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Estimation of shallow geothermal potential to meet building heating demand on a regional scale

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A B S T R A C T

Extracting shallow geothermal energy using borehole heat exchangers (BHEs) can help decarbonising the residential heating sector, particularly where no other low-carbon heating solutions are readily available. To assist urban planners and policy makers in developing carbon-neutral heating plans, the regional technical shallow geothermal potential must be known. Here, we calculate the technical geothermal potential of BHE fields on a regional scale while taking potential thermal interference between BHEs, geological conditions, as well as space available for BHE installation into account. The number of BHEs placed is maximized and heat extraction rate from each BHE is optimized taking regional regulations into account. When the methodology is applied to the German state of Baden-Württemberg on a building-block scale, results suggest an annual technical potential of 33.5 TWh. We then link this technical geothermal potential to heating demand scenarios on a building block scale and the results show that, depending on the renovation status of the buildings, between 44% and 93% of all building blocks can be heated using only BHEs. This allows for a rapid identification of building blocks for which BHEs are not able to meet the heating demand and where other means of heat supply will be needed.

1. Introduction

In order to achieve greenhouse gas emission reduction targets set out in the Paris agreement [1] and the EU's climate neutrality goal by 2050 as outlined in the European Green Deal [2], a large-scale transformation to renewable energies in the heating and cooling sector is needed. Energy used for heating and cooling accounts for the majority of the final energy use per household (79% in EU households), and about 30% of all energy consumed in the European Union is used for space heating and hot water generation [3]. The bulk energy used in the heating and cooling sector is still generated from fossil fuels (75% of heating and cooling in the EU in 2018), and to meet the climate and energy goals, on both EU and country level, the sector is in high need for decarbonisation and reduction of energy consumption. Widely discussed options for heating and cooling in future renewable energy systems include district heating [4], decentralization of energy systems [5], and the widespread use of heat pumps [6]. For the latter, shallow geothermal energy systems are particularly appealing as they are more efficient than water-air heat pumps as the ground has a more stable temperature than the ambient air. Therefore, a widespread global roll-out of shallow geothermal energy utilization would allow for a strong carbon emission reduction of the heating sector [7].

Shallow geothermal energy systems provide heating and/or cooling by exchanging heat with the shallow subsurface either via an open system, where ground water is accessed and acts as a heat carrier, or a closed system, where a synthetic heat carrier fluid is circulated through a closed tubing system in the ground for heat exchange. Both open and closed systems employ heat pumps to extract heat from the carrier fluid and supplying heating applications. While horizontal closed-loop systems can be installed, more commonly ground source heat pumps (GSHP) are set up with vertical boreholes heat exchangers (BHE). GSHPs are particularly interesting for areas with a low heat demand density for which a connection to a district heating network is not economically or environmentally efficient [8].

In recent years, the sustainability and long-term effects of

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shallow geothermal energy usage has been addressed in many studies. High BHE densities can lead to interference between single boreholes [9–11] and decreasing ground temperatures may lead to a decrease in GSHP efficiency over time [12,13]. When shallow geothermal systems are also used for space cooling heat is introduced into the subsurface which leads to increased groundwater temperatures which in turn may lead to subsurface urban heat islands under densely populated areas [14,15]. Numerous studies have explored the feasibility of geothermal use in urban areas with various approaches [16–18], often using geographic information systems in combination with analytical or numerical models. These studies can support urban planners and policy makers, however, to identify areas particularly suitable for GSHPs and to determine spatially defined regional differences regional studies of the technical geothermal potential are needed.

To date most studies that assess the regional-scale potential of geothermal energy estimate the theoretical potential, which is defined as the physically available energy in a given ground volume [19], instead of the technical potential, which is the technically extractable heat with consideration of the built environment and the interference between boreholes. Such studies include the estimation of thermal conductivity on a large-scale as the entire European continent [20] or ground temperatures across the whole of Canada [21]. Other studies quantify regional technical potential of single boreholes with different approaches [16,22,23] but lack to take the interaction and interference between boreholes into account. Only one recent study estimates the technical potential on a regional scale [24], however it fails to link the geothermal potential to the heating demand.

A different approach was developed in 2014 for the purposes of municipal energy consulting by the regional energy supplier badenova AG & Co. KG [25]. Based on a self-developed GIS-based analysis tool, it was possible to calculate the maximum possible energy output of borehole heat exchangers to satisfy the energy demand on the residential building level. Borehole and geothermal probe parameters are adopted to the surrounding conditions, also taking the interference between boreholes into account. This makes it possible to promote the use of geothermal heating at the level of residential quarters, considering local risks regarding the geological and subsoil conditions to reduce the inhibition threshold of the applicants.

Based this previous work, we estimate the technical geothermal potential of vertical heat exchangers of GSHPs on a more regional level and compare it to three different demand scenarios for residential buildings. We calculate the maximum number of BHEs that can be placed on a building block scale while taking the build environment into account. For the technical geothermal potential, the thermal interference between BHEs is included by estimating g-functions on a building-block level which allows for a rapid calculation of the technical geothermal potential. Heat extraction rates are maximized while considering federal and state restrictions on BHE depth as well as ground and fluid temperatures. Within this study, vertical closed-loop GSHP systems, which is the most widely used type of system in Germany, are considered. Groundwater flow, possible re-charging of the subsurface with heat from solar thermal generators and space cooling during summer days are neglected in the presented model and thus the estimated geothermal potential can be regarded as conservative. This potential is then linked to three different heating demand scenarios which take building renovation status into account. This allows for identification of building blocks in which GSHP systems can supply all the demanded heat as well as for determination of building blocks for which even for a low heat demand scenario additional means of heating supply are needed.

