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Site Finding Process Guideline for Locating Deep Geothermal Plants within Existing District Heating Network Areas – Case Study for the German Ruhr Metropolitan Region

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ABSTRACT

To increase the rate of renewable thermal energy, geothermal energy systems need to be integrated stepwise into conventional district heating networks. For this a spatial decision support tool is needed which can be used by decision makers of various fields. This paper provides such a tool. A guideline is presented while parallel a case study is implemented for the Ruhr metropolitan area in Germany. Spatial surface and subsurface data need to be processed in a graphical information system. To achieve a suggestion for decision makers the process needs to be done multiple times at different geothermal temperature levels. A weighting system is also necessary to obtain a priority order for the potential drill sites for the geothermal energy systems. The results are maps with categorized and class ranked potential drill sites for each possible geological horizon (or reservoir) and for each temperature level. This paper concludes with an exemplary analysis for the city of Gelsenkirchen as part of the Ruhr metropolitan area.

1. INTRODUCTION

Germany's energy demand is highly allocated towards thermal energy. Almost 40 % of the total energy demand is utilized for domestic heat. Besides that thermal energy on a higher level is needed for industrial use. The amount of renewable thermal energy is on a stable level for the past four years at around 12 % (value for 2015 not published yet). To achieve the German government's and European Union's climate protection aims, 15.5 % of the final, renewable, and thermal energy is targeted until the year of 2020. One way to realize those aims is to expand the market share of district heating networks (DHN) and integrate more renewable energies in those systems at the same time. Geothermal energy systems, e.g. geothermal heating plants, are independent of weather effects and don't emit particulates or exhaust, and are therefore highly suitable. The temperature level provided by the geothermal energy system needs to be adapted to the DHN needs though.

DHN are most commonly used in cities, or agglomerations of cities, with a dense population and a high density of thermal energy, respectively. Such areas are limited in space, available sites for a geothermal energy system and their drill site are often not easy to find. The thermal energy demand of the DHN and the thermal energy supply by geothermal sources don't fit necessary, too. It requires unifying and processing all surface and geological information. Furthermore it needs to be aligned with the demand of the DHN.

2. METHOLOGY

The aim of this study is to receive a spatial decision support (SDSS) tool for decision makers in the field of geothermal energy system planning, district heating supply, politics, urban planning, or suchlike. Subsurface and surface data are collected, modelled, and evaluated. As a result possible spatial areas are highlighted and sorted by a valuable ranking for different geothermal temperature ranges.

As shown in Figure 1 the workflow is separated in five steps. It begins with the definition of the investigation area (step 0). Most important is the spatial location of the existing DHN. Around this a defined buffer distance gives a first impression of the investigation area. This distance should be the maximum spatial distance (financial factor) between a possible geothermal plant and the DHN. Within this distance possible areas for drill sites occur. The actual geothermal reservoirs location remains unaffected since, due to directional drilling, even further spatial distances to the DHN could arise. If those factors are unknown in the stage of the project, assumptions need to be made. After defining the investigation area as a work space, exclusion zones need to be named and created (step 1). Those again reduce the investigation area and ensure a slim GIS model with only the necessary data sets included. All the remaining areas apply as potential drill sites.

