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Analysis of Different Climate-Neutral Heat Supply Concepts for a District Heating System near Munich with Deep Geothermal Heat as the Primary Heat Source

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Abstract. District heating systems are one key element of the transition towards a climate-neutral heat supply since they allow for the use of various renewable energy sources and the increase of renewable heat generation, in particular when combined with seasonal thermal energy storage. Deep geothermal heat is a renewable heat source that can be used to cover the thermal base load of such a district heating system. Also in combination with other renewable heat sources, such as solar thermal or heat pumps, a climate-neutral heat supply for districts or even complete cities can be realised. This paper deals with the analysis of different climate-neutral heat supply concepts that were elaborated for a district heating system currently in the planning phase using deep geothermal heat as the primary heat source, located in the town of Graefelfing near Munich, Germany. The authors present, discuss and assess various options regarding renewable heat sources and including (seasonal) thermal energy storage, to fully cover the thermal loads of a new district heating system in a technically, economically and environmentally favourable way. As a result of this study, a heat supply concept was selected, in which a heat pump using the return flow of the deep geothermal circuit as a heat source maximises the utilisation of the available deep geothermal heat source to cover more than 95 % of the annual heat demand by deep geothermal heat combined with a heat pump.

Keywords: District Heating, Deep Geothermal Heat, Heat Supply Concept, Energy Storage

1. Introduction

The town of Graefelfing has around 14,000 inhabitants and is located in the vicinity of Munich in an area that is suitable for the realisation of deep geothermal projects through the technology of extracting heat from underground hydrothermal layers in a depth of around 3 km by means of a so-called doublet system, i.e. with an extraction and an injection well. The municipality of Graefelfing wants to implement a district heating system for parts of the town to use the existing geothermal potential and to replace the current heat supply which is essentially based on decentralised boilers fuelled with fossil natural gas.

The Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE) of the University of Stuttgart elaborated and analysed different heat supply concepts for this district heating system using deep geothermal heat as the primary heat source. This means that the concepts mainly differ from each other by the type of auxiliary heat sources used to cover the thermal peak loads and how these auxiliary heat sources are integrated into the overall heat supply concept. The main objective was to compare and evaluate the different concepts from a technical and economic perspective under the local boundary conditions given.

2. Methodology

In a first step, the authors carried out calculations for the determination of the heat demand and developed scenarios for the initial setup and further extension of the district heating system together with representatives from the municipality. Based on this and the given information about the geothermal potential at the designated geothermal drilling site, a rough estimation of the annual share of geothermal heat related to the total heat demand was possible. In a further step, various concepts for covering the thermal peak loads were elaborated. The concepts were first of all analysed from a technical and energetic point of view, i.e. through basic energy balances with a resolution of 15 min, for instance the necessary thermal powers and the resulting annual shares of the different heat sources of covering the total heat demand were calculated. In addition, also dynamic system simulations using the software TRNSYS [1] were carried out to analyse specific aspects in detail.

Based on these technical results, the authors carried out an economic analysis by determining the heat generation costs. In this context, also the current German BEW funding scheme [2] for the setup of new district heating systems was considered. Furthermore, an environmental analysis was carried out for the selected heat supply concept by calculating for instance the savings in CO_2 equivalent emissions between the current way of heat supply and this designated future heat supply concept.

3. Results

3.1 Analysis of local boundary conditions

3.1.1 Annual heat demand and supply

In cooperation with the municipality of Graefelfing and further contracting parties involved, two heat supply scenarios (HSS) were defined considering a reasonable extent and time line for the setup and further extension of a district heating system in parts of Graefelfing. According to this schedule, the implementation of the district heating system and the heat supply infrastructure for the first heat supply scenario (HSS 1) shall be carried out in the year 2025. This is followed by a linear increase of the heat supply until **HSS 1** with a total annual heat supply of around **60 GWh/a** incl. thermal losses of the district heating system is reached in the year 2028. In the year 2025, no heat is supplied via the district heating system and in the two first operating years of 2026 and 2027, the annual heat supply via the district heating system accounts for about 20 and 40 GWh/a, respectively.

