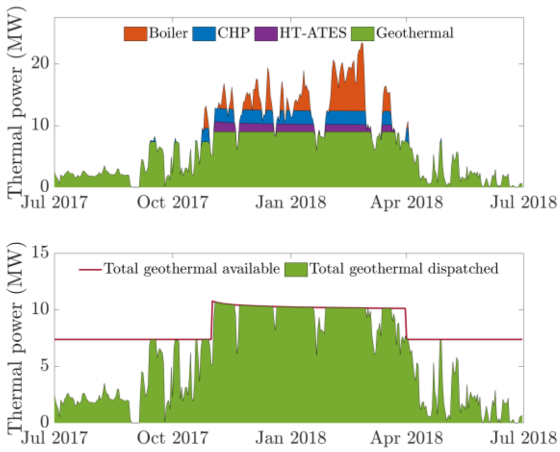

Figure 8: Simulation scenario 4 – Heat supplied by CHP, Boiler, geothermal heat plant, and HI-ATES with pump rate of 5l/s and comparison of available and dispatched thermal power from geothermal heat plant and HI-ATES combined.

4.3 Discussion of simulation results

Finally, we present the results of all scenarios in Table 2. With consideration of the two main comparison indicators, total CO2 emissions and geothermal power usage, we evaluate the impact of geothermal heat plant and the additional geothermal storage HT-ATES.

Table 2: Simulation results for all scenarios.

	Supplied heat (GWh)				CO_2 emissions (t)					Usage of geotherm. heat (%)***
	CHP	Boiler	Geoth.	HT-ATES	CHP	Boiler	Geoth.*	HT-ATES*	Total**	
Scenario 1	16.59	46.91	0	0	2654.4	13604	0	0	19174	0
Scenario 2	6.21	11.0	46.33	0	993.6	3176	1205	0	8290	59%
Scenario 3	5.45	5.87	44.94	7.25	872	1702	1168	189	6847	78%
Scenario 4	5.75	8.22	45.95	3.58	920	2384	1195	93	7508	69%

*** CO_2 emissions of 26 g/kWh to account for pumps. ** Including 2916 t CO_2 emissions of GEL1 and GEL2.**
***** Including heat used to fill HT-ATES during summer.**

We observe that the addition of the geothermal power plant has a huge impact on the total CO2 emissions reducing them by more than 50%. While this is great, the results also show that more than 40% of the heat produced by the geothermal power plant is not used due to being available during summer. This shows the great potential for seasonal load shifting. Hence, we observe that when adding HT-ATES, we can use 10-20% more of the generated heat from the geothermal heat plant. This reduces the CO2 emissions by another 7% in the best and 4% in the worst case, reducing especially the usage of the boiler. The results also indicate that a second seasonal geothermal storage might be viable in order to completely use the heat produces by the geothermal heat plant.

In summary, the inclusion of geothermal heat production shows a significant potential in lowering the CO2 emissions. However, a lot of that potential goes unused during summer which can partially be compensated for by including the geothermal storage HT-ATES for seasonal load shifting.

5. CONCLUSION

In the present paper, we (1) explore the impact of adding geothermal heat production to an existing second-generation district heating system, (2) present the additional benefits of a seasonal geothermal storage, and (3) discuss the implications this has on the CO2 emissions of the system.

We include the geothermal heat plant into a model of the existing district heating system and show that, through optimal scheduling of the generators, this drastically lowers the CO2 emissions. Since the geothermal heat plant produces heat contuniously, it also generates unused heat during summer. Hence, we include the geothermal storage HT-ATES which enables us to shift unutilized heat from the summer to the heating period in winter and further reduces the CO2 emission by 4-7% and increases the utilization of the available geothermal heat.

In future work, we recommend the extension of the models' complexity, meaning the inclusion of a complex deep geothermal model for the geothermal heat plant as well as a more complex model of the existing district heating system. Ideally, such a model should include sector coupling to account for the benefits of CHP's electricity production as well as to better account for the electricity used by the pumps of the geothermal systems. In terms of the simulation, longer time periods including predictions of future heat demand can also be investigated. Lastly, an optimization of flow rates for both, the geothermal heat plant and HT-ATES, might be worth looking into.

In the present consideration, other possibilities to use the summer surplus heat are not considered. These should be considered in a further step in the modelling. These include, for example, electricity production (sector coupling). Another interesting utilization option is the generation of cooling from geothermal energy, especially research facilities with laboratories, such as at KIT Campus North, have a high cooling demand.

