Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Environmental Performance and Key Drivers in Geothermal District Heating: Comparative LCA of Three Real Plants in the Southern German Molasse Basin

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Keywords: Geothermal district heating, Life Cycle Assessment, Environmental performance, Southern German Molasse Basin, Peak load and redundancy, Auxiliary energy demand

INTRODUCTION

Geothermal energy has gained attention as a promising renewable energy source and a potential alternative to Europe's predominantly fossil-fuel-based heating sector, which only has a 26.2 % renewable share (eurostat, 2022). Thereby, significantly lagging behind the goal of 42.5 % by 2030 (the European Parliament and the Council Of The European Union, 2023). While, in theory, geothermal energy has a renewable character, its environmental impacts differ greatly depending on the location and operational strategies. The range, thereby is significant - Zhang et al. (2020) reported 187.7 g CO_2 eq./kWh for a theoretical plant in China, whereas Douziech et al. (2021) found values as low as 3.8 g CO_2 eq./kWh for a French heating plant. This range begs the question how to define a renewable source – one approach was proposed by the EU Technical Expert Group on Sustainable Finance (2020) who defined a global warming potential (GWP) limit of 100 g CO_2 eq./kWh as being in line with the Paris Climate goals of limiting the global temperature increase to a minimum of 1.5 °C. This limit is designed to decrease by 5 % every five years, reaching net zero by 2050. Given the great potential of the Southern German Molasse Basin for geothermal systems, with up to 40 % of Bavaria's heat demand potentially being met (Keim et al., 2020), this study analyses three real operating plants. In contrast to previous research, which often relies on theoretical assumptions or single-case analyses, this work presents a comparative life-cycle assessment (LCA) of multiple operational geothermal district heating systems under real-world conditions. This comparative approach enables the systematic identification of key parameters that influence environmental performance, revealing how site-specific and operational factors shape overall sustainability outcomes. The findings provide empirically based insights into the factors driving environmental performance and offer practical indications for improving the design and operation of future geothermal district heating systems.

1 LCA METHODOLOGY

By conducting the LCA, the corresponding norms, namely ISO 14040 and 14044 (International Organization for Standardization, 2006, 2020), were applied. Therefore, the entire life cycle is analyzed in detail, encompassing the construction, operation, and decommissioning of the plants. Generally, the LCA includes four phases: definition of goal and scope, inventory analysis, impact assessment, and interpretation. However, detailed life cycle inventories have been omitted due to the constraints of this editorial format. In this respect, the format differs from that of the ISO. Additionally, to avoid exceeding the format's limits, the LCA results are only presented for greenhouse gas emissions. An extensive elaboration of the methods and LCIs can be found in previous work in Uhrmann et al. (2025).

1.1 Data source and methods

To the extent possible, real plant data provided by the operators were used for the inventories; otherwise, suitable literature, primarily from Frick et al. (2010), was applied. To be in line with the proposed quality standard from the guidelines by Parisi et al. (2020)It was made sure to include all the relevant inventory in- and outputs. The life-cycle assessment was conducted using SimaPro (v9.6.0.1) (PRé Sustainability) in combination with data from the ecoinvent database (v3.10). The “allocation cut-off by classification” system model was applied, and the corresponding impact factors for the environmental assessment were obtained from ecoinvent. In this study, on the one hand, the functional unit of 1 kWh supplied heat was chosen – thereby assuming a lifetime of 30 years (Parisi et al., 2020). Depending on the particular life cycle phase, either absolute values were consulted for comparability purposes, or the values were averaged over a year.

1.2 Geothermal plants

For this study, three real very different geothermal plants were assessed, all located in the southern German molasse basin. Their specifications and boundary conditions are detailed in Table 1:

Table 1. Specifications of the analyzed geothermal plants, plant A and B from (Uhrmann et al., 2025)