When HSS 1 is reached in the year 2028, the district heating system and the heat supply infrastructure shall be extended until a heat demand of about **93 GWh/a** incl. thermal losses of the district heating system is reached in the year 2035 (**HSS 2**). Between the years 2028 and 2035, the increase in heat supply via the district heating system shall be linear. After the year 2035, the heat supply via the district heating system shall be kept constant until the end of the period of consideration in the year 2045.

The abovementioned heat supply figures for the two heat supply scenarios HSS 1 and 2 were derived from calculations of the annual heat demand which are based on data made available by the municipality of Graefelfing, such as heat consumption data of public buildings of the municipality and geotagged heat demand data analysed with the help of geographical information system (GIS) software QGIS [3].

For the two heat supply scenarios, also load profiles containing the required thermal power with a time resolution of 15 min were determined. The corresponding calculations are mainly based on reference load profiles as defined in VDI 4655 [4] and by applying a simultaneity factor of 65 %.

Table 1 shows the results of the calculations for the heat demand and the maximum thermal power at the substation level, i.e. excl. thermal losses of the district heating system, and at the heat generation level, i.e. incl. thermal losses of the district heating system, for the two heat supply scenarios HSS 1 and 2.

Table 1. *Heat demand and maximum thermal power in the two heat supply scenarios (HSS)*

	HSS 1	HSS 2
Total annual heat demand at substations of heat consumers in GWh/a	50.1	78.0
Annual heat demand incl. thermal losses of the district heating system in GWh/a	59.6	92.9
Total maximum thermal power at substations of heat consumers in MW	24.7	38.6
Maximum thermal power incl. thermal losses of the district heating system in MW	25.8	40.3

The heat demand incl. thermal losses of the district heating system are the same figures as mentioned above related to the definition of the heat supply scenarios since this is the relevant amount of heat that must be generated and supplied into the district heating system. The figures incl. thermal losses are also relevant for the elaboration of the heat supply concepts and the dimensioning of the heat sources, generators and thermal stores.

3.1.2 Deep geothermal potential

Based on data made available by the municipality of Graefelfing and the further contracting parties involved, the deep geothermal potential for a typical doublet system is given by a **nominal thermal power of about 12 MW** which is available constantly throughout the year and thus accounts for a total available amount of heat of about 105 GWh/a. The nominal thermal power of 12 MW is based on the assumption of an average supply and return temperature of 90 and 57.5 °C, respectively, and a water flow rate of 99 l/s for the deep geothermal heat source.

However, the actual return temperature of the deep geothermal circuit depends on the applied flow rate which might be adapted at least seasonally according to the heat demand and on the return temperature of the district heating system. Furthermore, the use of a heat pump using the return flow of the deep geothermal circuit as a heat source can further decrease the return temperature and hence increase the amount of extracted heat from the deep geothermal heat source.

3.1.3 Potential for seasonal thermal energy storage

In a distance of about 800 m from the envisaged geothermal drilling site, there is an abandoned gravel pit that was identified as a potential site for a seasonal thermal energy store. The gravel pit could be transformed into a pit thermal energy store (PTES) with hot water as the thermal storage medium. In this case, the **available water volume** accounts for about **300,000 m³**.

3.1.4 Further considered boundary conditions

For the district heating system, a **supply temperature of 85 °C** and a **return temperature of 60 °C**, at the substations of the heat customers, were determined as a boundary condition. The heat supply infrastructure shall be established at a building in immediate vicinity of the geothermal drilling site. Beside this, there are some already existing decentral combined heat and power (CHP) plants and gas boilers that were included in the elaboration of the heat supply concepts. The total thermal power of all already existing decentral CHP plans and gas boilers accounts for about 3.2 MW, thereof 0.3 MW for the CHP plans and 2.9 MW for the gas boilers. The total electric power of the decentral CHP plants accounts for about 0.2 MW.

Concerning the fuel for these decentral CHP plants and gas boilers, but also for heat generation plants installed near the geothermal drilling site, a switch from fossil natural gas to biomethane shall be conducted in the year 2028.