2. Material and methods

2.1. Study area

The state of Baden-Württemberg is located in the south-west of Germany and is its third largest state both by population (11.07 million) and area (35 751 km^2) (Fig. 1). It has a diverse landscape, with dominant features being (1) the Upper Rhine Valley in the west, (2) the mountain range of the Black Forest which rises to the east of the valley, (3) the south German Scarplands north and east of the mountain range, (4) the high plateau of the Swabian Alb in the east of the Scarplands, (5) and the foothills of the Alps in the south-east of the state. This landscape is the result of a hundreds of million years long geological evolution and outcropping rocks cover most of the geological periods, ranging from Pre-Cambrian to Quaternary rocks [26]. Each of the five areas has a unique geological setting which has implications for shallow geothermal energy applications. For example, the presence of potentially swelling rock layers in the south German Scarplands leads to restrictions regarding the maximum drilling depth (Fig. 2). The Swabian Alb acts as an important freshwater reserve and drillings are generally restricted while at the transition from the Upper Rhine Valley to the Black Forest the geological setting is very complex, including swellable rock layers, and thus drilling is also prohibited in large areas (Fig. 2). The highest elevations can be found in the Black Forest (1 493 m) while in the northern Upper Rhine Valley has elevations as low as 85 m above sea level. The location within Europe

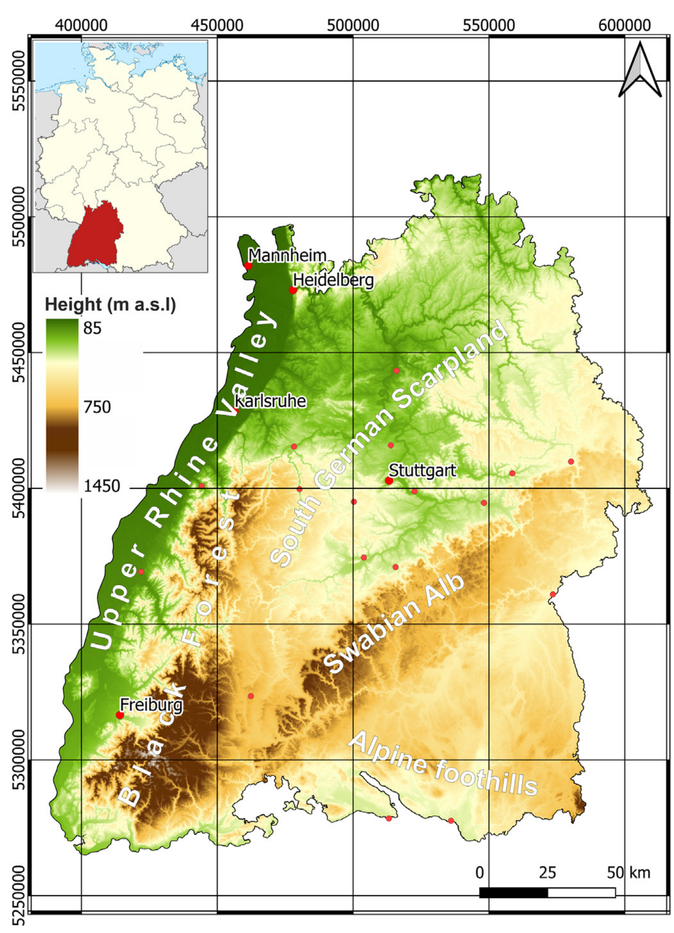

Fig. 1. Map of the state of Baden-Württemberg. Inset illustrates the location of the study area within Germany.

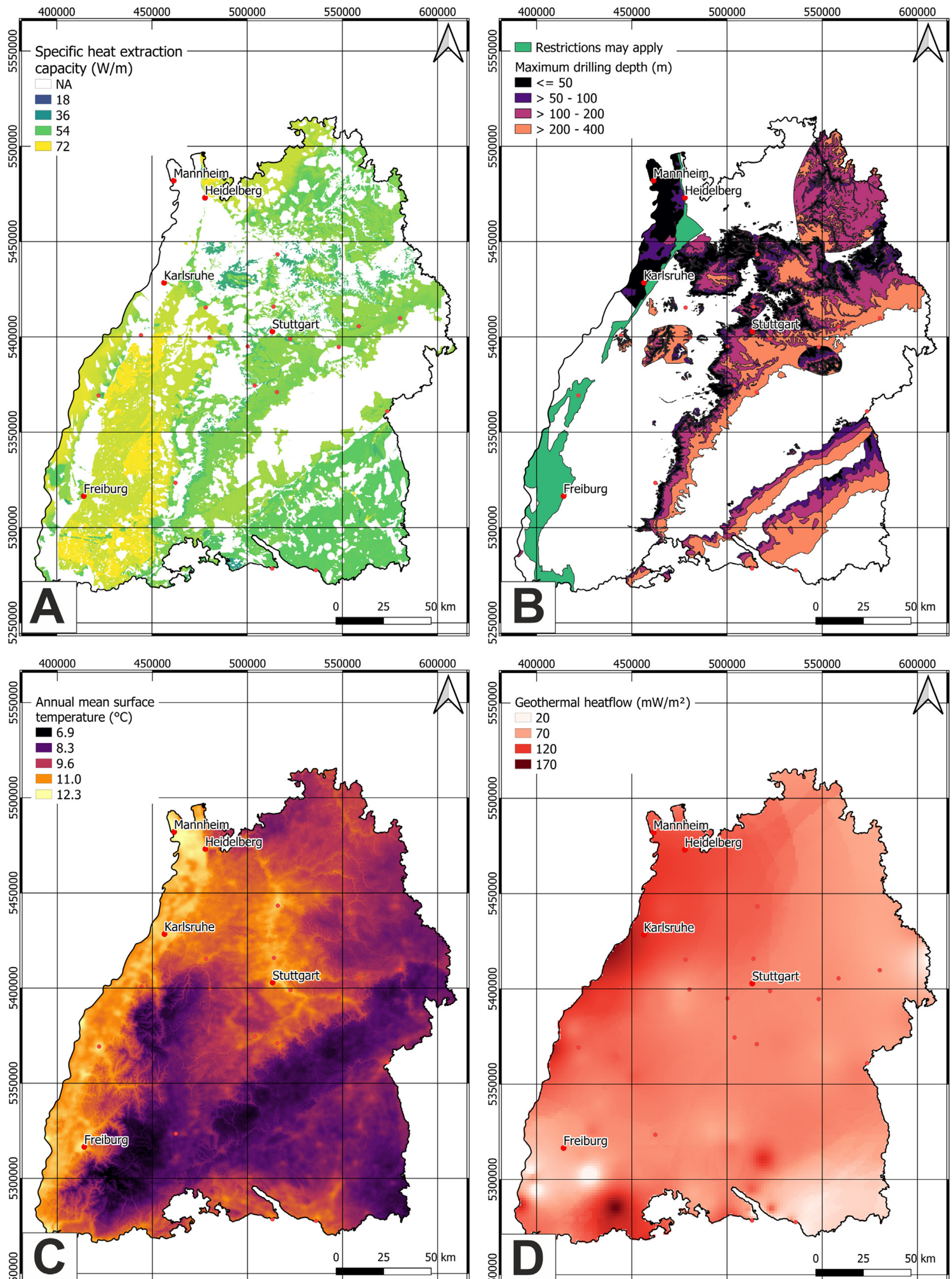

Fig. 2. Maps illustrating input data. (A) Specific heat extraction capacity from ISONG. Note that white areas are groundwater protection areas where BHE installation is not allowed. These areas are not included in the study. (B) Maximum drilling depth and areas where the subsurface setting allows BHEs only after individual examination. (C) Annual mean surface temperature based on MODIS data. (D) Terrestrial geothermal heat flow from the global heat flow database.

results in a more maritime climate in the west of the state and a continental climate in the east of the state. The Upper Rhine Valley has some of the warmest annual mean temperatures of all of Germany (>10 °C) while in the Black Forest mean annual temperatures can be lower than 4 °C.