Parameter	Unit	Plant A	Plant B	Plant C
Commissioning year	a	2005	2011	2021
Installed geothermal power	MW	16.7	8.2	60
Average yearly net heat output	MWh	55 497	46 876	347 464
Geothermal heat share	%	95.01	73.72	100.00
Peak load and redundancy heat share	%	4.99	18.28	0
Cogeneration unit heat share	%	0	8.00	0
Electricity demand network pumps/total heat	MWh_{el}/MWh_{therm}	0.012	0.009	n. c.*
Electricity demand downhole pumps/geothermal heat output	MWh_{el}/MWh_{therm}	0.0922	0.1022	0.0674
Residual power demand/geothermal heat output	MWh_{el}/MWh_{therm}	0.0002	0.0112	0.0052
Average measured well depth	m	4257	2308	3900
Number of wells	-	2	3	6
Brine temperature	°C	105	73	100
Brine Flow rate	l/s	93	100	120
DHN length	km	48.5	21.2	n. c.*

* not considered

They differ in their geological boundaries, like well depth, brine temperature, and brine flow rate, depending on their location in the Molasse Basin. The plant located north of Munich, plant B, has the lowest well depth, and plant A, located south of Munich, exhibits the highest. Plant C is located in the central urban Munich area, lying between the previously mentioned areas. Other differences include their consumer structure – whereas plant A and B are located in a rather rural area and are the sole suppliers of the heat network, therefore needing peak load and redundancy systems, plant C is located in the urban Munich area, where it supplies heat to a bigger district network with other heat producers. Plant A uses crude oil and plan B mainly natural gas for the peak load and redundancy boilers. Additionally, regarding plant composition, Plant B utilizes a natural gas-run cogeneration unit to meet the majority of its electricity demand, as well as provide additional heat. A detailed description of plant A and B including their LCIs can be found in (Uhrmann et al., 2025). Since all the plants have different commissioning years and significant electricity demand, the respective German mix for each year of operation is included. Past mixes are implemented using data from the German federal network agency (2023), and the development of the German mix by Fattler et al. (2019) is applied to the future mix.

2 RESULTS AND DISCUSSION

The environmental impacts of the plants differ greatly – hereby plant A falls at 81.37 and B at 195.18 g CO2 eq./kWh (Uhrmann et al., 2025) plant C has significantly lower impacts with only 23.85 g CO2 eq./kWh. The main contributors are the operation phase of the plants, namely the electricity consumption mainly caused by the downhole pumps but for plant a and B also the network pumps. Since the decommissioning plays a negligible role for the environmental impact, it is not further analyzed here but is included in the aforementioned total values per plant and kWh.

The following subsections compare the results and contribution of the different plants. To show their true impact, absolute values for the construction phase are shown. For the operational phase, the annual impacts are considered. This allows the parameters with the highest impact to be identified.

2.1 Construction Phase

Figure 1 shows the absolute values of the construction phase for subsurface, surface, and DHN components for the plants A, B, and C. For each category, the biggest single contributors are detailed, such as the casing for the subsurface or the trenchwork for the DHN. Since only plants A and B have peak loads and redundancy infrastructure, and only plant B has a cogeneration unit, these components are detailed for this category. The DHN is not analyzed for plant C since it is not the only supplier of a very large DHN, and no data was available.