3.2 Comparison of heat demand and deep geothermal potential

Before the elaboration of the heat supply concepts, a comparison between the annual heat demand and the available deep geothermal potential as defined in Section 3.1.2 of this paper was carried out with both a time resolution of one month and 15 min. The objective of this comparison was to gain a rough estimation of the annual share of geothermal heat of the total heat demand as well as an analysis of the suitability of using (seasonal) thermal storage.

As a result of this comparison, it can be concluded that for HSS 1, even without the use of any thermal storage, deep geothermal heat covers about 90 % of the annual heat demand. On a monthly basis, there is no heat deficit, i.e. the available deep geothermal heat exceeds the heat demand in every month. Therefore, the use of seasonal thermal storage is not reasonable in HSS 1. However, the use of short-term thermal buffer storage is reasonable to ensure a smother operation of the entire system and also to further slightly increase the annual share of deep geothermal heat of the total heat demand.

In contrast to that, the use of seasonal thermal storage is basically reasonable in HSS 2 since there are several months in a row with a heat demand being less than the available deep geothermal heat. This means that in the summer months, when the available deep geothermal heat exceeds the heat demand, a seasonal thermal energy store can be charged, while it is discharged in the autumn and winter months. Without any thermal storage, the available deep geothermal heat covers about 75 % of the annual heat demand, based on a calculation with a time resolution of 15 min, whereas with a seasonal thermal energy store, a geothermal fraction of around 90 % can be achieved.

3.3 Comparison of different heat supply concepts

3.3.1 Elaboration of heat supply concepts

As was already pointed out in Section 3.2, quite a high share of the annual heat demand is already covered by the available deep geothermal heat. Therefore, the main objective of the elaboration of the heat supply concepts was to define auxiliary heat sources used to cover the thermal peak loads and to elaborate suitable ways for their integration in the overall heat supply concept incl. the provision of reserve capacity. Basically, the following components were considered for these tasks:

- CHP plants
- gas boilers
- heat pumps
- electric boilers
- woodchips boilers
- thermal buffer stores
- seasonal thermal energy stores

Solar thermal collectors were not considered here, but in another study about the future district heating system in Graefelfing carried out prior to the analysis presented in this paper.

With the boundary conditions there, the use of solar thermal collectors was found to be reasonable in combination with a pit thermal energy store (PTES) and a heat pump which would lead to a very high share of > 95 % of renewable heat [5].

In agreement with the municipality of Graefelfing and the further contracting parties involved, woodchips boilers and electric boilers were excluded, the latter one mainly because of expected high investment costs for the provision of the required infrastructure, e.g. a voltage transformation station.

Finally, four heat supply concepts were defined that use the components listed in Table 2 (same in all four concepts) and differ from each other in the components listed in Table 3.

Table 2. *Considered components for all four heat supply concepts*

	HSS 1 + HSS 2
All four heat supply concepts	**Deep geothermal plant** to cover the thermal base load, **thermal buffer store** with a water volume of 1,000 m³, **existing decentral CHP plants and gas boilers** with a total thermal power of 3.2 MW (see Section 3.1.4) and further gas boilers for providing reserve capacity

Table 3. *Overview on the different components considered in the four heat supply concepts for the two heat supply scenarios HSS 1 and 2*

	Peak load provision in HSS 1	Peak load provision in HSS 2
Heat supply concept No. 1	mainly by a **heat pump** that uses the return flow of the deep geothermal circuit as a heat source	mainly by one or several **heat pump(s)** that use the return flow of the deep geothermal circuit as a heat source
Heat supply concept No. 2	by **gas boilers**	mainly by one or several **heat pump(s)** that use the return flow of the deep geothermal circuit as a heat source
Heat supply concept No. 3	by **gas boilers**	mainly be **CHP plants**
Heat supply concept No. 4	by **gas boilers**	mainly by a **pit thermal energy store** that is also used as a heat source for a **heat pump**

As can be seen from Table 3, the four heat supply concepts mainly differ in the way the peak load is provided in the heat supply scenario HSS 2. On the one hand, this peak load in HSS 2 is provided by CHP plants (concept No. 3) and on the other hand, this is carried out by one or several heat pumps (concepts No. 1, 2 and 4). In the case of heat pumps, the concepts differ concerning their way of integration: While in concepts No. 1 and 2, the return flow of the deep geothermal circuit is used as a heat source for the heat pump, a pit thermal energy store is used as the heat source of the heat pump in concept No. 4.