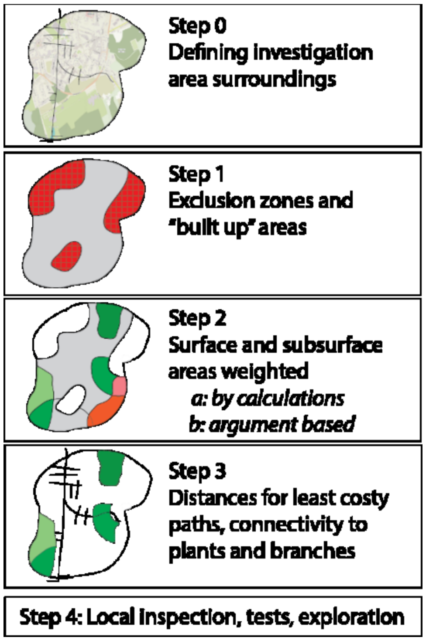

Figure 1: Workflow for the site finding process for deep geothermal energy systems with a connection to an existing district heating network; the definition of the investigation area is prepend as *step 0* for having a least common factor of all available project data. In *step 1* exclusion zones need to be deleted out of the model, whereas in *step 2* the extant areas need to be weighted. In the final *step 3* differently valuable areas result in specially defined respects. Subsequently the most potential areas are to be locally investigated (*step 4*).

Those possible sites need to be weighted (step 2). This can be performed argument based or by allocating value fields, which can be weighted and then multiplied afterwards. The former is the proper way for smaller investigation areas in which the amount of potential sites is manageable. This is the case if you use this method for narrowing down your investigation area and you reached a small scale already, or if only a few but bigger areas are left. With this method of argument based weighting for feasible sites, you have the ability of considering and comparing all advantages and disadvantages, even if different overlaying fields are incomparable. However, for working on a small scale study it is very time consuming for argument based considerations. In this case a calculation based weighting process is to be preferred. Different kinds of fields get self-created – or from other projects or literature derived – values. An additional self-created weighting factor weights the importance of the different kinds of fields. Since it sometimes is difficult to compare all possible field kinds with each other, n classes need to be created. As a result each possible site has n values.

Depending on the amount of remaining potential drill sites, the process has to change to an iterative process if none, or just a little number of sites, remained. Possible reentries into the process are the definition of the exclusion zones or the weighting factors. However, after creating a list with numerous sites, considerations have to be made at which point to cut off the list for shortening. The final favorite drill sites could link to the process of investigating the least costly paths between the found sites and the DHN (step 3). But this is the decision maker's choice. The site finding process for geothermal energy systems with a connection to an existing DHN ends at this point. Afterwards the found sites need to be visited for further investigations, possible explorations, or other testings (step 4).

All those steps, except the last one (step 4), need to be integrated and processed in a geographical information system (GIS). Prior data sets need to be collected and pre-processed. Like shown in Table 1, essential are data sets of the location of the DHN, developed areas, elements of nature, the location of possible geological horizons and their depth and temperature, respectively. Data sources can be (municipal or state) authorities, open access data websites on the internet, or data from the private sector.

Table 1: List of essential and optional data sets for the site finding process of geothermal energy systems to existing DHN.

Essential data sets	Optional data sets
Location of the DHN; Developed areas, such as buildings, streets, railroads; Elements of Nature, such as forests, waters, etc.; Location of geological target horizons incl. depth or temperature, respectively	Master plan of the investigation area's community; Nature reserves; Water protection zones; Flood zones; DEM and terrain slopes; Location of historical and current mining activities; Methane degassing maps; other

3. SITE FINDING PROCESS VIA GIS USING AN EXAMPLE CITY OF RUHR METROPOLITAN AREA, GERMANY

The process of site finding for the geothermal energy systems to connect with existing DHN can be fulfilled with any GI system. Favorable is one with the ability of allowing self-written scripts or process operations. But if not possible an all manual working process is possible, too.

3.1 Investigation Area

The investigation area of the Ruhr metropolitan area is located in western Germany in the state of North Rhine Westphalia. It has a population of around 5.2m in an area of 4,425 km². Eleven cities and four rural districts are combined in the historical coal mining area. The mining activity climax was reached in the 1970s, nowadays there is only one active coil mine remaining in the northern part of the investigation area. This will close down at the end of 2018. The Ruhr metropolitan area has one of the largest DHN in Europe with a total length of more than 2,000 km and an annual energy demand of 6,500 GWh. The maximum thermal power reaches 2,300 MW. Three operators run five primary DHNs which feed 25 secondary DHNs. One of the primary DHN runs at temperatures of up to 180 °C, the other two at a maximum of 130 °C. The connected secondary DHN are operated at lower temperatures. The back flow (BF) temperature is between 60 °C to 70 °C. All DHN-related values accord to the study of BET (2013). The later observed exemplary city of Gelsenkirchen is located in the center of the Ruhr metropolitan area and provides one secondary DHN with two branches, one in the north and one in the south of the city. The exact operating temperatures are not known, the decision maker has to select the right outputs.