REFERENCES

Baillieux, P., Schill, E., Edel, J.-B., Mauri, G.: Localization of temperature anomalies in the Upper Rhine Graben: insights from geophysics and neotectonic activity, *International Geology Review*, **55(14)**, (2013), 1744-1762

BNN: Karlsruher Uni will CO2-neutral werden - KIT tischt bei der digitalen Jahresfeier Riegel aus Insektenmehl auf, *Badische Neuste Nachrichten (BNN)*, URL: https://bnn.de/nachrichten/baden-wuerttemberg/kit-karlsruhe-tischt-digitale-jahresfeier-riegel-aus-insektenmehl-auf (last visited 06.05.2022), published in German, Karlsruhe, Germany (2021)

Böcker, J., Littke, R., Forster, A.: An overview on source rocks and the petroleum system of the central Upper Rhine Graben, *International Journal of Earth Sciences*, **106**, (2017), 707–742

Brown, T., Hörsch, J., and Schlachtberger, D.: PyPSA: Python for Power System Analysis, *Journal on Open Research Software*, **6(1),** (2018).

COMSOL: Comsol Multiphysics® v. 6.0. www.comsol.com. COMSOL AB, Stockholm, Sweden (2022).

DIN V 18599: Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung, *DIN V 18599*, Beuth Verlag, published in German, Berlin, Germany (2018).

DVGW: W 551 Code of Practice - Drinking water heating and drinking water piping systems; technical measures to reduce Legionella growth; design, construction, operation and rehabilitation of drinking water installations, DVGW, (2004).

Guelpa, E. and Verda, V.: Thermal energy storage in district heating and cooling systems: A review, *Applied Energy* **252**, (2019).

IEA: Germany 2020: Energy policy review. *International Energy Agency*, Paris, France, (2020), 228.

Karlsruhe Institute for Technologie (KIT): Jahresbericht 2020 des Karlsruher Instituts für Technologie (KIT), DOI:10.5445/IR/1000142169, published in German, Karlsruhe, Germany (2020).

Mock, J.E., Tester, J.W., and Wright, M.P.: Geothermal energy from the Earth: its potential impact as an environmentally sustainable resource, *Annual Revview of Energy and the Environment*, **22**, (1997), 305-356.

Ozgener, L., Hepbasli, and A., Dincer, I.: Effect of reference state on the performance of energy and exergy evaluation of geothermal district heating systems: Balcova example, *Building and Environment*, **41(6)**, (2006), 669-709.

Schmidt, T., Pauschinger, T., Sorensen, P.A., Snijders, A. Djebbar, R., Boulter, R. and Thornton, J.: Design Aspects for Large-scale Pit and Aquifer Thermal Energy Storage for District Heating and Cooling, *Energy Procedia*, **149**, (2018), 585-594.

Stricker, K., Grimmer, J. C., Egert, R., Bremer, J., Korzani, M. G., Schill, E., and Kohl, T.: The Potential of Depleted Oil Reservoirs for High-Temperature Storage Systems, *Energies*, **13**, Basel, Switzerland, (2020), 6510.

UBA (Umwelt Bundesamt): Erneuerbare Energien in Deutschland. Daten zur Entwicklung im Jahr 2021. Umweltbundesamt (2022), 28p.

U.S. Environmental Protection Agency (EPA): Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2018, EPA 430-R-20-002 (2020).

Vesterlund, M., Toffolo, A. and Dahl, J.: Simulation and analysis of meshed district heating network, *Energy Conversion and Management*, **112**, (2016).

Yabanova, I., and Keçebas, A.: Development of ANN model for geothermal district heating system and a novel PID-based control strategy, *Applied Thermal Engineering*, **51**, (2013), 908–916.

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Author contributions

Author contributions according to Contributor Roles Taxonomy (CRediT, https://www.casrai.org/credit.html): *Conceptualization*: P.Z., F.B.; *Methodology*: P.Z., F.B.; *Software*: P.Z., F.B.; Investigation: F.B., P.Z.; Data curation: P.Z., U.S.; *Writing - original draft:* P.Z., F.B.; *Writing - review and editing:* P.Z., F.B., S.W. E.S.; *Visualization:* P.Z., F.B.; *Supervision:* S.W., E.S., V.H.; *Project administration:* K.S., E.S.; *Funding acquisition:* E.S., V.H.