The peak load provision in the heat supply scenario HSS 1 is basically realised by gas boilers since the components listed in Table 2 already cover a high share of the annual heat demand, in particular the deep geothermal heat source, see Section 3.2. Only in concept No. 1, a (small) heat pump using the return flow of the deep geothermal circuit as a heat source is considered to analyse to which extend the use of such a heat pump is already reasonable in HSS 1.

3.3.2 Evaluation of the heat supply concepts

As was explained in Section 2, the heat supply concepts were analysed from a technical and energetic point of view by calculations with basic energy balances as well as TRNSYS simulations for the analysis of detail aspects. The considered period of the calculations as well as for the simulations was one year and the time step was 15 min. Based on the results of the thermal simulations an economic analysis was carried out.

From the **technical point of view**, the use of the thermal buffer store with a water volume of 1,000 m³ that is considered in all four heat supply concepts, see Table 2, was found to be reasonable already in HSS 1, but in particular with the further increase of the heat demand in HSS 2 since it allows for a smother operation of the system and also increases the annual share of geothermal heat of the total heat demand. Furthermore, the use of heat pumps was found to be advantageous compared to the use of CHP plants due to the higher exploitation of the available deep geothermal heat and therefore an increased annual share of geothermal heat related to the total heat demand.

Concerning the way of integration of the heat pumps, both abovementioned options are suitable and they give similar results, for instance regarding the annual share of geothermal heat related to the total heat demand and the seasonal performance factor (SPF) of the heat pumps. The advantage of using a seasonal thermal energy store as a heat source of the heat pump is that this heat source is basically also available in the case of an outage of the deep geothermal plant. However, the actually available thermal power that can be supplied by the heat pump in this case also depends on the present state of charge of the PTES at this point of time.

In principle, a heat pump using the return flow of the deep geothermal circuit as a heat source, can already be applied in HSS 1 (concept No. 1). However, the heat pump will show a rather low number of full-load hours then, in this case only about 550 h/a. So, for the heat pump(s) using the deep geothermal circuit as a heat source, the general recommendation is to wait until the heat demand of the district heating system is high enough and to increase the number and the thermal power of heat pumps according to the further extension of the district heating system.

From the **economic point of view**, a major result of the analysis was that all four heat supply concepts showed very attractive heat generation costs even without consideration of funding provided by the German BEW (BEW: Bundesförderung für effiziente Wärmenetze - Federal funding for efficient heating network). Due to confidentiality reasons, no absolute values for the heat generation costs can be mentioned here. Concept No. 3 was found to show the highest heat generation costs over the whole period of consideration with 20 years of operation of the district heating system. This means that from an economic point of view, the use of heat pumps was found to be advantageous compared to the use of CHP plants, in particular when considering BEW funding of investment and operational costs.

Concept No. 4 with the use of a PTES showed slightly higher heat generation costs than the concepts No. 1 and No. 2 with the heat pump using the return flow of the deep geothermal circuit as a heat source. The difference in heat generation costs between concepts No. 1 and 2 was found to be negligible, i.e. from an economic point of view, it does not matter when the heat pump(s) are installed. As was pointed out above, the general recommendation here is to wait until the heat demand of the district heating system is high enough. This in particular is relevant with regard to BEW funding, because in this program, the funding of operational costs for heat pumps is payed for only 10 years starting with the first year of the operation of the heat pump.

Furthermore, it should be noted that all four concepts are **climate-neutral** in the heat supply scenario HSS 2 **in the sense of the BEW funding scheme**. This is achieved by the switch from fossil natural gas to bio-methane in the year 2028 as was pointed out in Section 3.1.4.