Around the DHN of the Ruhr metropolitan area a buffer of 5 km was drawn in ArcGIS. This is the maximum defined distance between a potential drill site and the existing DHN. Because of the dense population around the investigation area, a possible investor for the geothermal energy system would rather provide another community with its thermal energy than build an even longer connection pipe as the defined distance.

The buffered area was clipped by the boarder of the essential data sets (see Table 1), all optional data sets fitted in that area as well. It is wise to proceed with an investigation area which includes (almost) all data sets as the least common factor, only. Otherwise a comparison of potential drill sites isn’t possible.

3.2 Surface Data and Model

The data sets for the surface part were provided by many, from municipal to state authorities, as well as open street maps data sets. After transforming all to the same coordination system the data sets were clipped with the investigation area. All buildings, depending on their height and kind, all streets and railroads as well as the waters were provided with legal safety distances. Totalized this results in the exclusion areas including all kinds of nature reserves for the highest possible social acceptance of the study. Those exclusion zones were erased out of the investigation area, the first set of potential drill sites remains.

Those again are processed directly with legal and suggested safety distances for drill rigs. Since in the state of North Rhine Westphalia a safety distance of 1.1 times the drill rig’s height is dictated as well as the boundary of aiming for the needed feed flow temperature of the DHN is to be considered, a safety radius of 50 m was defined. Drill rigs for the German market were considered only, compare Buja (2012). All potential drill sites were sorted by area size. The smallest footprint of a drill for the boundary conditions for the German market is 760 m² (without periphery), see Bauer et al. (2014). Therefore every smaller site was deleted.

Besides the essential data sets, the optional data sets were processed. These have no influence on the selection of the sites but on their weightings, see chapter 3.4. More detailed information on the selection of data sets and the impact of their quality is published by Knutzen (2015).

3.3 Subsurface Data and Model

On the side of the subsurface, data sets were provided from state authorities, Agemar and Schellschmidt (2012), Limberger (2013), Limberger et al. (2014), and Bussmann and Knutzen (2015). The geology of the Ruhr metropolitan area is characterized through the Variscan orogeny and its faulting. Syncline and anticline change frequently within several hundred meters in the southern part of the investigation area. Towards the north the faulting flattens. From South West to North East the geological horizons submerge, in the area of the former, coil formations intersect the surface, while in the latter those are to be found at a depth of around 1,400 m and deeper. In terms of geological period, the coil mining was practiced in the Carboniferous. At the floor the Devonian continues. Mainly claystone predominates, thin layered and frequently alternating with rock of a higher quartzite amount.

For geothermal utilization enhanced geothermal systems (EGS) are to be considered only. At the North West of the Ruhr metropolitan area, but far outside the investigation area, one possible but not confirmed yet hydrothermal reservoir may exist around the city of Krefeld. The aimed geothermal EGS horizons have a thickness of more than 100 m. Their extensive spread over most of the investigations area is compelling as well as the present of a suitable sedimentary rock, like sand- or limestone. Throughout scientific literature those formations are somehow quantifiable. Harder quantifiable, but imaginable, are the utilization of hydrothermal circulation in areas of tectonic faulting systems and tectonically extensions of faulting systems, respectively.