The state has adopted legislation to reduce its greenhouse gas emissions by 42% by 2030 and by 90% by 2050 compared to emission in 1990. One key aspect of the legislation is that all municipalities have to (1) report their energy usage annually and municipalities with a population >20 000 (2) have to develop a municipal heating plan [27]. These heating plans will form the base for climate-neutral heating supply in 2050. In 2017 around 90% of the final energy consumption of households in Baden-Württemberg was from fossil fuels, with heating predominantly supplied by heating oil and natural gas [28]. In 2019 around 43 000 GSHP systems were operating in the state, with annually around 3000 more systems being installed. The implementation of new GSHP systems must follow particularly strict regulations in this region due to several prominent damage events where improper installation of BHEs in areas with complex geology led to surface uplift/subsidence [29].

2.2. Input data

Heating demand of residential buildings in Baden-Württemberg was provided as shape file on a building-bloc scale by the ministry of environment, climate, and energy. The same data can be accessed, but not downloaded, online (www.energieatlas-bw.de). This heating demand data is based on a census on building type, year of construction and living area in the year 2011 as well as studies on heating demand of building types and ages. The Energieatlas provides three different heating demand scenarios: “as is” which reflects the heating demand at the year of construction but with coated double glazing independently of the construction year, “conventional renovation” which assumes a 12 cm insulation of roof and walls as well as coated double glazing, and “forward-looking renovation” which roughly translates to a KfW-55 efficiency house with a wall insulation of 18 cm, roof insulation of 24 cm, triple glazing, and a heat pump for heating and hot water.

Data on building layouts, roads, railways, and surface waters are freely accessible as vector data from the OpenStreeMap (OSM) Project and were downloaded for the whole state from the Geofabrik servers (https://download.geofabrik.de/) on the May 25, 2020.

Annual average surface temperatures (C°, mean of 2002–2012) with a spatial resolution of 250 × 250 m are based on MODIS data [30] and raster data is available processed and ready to use from the Hotmaps project (Fig. 2c, www.hotmaps.eu (accessed May 28, 2020)).

Terrestrial heat flow (W/m^2) was interpolated from data available at the IHFC Global Heat Flow Database (https://ihfc-iugg.org/products/global-heat-flow-database) using the 2018 release, which is based on an earlier version [31].

The maximum heat extraction rate (W/m borehole length) for different borehole lengths and usage times, as well as areas with restrictions for BHE installation (due to ground water protection areas or the presence of swellable rocks in the subsurface) were provided as raster data by the state office for geology, resources, and mining (Fig. 2a and b). This data is also accessible online in the information system for shallow geothermal energy (ISONG, https://isong.lgrb-bw.de/). ISONG data is based on a 3D geological model for the whole state of Baden-Württemberg, the maximum heat extraction data is calculated following VDI 4640. It is notable that for about 1/3 of the state's area BHE installations are restricted due to the geological setting or ground water protection areas.

2.3. Methods

2.3.1. Calculation of available space for BHEs

For the area of each building block (as defined in the Energieatlas) which does not fall into restricted regions (Fig. 2a), the area which could be used for BHE installation was determined by excluding buildings, roads, and railways, footpaths, and surface water (OSM data). A buffer of 3 m was placed around each building to ensure that BHEs could technically be placed, which is larger than the minimum distance of 2 m recommended by the German technical guideline VDI 4640 part 2 [32] and similar to other studies [33,34]. As road and railway data is provided as vectors only, buffers were also placed around these, with the width of the buffer depending on the type of road as defined by OSM contributors. It is assumed that BHEs can be placed beneath pavements and parking areas [34]. In the resulting area per building block (Fig. 3) the maximum number of BHEs were distributed using a 10 m spacing, which is the minimum distance required by the regional law, and the QGIS “random points in polygons” algorithm. We use this approach instead of a grid-based approach often used in other studies [24,34–36] as this allowed for a better utilization of the available space. A total of 129.488 building blocks were analysed. The data used for BHE distribution and heat supply computations include raster, areal, and line data. Modification and computation of spatial data was done using QGIS (v. 3.14) and all input data was transformed into WGS 84 (EPSG:4326) prior to modification.

2.3.2. Calculation of the technical geothermal potential and heat supply rate

The geothermal potential of the BHEs fields and associated heat pumps are calculated for each field as follows (e.g. Ref. [36]):

$$E_{\mathrm{BHE}} = \sum_{i}^{n} q_{\mathrm{BHE},i} \times l_{\mathrm{BHE},i} \times t_h \Big/ \left(1 - \frac{1}{COP}\right) \tag{1}$$

where q_{BHE} (W/m) is the heat extraction rate of each BHE, l_{BHE} (m) the length of each BHE, t_h (in hours) is the operational time, and dimensionless COP the coefficient of performance of the heat pump. The heat extraction rate of each BHE in a steady state can be divided into three main components [37]:

$$q_{\mathrm{BHE}}(t) = q_0 + q_p \times \sin\left(\frac{2\,\pi\,t}{t_p}\right) + q_{peak}(t) \tag{2}$$

where q_0 (W/m) is the stationary component, which includes the impact of the extraction rate on the subsurface over long periods of time as well as the interaction between multiple BHEs, q_p (W/m) is the annual periodic component ($t_p = 1$ year), which captures the fact that heating will mainly take place in the winter, and q_{peak} (W/m) is the peak load over small periods of time (e.g. $t_{peak} = 24$h). Each extraction component results in a change of the subsurface temperature at the borehole wall compared to the undisturbed subsurface temperature (T_0, in °C). The time-dependent change of the subsurface temperature (ΔT) depends on the dimensions of the BHE field and can be calculated using g-functions [38]:

$$\Delta T = T_{BHE} - T_0 = \frac{q_{\mathrm{BHE}}}{2\,\pi\,\lambda_e} \times g(Es, r_b/l, B/l) \tag{3}$$

with λ_e (W/mK) being the heat conductivity of the subsurface, g being the g-function which depends on the Eskilon number Es, which is the dimensionless ratio of real time to the physical time constant of the borehole, the ratio of BHE radius (r_b, in m) to BHE length (l, in m) and the ratio of BHE spacing (B, in m) to BHE depth (in m). In this study g-functions for each BHE field are estimated by