Based on the results presented above and in agreement with the municipality of Graefelfing and the further contracting parties involved, **concept No. 1 was selected as the favourite heat supply concept**. The reason for already installing a (small) heat pump in HSS 1 was to ensure a sufficiently high share of renewables of > 90 % within the first phase of the operation of the district heating system which is relevant regarding the BEW funding.

3.4 Results for the selected heat supply concept

3.4.1 Basic scheme of the concept

Figure 1 shows the basic scheme of the selected heat supply concept for the heat supply scenario HSS 2. The deep geothermal heat source with a nominal thermal power of 12 MW, based on a supply temperature (ST) of 90.0 °C, a return temperature (RT) of 57.5 °C and a flow rate of 99 l/s, covers the thermal base load of the district heating system. If the available deep geothermal heat is higher than the thermal load of the district heating system, the thermal buffer store with a water volume of 1,000 m³ can be charged, which increases the annual share of geothermal heat of the total heat demand.

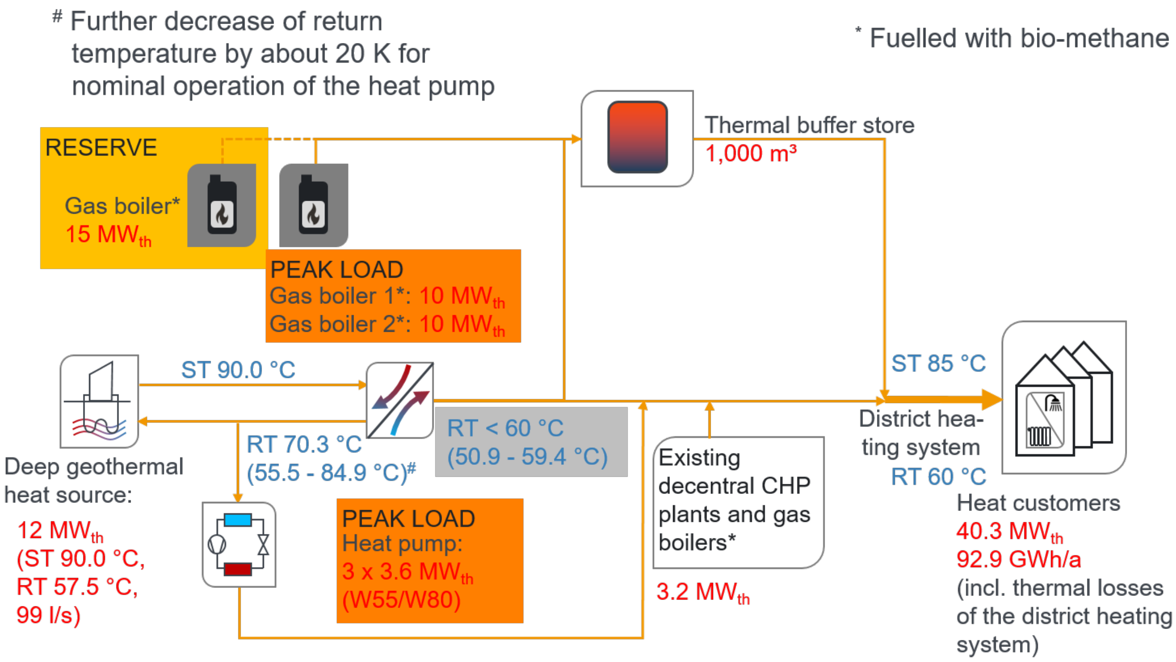

Figure 1. *Basic scheme for the selected heat supply concept with a district heating system using deep geothermal heat as the primary heat source, for the heat supply scenario HSS 2*

The peak load is primarily covered by three heat pumps, each with a nominal thermal power of 3.6 MW at the operating point W55/W80, i.e. with a water inlet temperature into the evaporator of 55 °C and a water outlet temperature from the condenser of 80 °C. Furthermore, the peak load is covered by two gas boilers, each with a nominal thermal power of 10 MW, as well as the existing decentral CHP plants and gas boilers with a total nominal thermal power of 3.2 MW, cf. Section 3.1.4. A further gas boiler with a nominal thermal power of 15 MW is only used for providing reserve capacity. In HSS 2, all CHP plants and gas boilers operate with bio-methane as a fuel.