The possible EGS horizons are: (1) Grauwacke, (2) Kaisberg, (3) Kohlenkalk / Kulm, and (4) Massenkalk. Grauwacke and Kaisberg are located within the Upper Carboniferous, Kohlenkalk / Kulm within the Lower Carboniferous, and Massenkalk within the Devonian. The formation Kohlenkalk / Kulm is separated in two different facies, according to Korn (2014), the former is located south west of Essen with sedimentations of carbonate stage on the shelf edge of the London-Brabanter massif, the latter east of Bochum with chalky deep sea sedimentations. Assumed is a thickness of 200 m. Grauwacke’s and Massenkalk’s thickness is conservatively applied with 300 m while for the Kaisberg 180 m were chosen. The variation of the literature values for density, specific heat capacity, and thermal conductivity is little. Furthermore, since the effect of different rock properties is little on the study's result, too, the rock properties are all the same for all geological horizons. Density is stated with 2,650 kg m^{-3}, the specific heat capacity with 710 J kg^{-1} K^{-1}, and the thermal conductivity with 2.5 W m^{-1} K^{-1} (Hunter and Holl (2012), Alber et al. (2003)).

Generally the temperature increases from the South West to the North East, geothermal gradients are in a range of 2.5 K 100 m^{-1} to 3.1 K 100 m^{-1} within a range of 78 % of the Gaussian distribution. The gradients and temperature layers were created in 1,000 m steps. Values between those steps are linear interpolated since there aren't any rapid changes. Data sets of geothermal gradients were not available, but the temperature models from Agemar, Limberger (both various sources), and Bussmann and Knutzen (primary source: geological survey) at differently quality and raster size models. The data set of Limberger has a very low resolution with comparable lower temperatures, Agemar's data set has a high resolution and slightly lower temperatures than Bussmann and Knutzen (moderate resolution).

Between 3,000 m and 5,000 m all sources delivered values, Agemar not at an extensive spread (lowering with depth). All values were weighted, if Agemar was available, the temperature values of Bussmann and Knutzen with 0.7, Agemar 0.2, and Limberger 0.1, if not, 0.8 for Bussmann and Knutzen and 0.2 for Limberger. For 1,000 m and 2,000 m, if Agemar was available, 0.4 for Agemar, 0.2 for Limberger, and 0.4 through the calculated geothermal gradient between 3,000 m and 4,000 m, if not, than 0.5 for Limberger and 0.5 for the gradient. Between 7,000 m and 10,000 m 0.5 of Limberger occurred and 0.5 of the calculated gradient of between 4,000 m and 5,000 m. One test run for each 1,000 m step was performed in which no weightings occurred. In summary, the standard deviation increased and the total values decreased compared to the weighted test runs. The temperature data sets were normalized in terms of the mean sea level. This was not possible for the geothermal gradients but the effect of no normalization is minimal in that case.

For this investigation temperature ranges for the DHN from 80 °C to 180 °C in 20 K steps were made (BF: 60 °C) as well as 40 °C to 80 °C (RF: 20°C) in addition for the use of heat pumps (HP). This way five plus two different results of the site finding process result since the process is made individually for each temperature range step. The energy content was calculated:

$$Q = c_v \cdot \rho \cdot (h + 8 \cdot (a \cdot t)^{0.5}) \cdot (\vartheta_{FF} - \vartheta_{BF}) \cdot R \tag{1}$$

where c_v, ρ, h, a, t, $\vartheta_{FF,BF}$, R are specific heat capacity, thickness of formation, temperature conductivity, time, temperature, and a recovery factor, respectively. Unit of the energy content is W m^{-2}, depending on the expansion of the stimulation process the total energy content can be calculated. The recovery factor has been chosen conservatively with 0.02, see Grant and Garg (2012), while the time component was set to 30 years. The equation bases on the thermal energy content equation and Nathenson (1975).

Inside the GIS model, the depth layers are under laying the energy content layer. Thereby depth information are always present and requestable for all potential drill sites. Due to the possibility of directional drilling the subsurface investigation area increases over the surface investigation area. Every exclusion area is reachable from the subsurface, but areas as water protection zones should not be crossed at any depth. All EGS formations [(1) to (4)] for direct use cover approximately 89 % of the investigation area, including the HP range more than 95 % are covered. The south western part of the investigation area is not covered at any time.