Fig. 3. Maps illustrating the process of distributing BHEs: (A) shows the annual heating demand per building block. (B) For each building block unsuitable areas (buildings, roads, railways, waterways) are excluded. (C) BHEs are randomly distributed with a 10 m spacing to maximise the amount of BHEs available per building block.

using a range of stationary end values (ln(Es) = 3) which depend on the number of BHEs in the field (Table 1). The undisturbed subsurface temperature T_0 can be estimated using mean annual surface temperature (T_s, in °C), the heat conductivity of the subsurface λ_e and the terrestrial heat flow density (q_{geo}; W/m^2):

$$T_0 \approx T_s + \frac{l}{2} \times \frac{q_{geo}}{\lambda_e} \tag{4}$$

While equation (3) calculates the temperature difference between borehole wall and the subsurface, the temperature difference between undisturbed soil and the borehole fluid (brine) is also of importance and can be calculated as follows:

$$\Delta T_{brine} = q_j \times (R_j + R_b) \tag{5}$$

where q_j is one of the heat extraction components, R_j the correlating thermal resistivity (mK/W), and R_b the borehole specific thermal resistivity (mK/W) which depends on the used cement and the borehole radius. The thermal resistivities R_0, R_p, and R_{peak} are functions of the borehole radius r_b and the heat conductivity of the subsurface λ_e and can be defined as follows [37,38]:

$$R_0 = \frac{1}{2\,\pi\,\lambda_e} \times \left[g(ln(Es) = 3,\ (r_b/l)) - \frac{r_b}{l\ \times 0.0005}\right] \tag{6}$$

where the g function is taken from published tables (e.g. Ref. [38].

$$R_p = \frac{1}{2\,\pi\,\lambda_e} \times \sqrt{\left(ln\left(\frac{2}{r_{pb}}\right) - \gamma\right)^2 + \frac{\pi}{16}}\ with\ r_{pb} = r_b \times \sqrt{2} \Big/ d_p\ and\ d_p = \sqrt{a \times t_p/\pi} \tag{7}$$

$$R_{peak} = \frac{1}{2\,\pi\,\lambda_e} \times \left[ln\left(\frac{\sqrt{4\ \times a \times t_{peak}}}{r_b}\right) - \gamma \Big/ 2\right] \tag{8}$$

With a being the thermal conductivity of the subsurface:

$$a = \frac{\lambda_e}{\rho_e\ \times c_p} \tag{9}$$

For this study the volumetric heat capacity (ρ_e x c_p) is assumed to be 2.18 MJ/(K/m^3) [39].

Based on equations (1)–(9) an R code, similar to the GEO-HAND^{light} tool (https://innosued.de/energie/geothermie-software-2/), was developed. It optimizes heat extraction rates from a given borehole field while taking the guideline VDI 4640 [32] as well as state specific guidelines on BHEs [29] into account. These include that the maximum temperature difference between brine when it enters the borehole and the undisturbed subsurface temperature cannot exceed 17 °C and that the same temperature difference during continuous operation may not exceed 11 °C. Additionally, the temperature of brine entering the borehole may not be below −3 °C to prevent freezing of the subsurface. The model assumes no groundwater flow as creating a regional groundwater flow model was outside the scope of this study. Excluding groundwater flow results in a conservative model for most conditions. Geological data within each building block is assumed to be constant, which is true for >95% of cases.

The striped area indicates a complex geological setting as defined by ISONG and thus this area is excluded from the study.

Table 1
Parameters used to determine heat extraction rates.

Parameter	Value		Source
COP	4.3		State guidelines
BHE length (l)	max = 100 m		ISONG
BHE spacing (B)	10 m		State guidelines
BHE radius (r_b)	0.065 m		DN40 U pipe
Heat extraction rate (q)	23–72 W/m		Target variable
Operation (t)	1800 h/year		Heating only
Volumetric heat capacity (ρ_e c_p)	2.18 MJ/(m^3/K)		Koenigsdorff et al. [39]
Heat conductivity (λ)	2.25 W/mK		Simplified after ISONG
Thermal resistivity borehole	0.1 mK/W		
Annual periodic component (t_p)	8760 h		One year
Peak load time (t_{peak})	24 h		One day
g-functions (ln(Es)=3, rb/H = 0.0005, B/H)	No. BHEs	Value	
	1	6.6	
	2	7.2	
	2–5	9	
	5–16	12.2	
	16–18	13.7	
	18–50	17.8	
	50–100	21	
	100–150	30	
	>150	50	

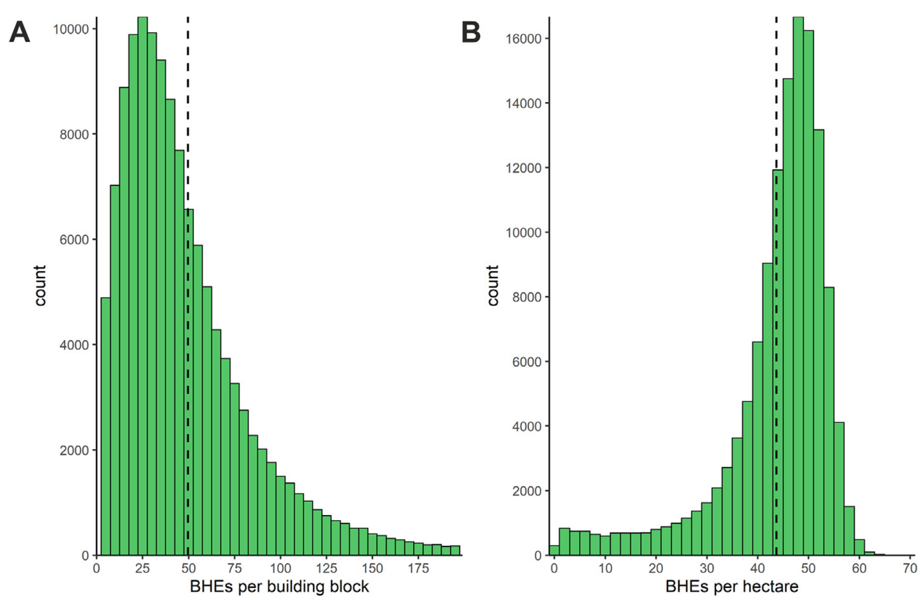

Fig. 4. Histograms illustrating (A) the number of BHEs per building block and (B) the number of BHEs per building block normalised to area. Dashed lines indicate the mean number of BHEs.