In blue font in Figure 1, relevant temperatures are highlighted. These temperatures were either given as boundary condition for the TRNSYS simulations, such as the supply temperature of the deep geothermal heat source of 90.0 °C and the supply and return temperature of the district heating system at the heat customers of 85 and 60 °C, respectively. All other temperatures given in Figure 1 are a result of the TRNSYS simulations. On the one hand, this is the return temperature of the district heating system at the heat exchanger for the geothermal heat integration, which ranges from 50.9 to 59.4 °C. On the other hand, this is the return temperature of the deep geothermal circuit, i.e. after the heat exchanger for the geothermal heat integration, but before the evaporator of the heat pump. As can be seen in Figure 1, this temperature ranges from 55.5 to 84.9 °C, with an annual average of 70.3 °C. High return temperatures of up to 84.9 °C appear in the summer months when the heat demand and therefore the heat extraction from the deep geothermal heat source is low. When the three heat pumps operate under nominal conditions, this return temperature is further decreased by about 20 K. The minimum return temperature in the deep geothermal circuit after the evaporators of the heat pumps accounts for about 36.2 °C, i.e. this is the minimum temperature of the water flow being rejected into the underground hydrothermal layer.

For the heat supply scenario HSS1, the scheme of the heat supply concept is basically the same as shown in Figure 1, but with two differences: First of all, only one heat pump with a nominal thermal power of 3.6 MW at the operating point W55/W80 is installed. When this heat pump operates under nominal conditions, the decrease of the return temperature in the deep geothermal circuit caused by the heat extraction in the evaporator of the heat pump accounts for about 7 K. Second, as was already mentioned several times above, the CHP plants and all the gas boilers operate with fossil natural gas since the switch to bio-methane will not happen before 2028.

3.4.2 Energetic assessment of the concept

Figure 2 shows the simulated monthly comparison between heat demand (outer columns) and type of heat supply (inner columns) of the selected heat supply concept for the heat supply scenario HSS 2. In the summer months June to August, the total heat demand is covered directly by the deep geothermal heat in combination with the thermal buffer store (inner yellow columns). In May and September, the deep geothermal heat covers almost the complete heat demand, but in the period October to April, the deep geothermal heat can only partly cover the heat demand. In this period, the highest share of the remaining heat is supplied by the heat pumps which use the return flow of the deep geothermal circuit as a heat source. In Figure 2, this heat is illustrated by the inner light green columns and the electricity required for the operation of the heat pumps is illustrated by the inner purple columns. The still remaining heat demand is then covered by the existing decentral CHP plants (inner red columns, very low share due to their small installed thermal power of only 0.3 MW, cf. Section 3.1.4), the existing decentral gas boilers (inner orange columns) and the two peak load gas boilers (inner dark green columns) with a nominal thermal power of 10 MW each, see Section 3.4.1.