3.4 Weighting Factors

All GIS model data needs to be categorized, and weighted afterwards. The surface data was divided into two categories: the technical part and the spatial part. The third category covers all geological parts. Each potential drill site contains three fields, one for each category. In the end three different priority classes were created, priority class 1 to 3. A class summarizes all categories. Class 1 contains all those drill sites which belong to the top 20 % in each category. Analog to this class 3 contains the bottom 40 %. All remaining areas create class 2. In case of a short fallen amount of class 1 drill sites any kind of weighting factor could be adjusted with associated consequences.

Each field in a category gets a value and a weight. The values range from 3 to -3. All positive values symbolize a favorable property, increasing by its value, 0 is neutral, and all negative values symbolize an obstacle, decreasing by its value. The weighting factor is a value between 1 and 0, the sum of all equals 1. If more than one value of its kind is calculated for a field the higher value is preferred. This represents a subjective procedure but could be substantiate with literature or study values if available. A comparison of alternatives is advised and was accomplished but will not be presented in this paper.

3.4.1 Technical category

Nine items are included in the technical category. The weighting prefers the drill side size followed by the distance to existing plants (and DHN connection points), the geological horizon distance, and the geothermal gradient. Table 2 pictures the nine items, its values, and weights. The minimum drill site size is set to 760 m². The smallest available drill rig without periphery is able to fit here, more than 6,000 m² is favorable to have a full size and proper equipped standard drill site. The geological horizon distance mirrors the effort and costs for directional drilling while the distance to DHN plants and connection points mirror the same effect on surface. The distance to the actual DHN is from lower interest since the importance between thermal source and connection point is from higher interest. The geothermal gradient is an indicator for the target depth of the geothermal project which is the highest matter of expense. Methane degassing areas and mining areas do not prohibit the drilling project but increase the effort and costs. The shorter the distance to a natural water reservoir is, the bigger the chance of using its cheap water access for the drilling process other than more expansive water access of a hydrant. The terrain slope could go along with a terrain straightening.

Table 2: Surface items of the technical category

Weight		Value
.257	Drill Side Size	
	> 760 m^2	-1
	> 3380 m^2	1
	> 6000 m^2	3
.153	Geol. Horizon Distance	
	below	3
	< 1000 m	3
	< 2000 m	2
	< 3000 m	1
.205	Plants and DHN knots	
	< 1000 m	3
	< 2000 m	2
	< 3000 m	-1
	≥ 3000 m	-3
.051	District Heating Net	
	< 1000 m	1
	< 2000 m	0
	< 3000 m	0
	≥ 3000 m	0
.154	Geothermal gradient	
	$< 2{,}5$ W m^{-1} K^{-1}	-1
	$< 3{,}0$ W m^{-1} K^{-1}	0
	$\geq 3{,}5$ W m^{-1} K^{-1}	1
.026	Methane gas degassing	
	possible degassing area	-1
	leakage point	-2
.051	Mining areas	
	historical and current	-2
.051	Waters: access for drilling, testing, stimulation	
	< 500 m	2
	< 1000 m	1
.051	Terrain slope	
	< 3 %	0
	< 10 %	-1
	≥ 10 %	exclusion

3.4.2 Spatial category

Three items are included in the spatial category. The weighting prefers the FFH and Natura 2000 protection area distances slightly over the kind of master plan fields. The master plan regulates the approval procedure of each community, obstacles and advancements go along. The distances to FFH and nature reserves as well as water protection areas allow for legislation and suggestions of environmental organizations and associations.