Besides the maximum geothermal potential (E_{max}), which utilizes all placeable BHEs of a building block, the number of BHEs needed to supply heat for the three different heating demand scenarios (see section 2.2.) as well as the number of BHEs needed per building for each of these scenarios were calculated.

3. Results and discussion

3.1. BHE placement

In the 129 488 building blocks a total of around 6 426 000 BHEs could be placed, with an average of 49.6 BHEs per building block and a median of 39 BHEs per building block (Fig. 4a). Considering that the area of building blocks varies from less than 500 m^2 to close to 1 million m^2, analysing the number of BHEs per hectare gives a better understanding of the BHE density, which averages at 43.6 BHEs per hectare and has a median of 46.5 BHEs per hectare (Fig. 4b). The vast majority of BHEs has a depth of 100 m with only around 40 000 BHEs being in areas where the drilling depth is limited to 50 m.

Utilizing OSM data for renewable energy planning is widely used when more detailed official standardized data is not available [40,41], however it comes with limitations. In our study a buffer of the same width was placed around all roads of the same OSM class and thus it is assumed that all roads of the same type have the same width in the whole study area. While cross-checks with satellite imagery show that in most cases the used width is acceptable, there are instances where roads are much wider or smaller than assumed in the model. This subsequently impacts the number of BHEs which are placeable within the building blocks affected. It should also be noted that the building block area defined by the Energieatlas, which is the area used to distribute BHEs, generally does not extend

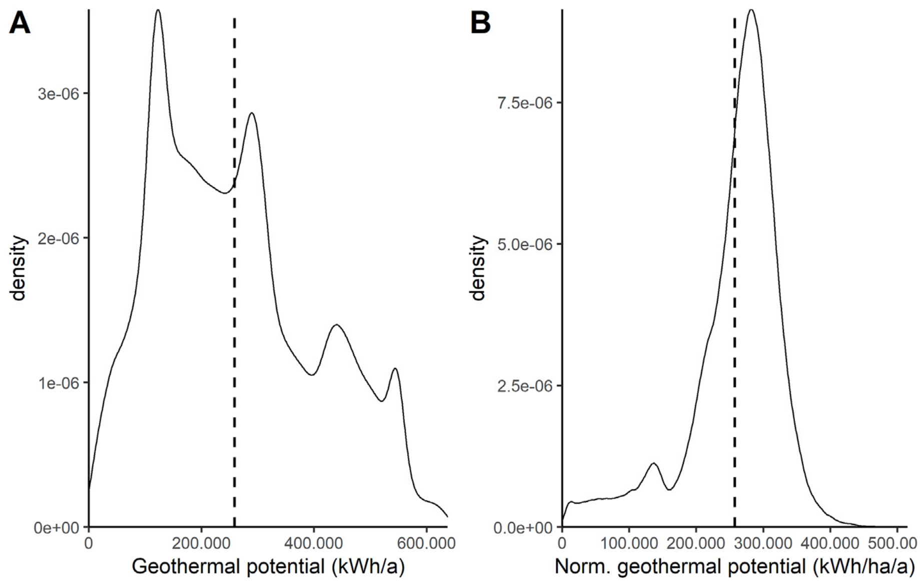

Fig. 5. Density plots showing (A) the geothermal potential per building block and (B) the geothermal potential normalised to area (hectares). Dashed lines indicate the mean geothermal potential.

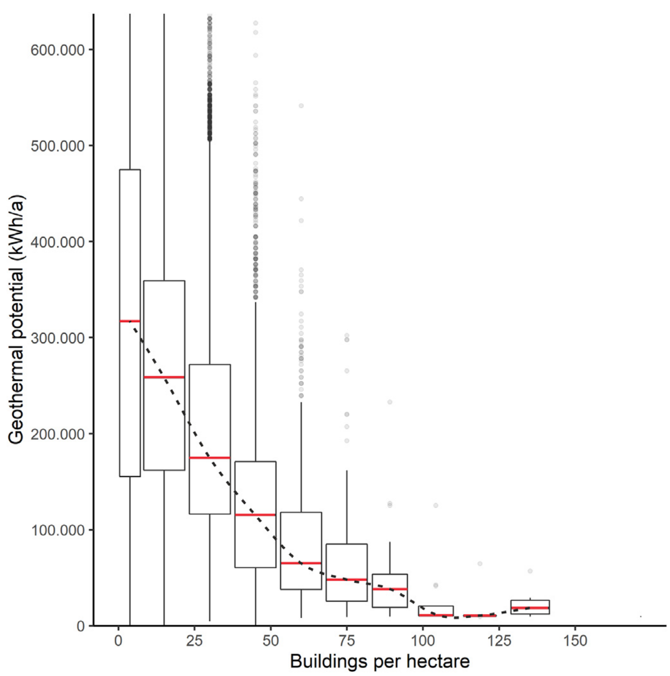

Fig. 6. Boxplot illustrating that the geothermal potential per building block is largely dependent on the building density, with building blocks with a low building density generally exhibiting higher geothermal potentials than building blocks with a high building density. Dashed line indicates the median trend.

more than a few meters from the buildings within the building block. However, for building blocks located at the edge of villages or cities, adjacent undeveloped space could be used for BHE placement. This would significantly increase the number of potentially placeable BHEs.

3.2. Technical geothermal potential

The technical geothermal potential of building blocks ranges from 0 to more than 600 000 kWh per year, and averages at 257 000 kWh per year and hectare when the building block areas are normalised (Fig. 5). Overall, the technical geothermal potential of the whole state yields an annual total of 33.5 TWh. There are no regional trends visible within the geothermal potential. The geothermal potential of a building block is largely controlled by the building density of the building block, with building blocks with a high number of buildings per hectare having a low geothermal potential and building blocks with a low building density exhibiting high geothermal potentials (Fig. 6). This leads to low geothermal potential in city centres with a high building density while residential areas at the fringes of a city or in rural areas generally have higher geothermal potentials (Fig. 7).

The technical geothermal potential with a mean of 25.7 kWh/m^2/a (Fig. 5b) is in the same order of magnitude as the technical geothermal potential of a regional study in Northern Switzerland where Walch et al. [24] estimate it to be 16.4 kWh/m^2/a. The difference is likely due to a range of factors, including differences in the geological settings, the BHE distribution algorithm, as well as the correction for thermal interference between neighbouring BHEs and BHE fields. The fact that the technical geothermal potential correlates with the building density of the building blocks is not surprising, as building blocks with few buildings generally have more space available for BHEs. To identify areas which are well suited for GSHPs, building density may thus be a good approach.