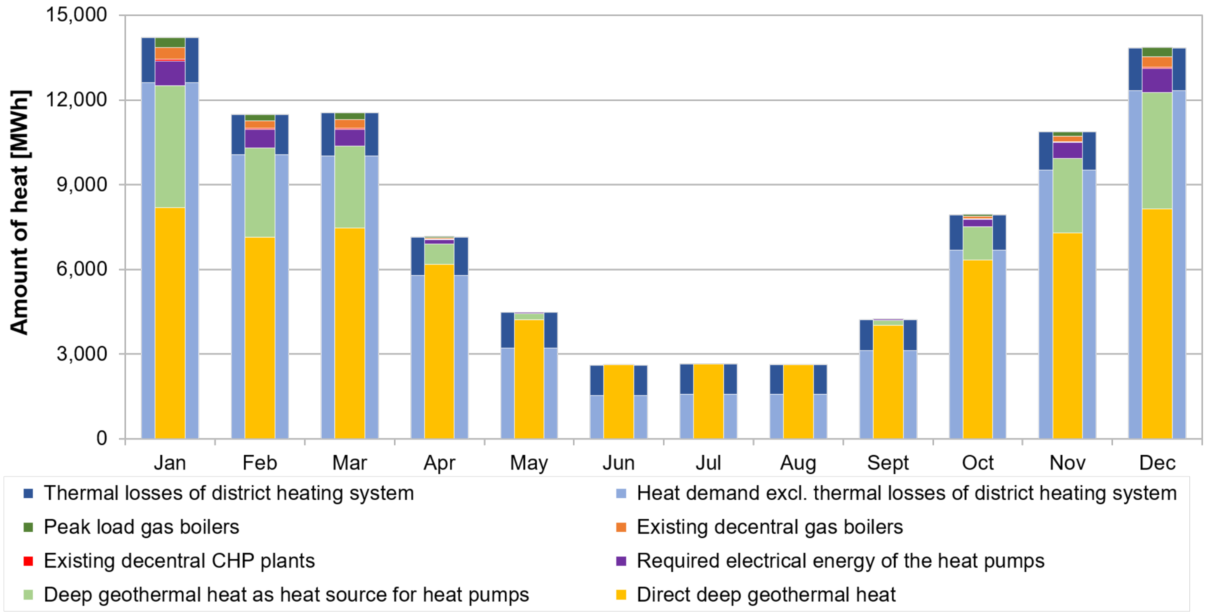

Figure 2. *Monthly comparison between heat demand and heat supply for the selected heat supply concept with a district heating system using deep geothermal heat as the primary heat source, for the heat supply scenario HSS 2 determined by means of TRNSYS simulations*

For the heat supply scenario HSS 2, this gives an annual share of geothermal heat of the total heat demand of 71.4 % excl. and of 92.1 % incl. the heat extracted from the return flow of the deep geothermal circuit as a heat source for the heat pumps. When the electricity required for the operation of the heat pumps is added to this, in total 96.5 % of the heat demand is covered by the deep geothermal plant and the heat pumps. This means that only 3.5 % of the heat demand needs to be covered by the CHP plants and gas boilers. Furthermore, as a result of the TRNSYS simulations, a seasonal performance factor (SPF) of 5.7 was determined for the heat pumps.

3.4.3 Environmental assessment of the concept

Figure 3 shows a comparison between the CO_2 equivalent emissions for the current heat supply (blue columns) that is based on decentralised boilers using fossil natural gas and the selected heat supply concept (orange columns) with a district heating system using deep geothermal heat as the primary heat source as described in Section 3.4.1. As can be seen from this figure, the CO_2 equivalent emissions for the current heat supply account for about 20,000 t/a. With no changes in the heat supply, these emissions would stay the same for the whole period of consideration, because the specific CO_2 equivalent emissions for fossil natural gas are assumed to be constant. For the selected future heat supply concept, the CO_2 equivalent emissions start at the same level in the year 2025 since the year 2026 is the first one with heat delivered via the district heating system as was pointed out in Section 3.1.1.