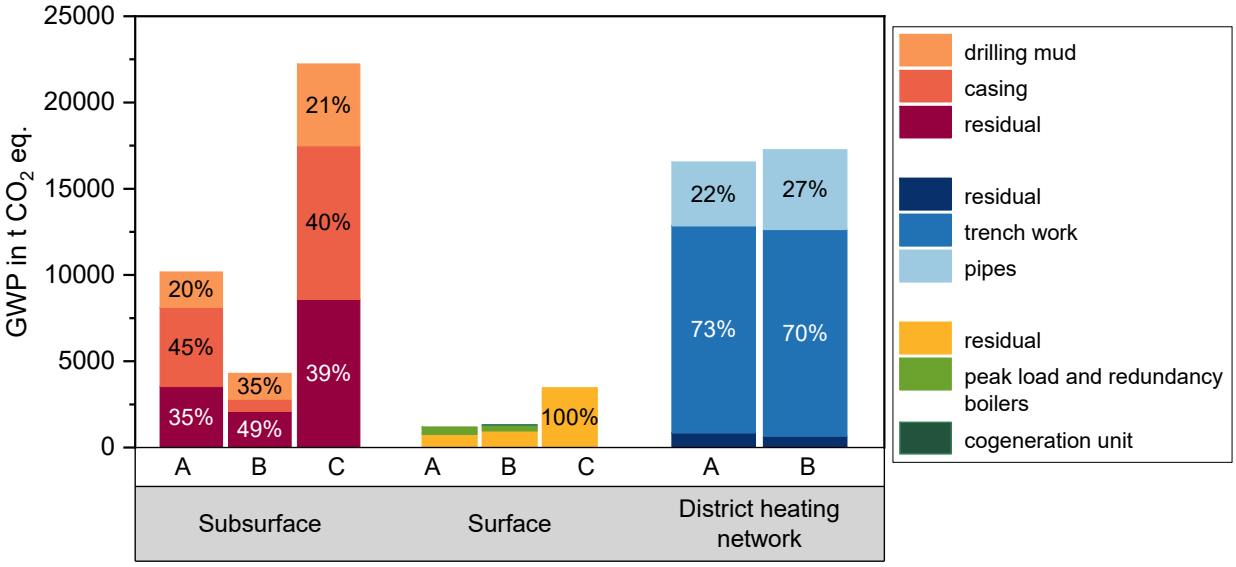


Figure 1 Absolute GWP for the construction of the subsurface and surface components as well as the district heating network for the plants A, B and C

In general, it is apparent that the subsurface and the DHN have a larger impact; the surface components are almost negligible in comparison for plants A and C. However, due to the smaller well depths of plant B (with an average of 2308 m compared to around 4000 m of plant A and C, see Table 1) the subsurface GWP value of 4 295 t CO_2 eq. for plant B is in the same magnitude it's surface impact of 1 308 t CO_2 eq.. As expected, the largest plant, plant C with six wells, shows the biggest impact with in total 22 232 t CO_2 eq. for the subsurface components and 3 450 t CO_2 eq for the surface components.

Looking at the results for DHN, it seems somewhat surprising that the GWP is almost the same, even though plant B's DHN length is less than half of plant A's (see Table 1) with 21.2 km compared to 48.5 km. This can be explained by the pipe size distribution: plant B's DHN is composed of 47% main distribution network, compared to plant A's 11 % (Uhrmann et al., 2025). This means that for plant B, the share of larger pipe diameters and, therefore, higher material inputs is significantly larger than for plant A.

2.2 Operation Phase

To analyze the operational phase, the results are related to one-year to facilitate accurate comparison among the three plants (see Figure 2). The maintenance work of the plant is not shown here since its impact is negligible for all plants. The GWP values per plant are shown for the auxiliary fuel-based energy – for plant A, this means the oil-based peak load and redundancy, for plant B, the natural gas-based peak load and redundancy coverage, whereas plant C doesn't use any fuel-based auxiliary energy. Additionally, the GWP values are paired with the related amount of energy (dark blue bars and right y-axes) – for the case of fuel-based auxiliary energy, that means the heat provided by fuel-based sources including the cogeneration unit of plant B. For the electricity demand the main sources i. e. well pumps and for plant A and B the network pumps are detailed. These values are paired with the electricity demand for each plant. It should be noted that for plant B 70 % of the demand is covered by the cogeneration unit.