Identified technical geothermal potentials are likely underestimated for the rural areas and slightly overestimated in urban areas due to the BHE placing method and its shortcomings. Consideration of groundwater flow would increase the technical geothermal potential for most building blocks which would similarly increase (up to 40%) for urban areas if the urban heat island effect would be included [14,15]. While our modelling approach takes the thermal interference of neighbouring BHEs into account, which is often not considered even on a district [34,36] or city scale [35], it does so by using an estimated g-function based on the number of BHEs per building block. It thus does not consider the effect of BHEs on neighbouring building blocks which will also interfere. Future work should thus include this effect and may also calculate the true interference per building block by calculating the g-function for each BHE field, e.g. using available Python libraries [42]. Overall, the technical geothermal potentials provided in this

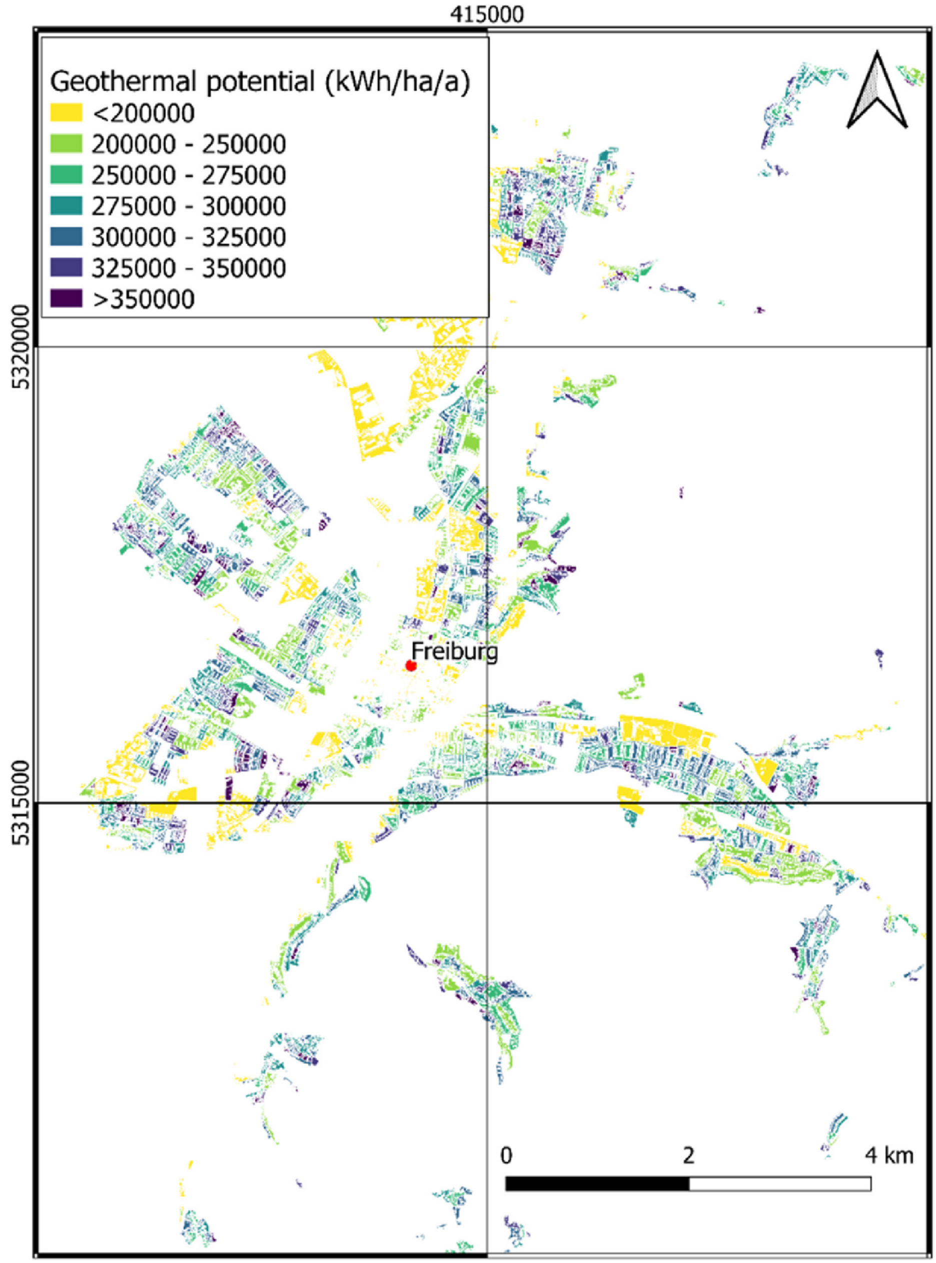

Fig. 7. Map illustrating the geothermal potential for parts of the city of Freiburg. Note how the centre of town (around the town name) has a low potential while residential areas at the edge of town have higher potentials.

study are conservative estimates which can be used for regional and local planning of using renewable heating energy but are no replacement for a detailed study prior to constructing individual BHE fields.

3.3. Heating supply rates

The geothermal potential per building block calculated above can be contrasted with the heating demand of the different building status scenarios included in the Energieatlas data (Fig. 8). For the heating demand scenario "as is" the heating demand of about 44% of all building blocks can be covered by GSHPs alone. This number increases to 65% in the "conventional renovation" scenario and to 93% of all building blocks in the "forward-looking renovation" scenario. While in the "as is" scenario mainly building blocks with a low heating demand can be supplied exclusively by GSHPs, in the "forward-looking renovation" scenario even building blocks with a heating demand of 1 000 MWh/a can be heated solely by GSHPs (Fig. 9). The number of BHEs needed to successfully heat a building exclusively by shallow geothermal energy also drastically decreases from the "as is" with a mean of 6.2 BHEs to the "forward-looking renovation" scenario where on average only 1.3 BHEs per building are needed (Fig. 10).

On a regional scale it becomes clear that the minimum drilling depth exerts a strong control whether the heat demand of a building block can be covered by GSHPs or not: for the "as is" and "conventional renovation" scenarios many of the building blocks for which heat demand cannot be covered by GSHPs are located in the South German Scarpland around Stuttgart where maximum drilling depth is often restricted to 50 m (Fig. 11, Fig. 2b).