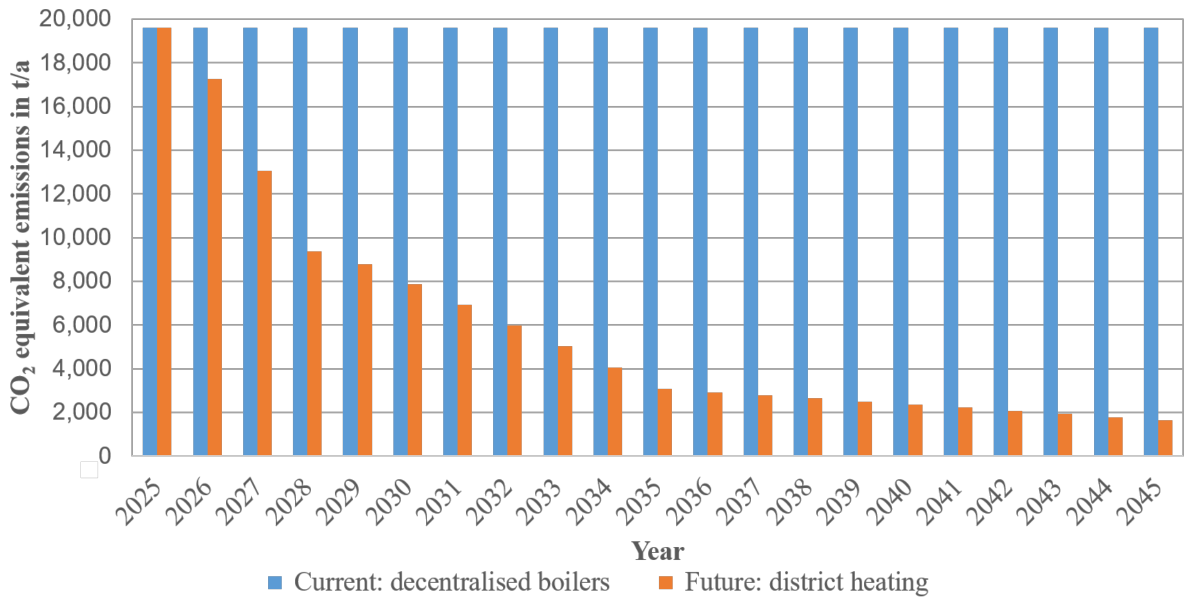

Figure 3. *Comparison between the CO_2 equivalent emissions for the current heat supply based on decentralised boilers using fossil natural gas and the selected heat supply concept with a district heating system using deep geothermal heat as the primary heat source*

With the increase of the heat demand that is covered mainly by deep geothermal heat via the district heating system in the years 2026 to 2028, the CO_2 equivalent emissions considerably decrease. Additionally, the CO_2 equivalent emissions decrease in the year 2028 for the selected future heat supply concept due to the change of fuel for the CHP plants and gas boilers from fossil natural gas to bio-methane. With the further extension of the district heating system, more and more heat consumers are supplied with mainly geothermal heat via the district heating system, which leads to a further decrease of the CO_2 equivalent emissions. As was pointed out in Section 3.1.1, the district heating system is supposed to reach its intended final extension in the year 2035. Nevertheless, as can be seen in Figure 3, there will still be a slight decrease in the CO_2 equivalent emissions also after that year. This is due to the fact that the specific CO_2 equivalent emissions for the grid electricity that is required for the operation of the supply pump of the deep geothermal plant as well as the heat pumps, will also decrease. In the year 2045, the CO_2 equivalent emissions account for < 2,000 t/a.

4. Conclusions

Based on the technical and economic evaluation of four different heat supply concepts for the future heat supply of Graefelfing via a district heating system, a concept was selected where beside the deep geothermal heat as the primary heat source, the peak loads are mainly covered by heat pumps that use the return flow of the deep geothermal circuit as a heat source. The remaining heat is supplied by further gas boilers and to a very minor extent by CHP plants, both fueled with bio-methane from the year 2028 on.

With this heat supply concept, a share of renewable heat of 100 % and thus a completely climate-neutral district heating system in the sense of the BEW funding scheme is achieved. Compared to the current heat supply in Graefelfing based on decentralised boilers using fossil natural gas, the **total savings in CO_2 equivalent emissions** for the whole period of consideration 2025 to 2045 account for about **288,000 t**.

Data availability statement

Selected data may be requested from the authors.

In general, this article refers to confidential information made available to the authors by the contracting parties of this study.

Author contributions

Conceptualisation: Harald Drück, Sven Stark, Stefanie Lott.

Methodology and Investigation: Sven Stark, Stefanie Lott.

Visualisation: Sven Stark, Stefanie Lott, Harald Drück.

Project administration and Supervision: Harald Drück.

Writing – original draft: Sven Stark.

Writing – review and editing: Harald Drück, Stefanie Lott.

Competing interests

The authors declare that they have no competing interests.

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