Table 3: Surface items of the spatial category

Weight		Value
.272	Kind of Master Plan Field	
	general residential building area	-3
	mixed use area	0
	business and industrial area	1
	industrial area auxiliary	1
	building area for public needs	-3
	agricultural buildings	exclusion
	military area	(1)
	streets, pedestrian area	exclusion
	greater parking lots and other traffic areas	-2
	rail road areas in use	exclusion
	rail road areas wasteland	3
	airfield areas	-3

	building area for sports and recreation, other public areas, green space and cemetery, allotment garden, play- and sports ground	exclusion
	public utility infrastructure and disposal	-3
	tip and removal areas	exclusion
	camping areas and weekend homes	-2
	green areas along traffic areas	2
	water areas	exclusion
	agricultural land	2
	forest	-3
	residential, business, and industrial wasteland	3
	fallow land and other wasteland	3
	tips	exclusion
.364	Distance to Protection areas	
	FFH < 200 m	-3
	nature reserves < 200 m	-3
.364	Water Protection Area	
	< 300 m	-3
	< 600 m	-2

3.4.3 Geological category

A decision maker who uses this tool needs to know for which part of the DHN he wants to use this for. Thereby a certain temperature range only will be interesting for him. The geological category equals the range of temperatures and also their energy contents. Four geological horizons and seven different temperature ranges produce 28 items. The weightings have to be made by the decision maker himself. Those different horizons, temperatures, and depth can't be pictured within this paper. Chapter 4 provides a small example as the result of this work for one part of the geological category.

4. RESULTS AND CONCLUSION

These kinds of studies produce many maps as the outcome. To get an idea of the location of the potential drill sites any kind of topographical map should be placed underneath. The outcome is parted in three different kinds for each temperature level of each geological horizon: (1) potential drill sites are shown with the priority classes 1 to 3, chapter 3.4 explains the weightings of those classes, DHN, power and heating plants are displayed as well; (2) energy content (kW m^{-2}) is shown with the (3) depth maps of the energy content underlaid. Inside the GIS model, all information of each potential drill site for the priority classes, category values including weightings, energy content, and depth are given. It is not possible to picture all those information within one graphic but to number the potential drill sites and refer to a listing. Thereof it was abstained in this paper.

Generically the city of Gelsenkirchen was picked to give an overview about the results of this study. Figure 2 shows a topographical map of Gelsenkirchen and its surroundings. Gelsenkirchen itself is highlighted, also displayed are the current DHN (black solid lined) and a future extension (red crossed line), power and heating plants (black triangles). Class 1 drill sites are green colored while class 2 is orange colored and class 3 is red colored. Figure 2 displays the geological formation Massenkalk at a temperature range from 140 °C to 159 °C, only. Backflow is set to 60 °C, the formation thickness to 300 m plus a conduction length of 30 years with a recovery factor of 2 %, compare equation (1).

Over the city of Gelsenkirchen 280 potential drill sites occurred, 12 are allocated to class 1, 104 to class 2 and 32 to class 3. The amount of drill sites is independent in terms of size. Class 1 covers 18.2 % of all potential drill sites over the entire city in terms of size, class 2 covers 56.3 %, and class 3 7.2 %. This matches the assumption made in chapter 3.4 for the weighting of the priority classes. The amount of potential drill sites for the connection to an existing DHN is sufficient. A further iterative run of the process is not needed. Furthermore a change of the category values and weighting factors will affect the result. A comparison of alternatives is not presented within this paper but will be published.

Summarized, essential and optional data sets were (partly) digitalized, pre-processed, the coordination system was equalized. Afterwards an investigation area was created out of the prior which is the basis for this study. Furthermore the data sets were parted in surface and subsurface. Defined exclusion areas reduced the size of the investigation area, the remaining areas were processed for the fit of the smallest in Germany available drill rig for the boundaries of the project. Additionally the data sets were categorized and weighted. Potential drill sites with the best values of all categories were pooled as class 1 priority drill site, analog to this class 2 and 3. This procedure was done for 28 different temperature layers. A decision maker from the field of district heating, geothermal project planning, financial investment, politics, or suchlike got a tool created which helps to integrate a renewable thermal energy source into an existing DHN.