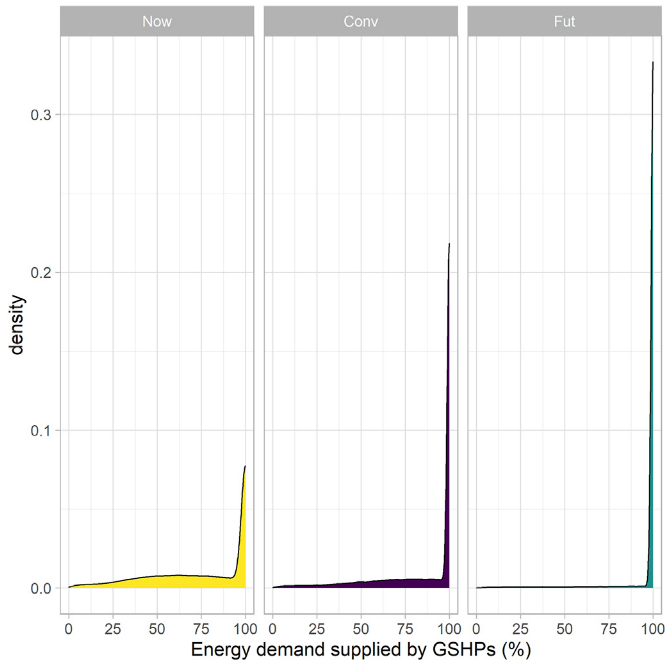

Fig. 8. Density plots of the annual heating demand of all building blocks covered by GSHPs for the three demand scenarios (Now = "As-is", Conv = "Conventional renovation", Fut = "forward-looking renovation").

Additionally, building blocks for which heat cannot be supplied only by GSHPs in all scenarios are located in densely populated areas.

The heating supply rates of 44% for the "as is" building renovation scenario is similar to what has been observed in other studies for urban areas: Schiel et al. [35] estimate 40% of parcels in a German urban area could be supplied with GSHPs while Zhang et al. [34] report that 69% of the heating demand of the district of Westminster, UK, could be supplied by GSHPs. For another urban quarter in Germany Tissen et al. [36] estimate 22–34% of the heating demand could be supplied by BHEs before and 47–71% after building renovation. It is noteworthy that in our study not only urban quarters, but also rural areas are included, and the heating supply rate still does not increase. This is likely due to the fact that the heating supply for the "as is" scenario in urban areas comes closer to the study of Tissen et al. [23] and is significantly higher in rural areas. The higher heating supply rates of 65% and 93% for the renovated building scenarios are in line with the results of Tissen et al. [23]. The significant decrease in needed BHEs per building to cover the heating demand in the "forward-looking renovation" scenario as compared to the "as is" scenario is also interesting from a cost perspective: the on average five saved BHEs per building would, when construction costs of 60 €/m are assumed, save 30 000 € of BHE installation cost per building which could be invested into the building renovation.

4. Practical implications and future work

Regional scale estimations of the technical geothermal potential are required for urban and rural planning, policy making, and the development of regulations [24]. For the state of Baden-Württemberg large municipalities with more than 20 000 inhabitants must develop a heating plan which will form the base for climate-neutral heating supply in 2050. The geothermal potential and heating supply rates provided in this study will assist the urban planners and policy makers involved in the heating plan development to

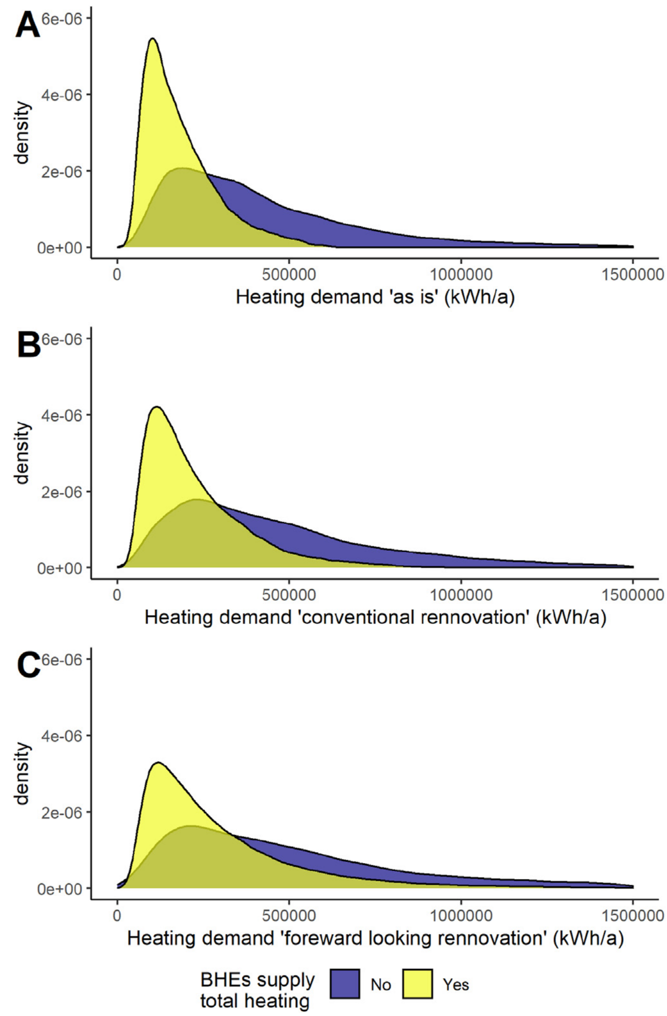

Fig. 9. Density plots illustrating the heating demand of building blocks where BHEs can supply to total heating demand for the three different energy demand scenarios.

estimate the potential of GSHPs in any neighbourhood in the state. Additionally, it can be used to identify (urban) areas in which GSHPs are no option even for renovated buildings due to the building density and geological setting and where other means of heat supply will be needed. To ensure access to the data from this study it will be stored with the state energy bureau which will provide it to the municipalities. Other German states and European countries will soon have similar regulations for municipal heating plans in place as policies will take the greenhouse gas emission reduction targets into account. More studies on the regional technical geothermal potential will thus be needed.