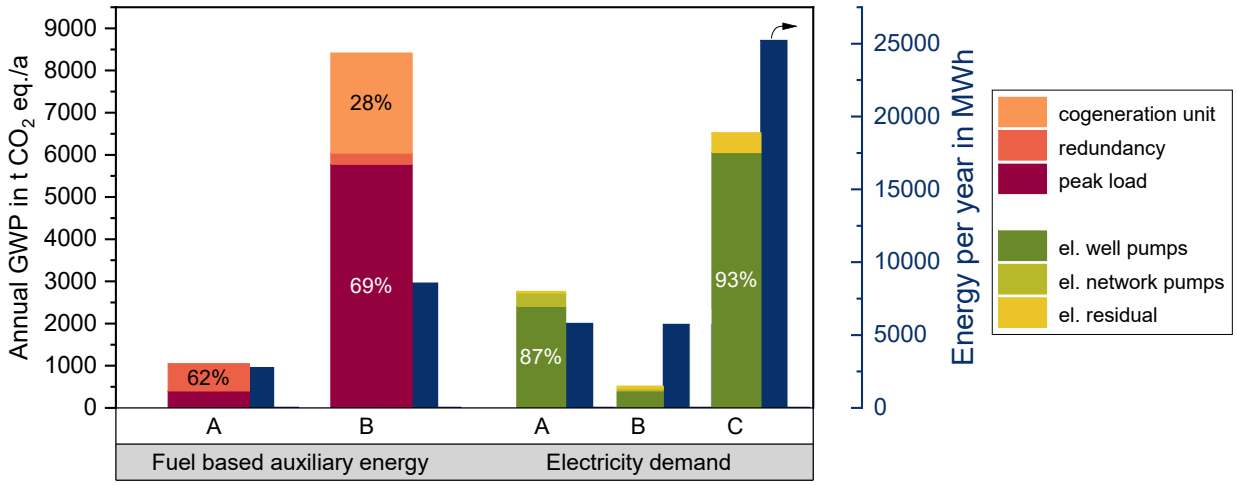


Figure 2: The GWP values per year for the operation phase of plants A, B and C (left, colourful bars and left-hand axis) and energy per year regarding electricity demand and auxiliary energy per plant (blue, right bars and right-hand axis)

Regarding peak load and redundancy, notable differences can be observed between the three plants. Plant A exhibits a high share of peak load operation, primarily due to unfavorable brine conditions that frequently cause pump failures and result in increased maintenance requirements. In contrast, Plant B shows a considerably higher need for additional heat supply because of its relatively low brine temperature. Furthermore, it uses natural gas in a cogeneration unit to cover around 70 % of its electricity demand (for the section electricity demand only the coverage by the grid is shown), making fuel-based energy the dominant contributor to its global warming potential (GWP). For Plant A, the situation is reversed: here, electricity consumption from the grid represents the largest emission source. Across all plants, electricity demand from the downhole pumps accounts for the majority of total electricity-related emissions. The impact of electricity consumption also depends on the year of commissioning, as the German electricity mix has gradually incorporated a higher share of renewables but still retains a significant fossil component. Consequently, the electricity mix applied for Plant C (commissioned in 2021) results in a substantially lower environmental impact compared to Plant A (commissioned in 2005). Overall, Plant C achieves the lowest GWP among the analyzed systems, mainly due to its significantly higher geothermal heat output and the absence of additional emissions from peak load or redundancy systems.

3 CONCLUSION

This study provides a comparative life-cycle assessment of three operational geothermal district heating plants in the Southern German Molasse Basin, highlighting how geological, technical, and operational factors shape the environmental performance of such systems. The results show that critical parameters vary depending on the geological boundary conditions and the configuration of the district heating network (DHN). For plants with shallower wells, the relative impact of the DHN is considerably higher compared to the subsurface and surface installations. The consumer structure and the associated network layout — particularly the required distances and pipe size distribution - are therefore decisive for the overall environmental footprint.

Electricity consumption was identified as the dominant contributor to global warming potential (GWP) across all plants, mainly due to the high energy demand of the downhole pumps. The share and origin of electricity supply play a key role: when grid electricity with a fossil-based mix is used, it significantly increases the total impact. Similarly, the need for auxiliary energy depends strongly on the temperature of the geothermal source. In cases such as Plant B, where the brine temperature is only slightly above 70 °C, additional energy is required to reach the DHN supply temperature. If this energy is provided by fossil fuels, the resulting emissions substantially increase the GWP. The analysis further shows that integration into a large, multi-source district heating network, as in the case of Plant C, leads to higher full-load hours, a more balanced annual operation, and a lower relative impact. Higher simultaneity and base load demand, particularly during summer months, enable more efficient system utilization and reduce the need for redundant peak-load capacities.

Overall, the findings demonstrate that reducing fossil-based electricity use and optimizing system integration represent the greatest potential for minimizing environmental impacts in geothermal district heating. The comparative analysis of real operating plants provides valuable, transferable insights that can guide the

planning, design, and operation of future geothermal systems under varying geological and infrastructural conditions.

ACKNOWLEDGEMENTS

We gratefully acknowledge the Bavarian State Ministry of Science and Arts within the framework of the "Geothermal Alliance Bavaria" project for funding. Furthermore, Joshua Pohle is acknowledged for his contribution on the LCA-model for plant B. and Laura Vollath for her work on the LCA model of plant C.

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