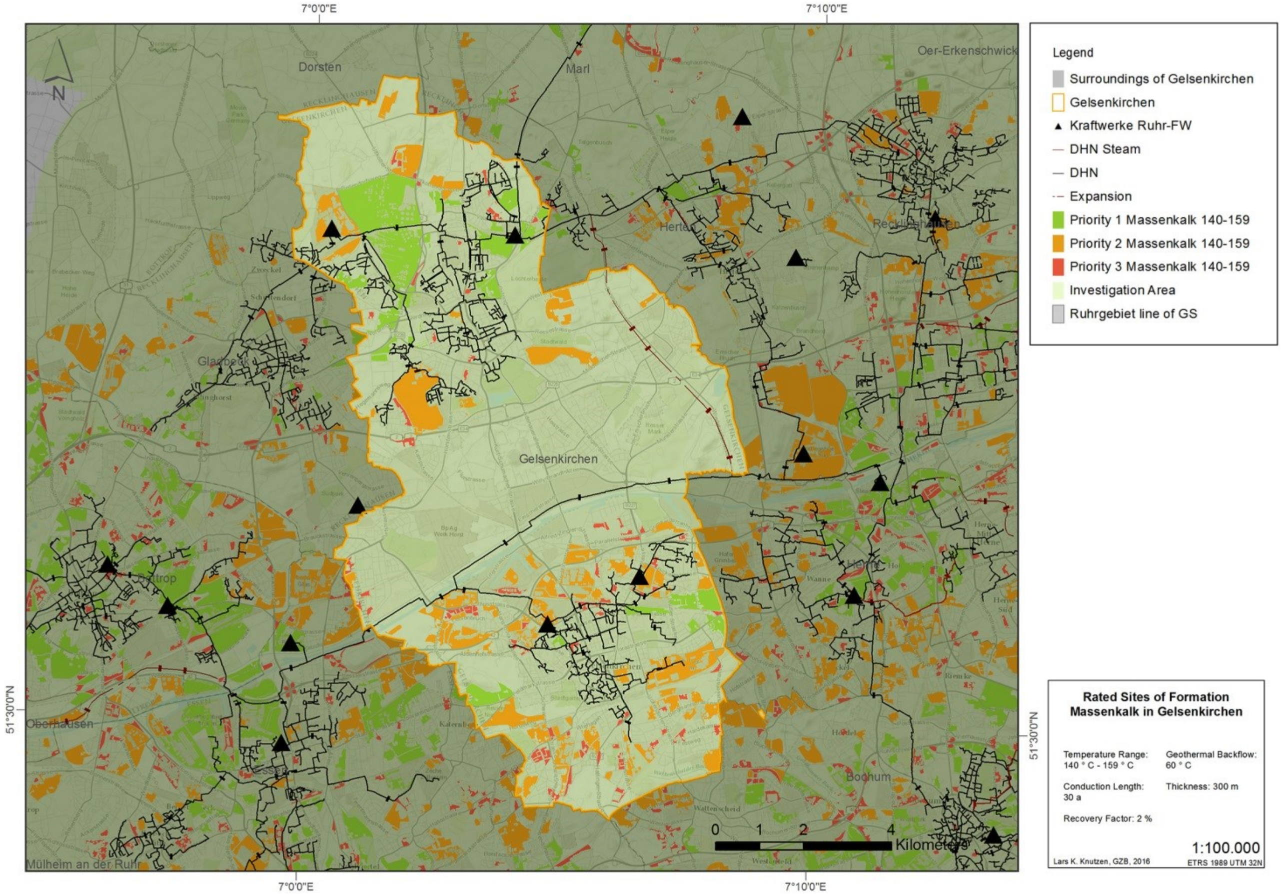

Figure 2: Map of the city of Gelsenkirchen (highlighted area), in the center of Ruhr metropolitan area, with the existing DHN (black lined), future DHN connections (red crossed line), power and heating plants (black triangles), green colored class 1 drill sites, orange colored class 2, and red colored class 3. A topographical map (source: ESRI) is placed in the background.

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