Future work will aim to improve the estimation of a technical geothermal potential on a large scale (state, country) by addressing several of the limitations highlighted in this study, including using official land register data for BHE distribution, implementing heat transfer from groundwater flow in the model as well as including the urban heat island effect. For areas in which BHEs are not an option due to groundwater protection areas or due to the geological setting the use of horizontal shallow geothermal systems should be analysed. Other practical factors such as additional costs arising from using drilling equipment on steep slopes and the suitability of the building ground should also be considered, however these are commonly part of the case-by-case assessment at the preliminary design stage of an individual BHE system. Understanding and

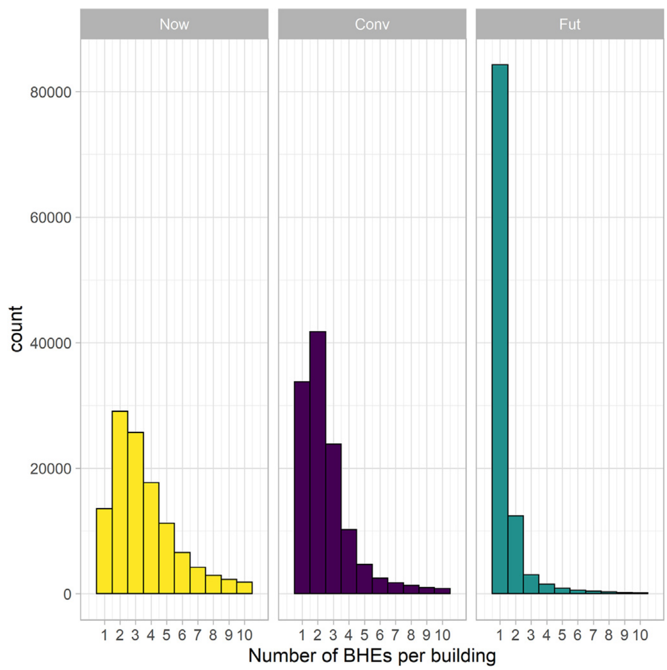

Fig. 10. Bar plots illustrating the number of BHEs needed per building to cover the heat demand for the three different renovation scenarios. Note how forward-looking renovations (Fut) decrease the amount of BHEs needed drastically (Now = "As-is", Conv = "Conventional renovation", Fut = "forward-looking renovation").

quantifying the uncertainties of all included data and the modelling approach will also significantly improve the reliability of the technical geothermal potential on a regional scale. By using machine learning approaches the (geological) input data needed for the model may be estimated on a regional [43] or country [44] scale, which indicates that continental scale technical geothermal potential studies are possible in the near future. Next to the technical and economic aspects of shallow geothermal energy, the decarbonisation potential of this technology, especially with regards to replacing heating oil systems in rural areas, should also be part of further studies. For this data on the installed heating systems is necessary.

Heating demand data, which is necessary for heating plan development and the utilization of renewable technologies, must also be improved. The heating demand scenarios used in this study can only be the first step towards more detailed models in which the true demand of each residential building is included. Energy efficiency renovations to the "forward-looking renovation" standard used in this study may not be realizable for reasonable costs for many buildings, particularly of half-timbered buildings which are common in Central Europe.

5. Conclusions

In this study the technical geothermal potential from ground-source heat pumps for individual building-blocks on a regional scale is estimated and the thermal energy that these vertical borehole heat exchangers provide is linked to the heat demand of the individual building blocks for different demand scenarios. The proposed method to estimate the geothermal potential takes the available area for borehole installation, the technical and geological parameters of the boreholes, and the thermal interference between boreholes into account as well as restrictions on borehole and heat extraction parameters governed by state and federal law.

Our results provide a first estimate of the technical potential of shallow geothermal energy in the state of Baden-Württemberg. Depending on the demand scenario between 44% and 97% of all building blocks can be supplied with sufficient energy from ground-source heat pumps. Particularly rural and suburban areas have high heating supply rates even in high demand scenarios. This indicates that the implementation of shallow geothermal energy sources should be focused outside of cities where they can replace conventional fossil fuelled heating systems. This work can be used to assess the techno-economic aspects of a wide-spread rollout of borehole heat exchangers and will be used for the required heating plans each municipality in the state has to develop. As such is contributes to the development of low-carbon heating sectors in Baden-Württemberg by highlighting where shallow geothermal

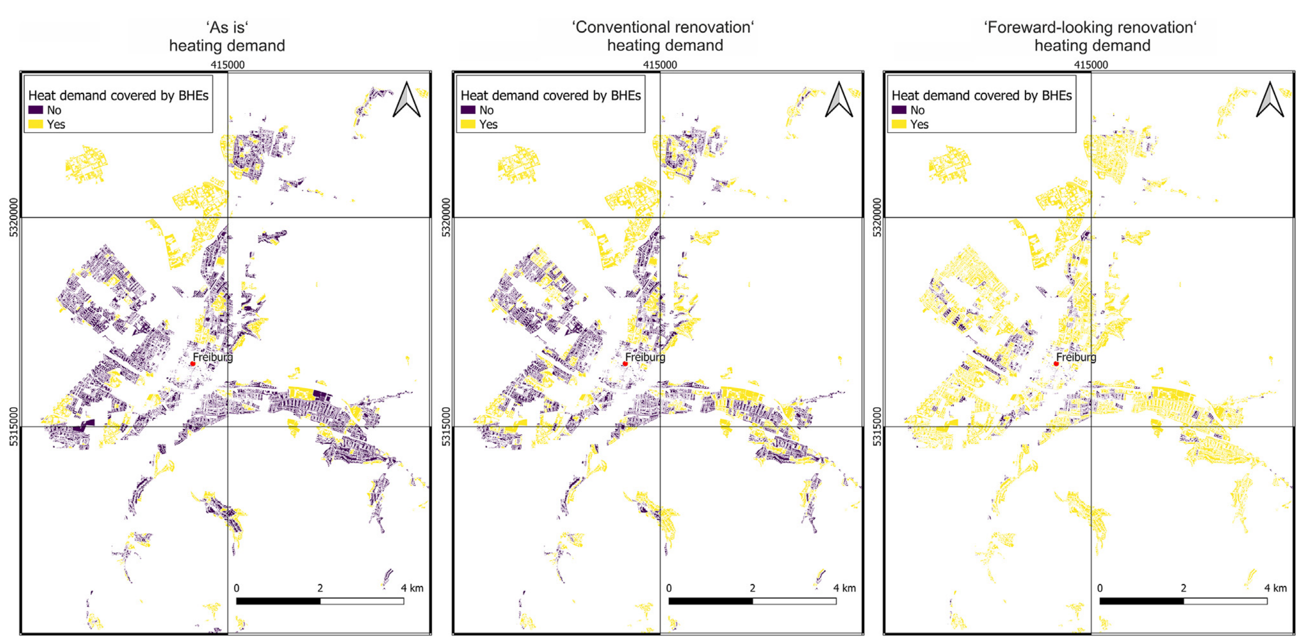

Fig. 11. Maps illustrating for which building blocks of the city of Freiburg heat demand can be covered by GSHPs for the three different heat demand scenarios.

energy can play a larger role and by highlighting (urban) areas where other heat sources, such as district heating networks, are needed.

CRediT authorship contribution statement

Johannes M. Miocic: Conceptualization, Methodology, Formal analysis, Validation, Writing – original draft, Visualization, Funding acquisition. **Marc Krecher:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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