Analysis of a base-load-capable heat supply of quarters considering aquifers in disused mines as heat storages for locally specific renewable (waste) heat potentials

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Abstract

Germany and many parts of the world were shaped by mining for centuries. These abandoned mines have a considerable potential as a source of energy and raw materials and offer a wide range of energy storage options. These energy storage facilities can greatly contribute to renewable heating and cooling systems in buildings. Specifically, Aquifer Thermal Energy Storage (ATES) is an appropriate option, especially for intermediate storage of seasonal energy surpluses from fluctuating renewable energies and waste heat, e.g., from industrial plants. The project MineATES is investigating various base-load supply options for buildings using aquifer heat storage. Simultaneously, three site-specific sub-surface tests in Germany were carried out to determine criteria for feasible ATES energy supply options.

The novelty is the development of a fully automated model using spatial data, which systematically records potential heat sources and performs site-specific analysis to calculate the storable thermal energy potentials considering waste heat, solar thermal applications and other fluctuating renewable energies. The model includes an interface to use measured site-specific storage efficiencies and heat losses to analyze ATES in different scenarios and locations. Thereby, storage load cycles and consumer load profiles are considered to estimate optimal energy dissipation. Additionally, heat production costs for various supply options will be estimated in future.

The core result of the project is a criteria catalogue evaluating the suitability of ATES systems in heat supply concepts at locations worldwide based on GIS-simulations and site-specific tests. Initial results at a site in Freiberg/Saxony, show that the inclusion of waste heat sources in supply concepts with ATES systems are essential to guarantee economic feasibility. In particular, the storage of solar thermal energy, but also electricity from wind and PV which is not fed into the grid from ground-mounted systems as well as industrial waste heat enable a base-load capable supply. Furthermore, combination with an energy supply network should be highly feasible and economically viable.

Considering legal requirements, the project MineATES yields in various criteria for the development of future ATES-systems. This will leverage ATES-based systems based on scientifically developed criteria which can be used by planning- and implementing institutions. Thus, for regions that have the possibility to establish ATES systems, tangible recommendations for an innovative renewable and base-load-capable heat supply will be shown. Leveraging the project's influence, the German Upper Mining Authority is already involved as a partner.

Key-words: Aquifer thermal energy storages, base-load energy supply, waste-heat, fluctuating renewable energies, system optimization

Introduction

To achieve sustainable heat generation in the building sector, a future utilisation of renewable resources is required. Especially geothermal energy is a highly feasible option leveraging the carbon neutral heat supply of the future because it is one of the only base-load capable renewable heat sources. Furthermore, it has the advantage to perform a cyclic energy regeneration in times of a low heating demand. This advantage especially applies to the utilisation of mine water. Regions with extensive old mining operations can therefore benefit from these existing structures. However, extracting much heat will likely cause the mine to cool down in the long term, resulting in a failure of the connected energy supply system. To counteract this, the idea in the MineATES project is increasing regeneration by feeding subsurface green (waste) heat and thus considered the former mining structures as a low-temperature aquifer heat store (ATES). Regeneration can also take place by connecting other possible regenerative heat resources. To map and quantify the entire annual course of the required heat input and output of the mine water, a methodology needs to be developed to record requirements and potentials. The core result of the project will be a criteria catalogue evaluating the suitability of ATES systems in heat supply concepts at locations worldwide based on geospatial simulations and site-specific tests. One district of the city of Freiberg/Saxony, which is one of three real laboratory municipalities in the MineATES project, forms the basis to explain the ongoing work in this paper. The algorithm for geospatial simulations is developed in three steps: Analysis of heat demands (heat sinks), Analysis of nearby green (waste) heat potentials to feed the heat storage (heat sources) and georeferenced balancing considering the load profiles per area.

Step 1: Spatial Analysis of house-specific heating demands

The DBI Gas- und Umwelttechnik GmbH in Germany are experts in geospatial modelling for more than a decade. In many research projects, the basis for the current modelling was established. The DBI building atlas (DBI 2023) forms a geodatabase with address coordinates of each individual building in Germany. In the MineATES project the data records for the investigation area will be clipped from the whole database and further enriched with location-specific parameters to calculate house-specific heating demands using geospatial analysis. Fig. 1 shows a scheme of the process.

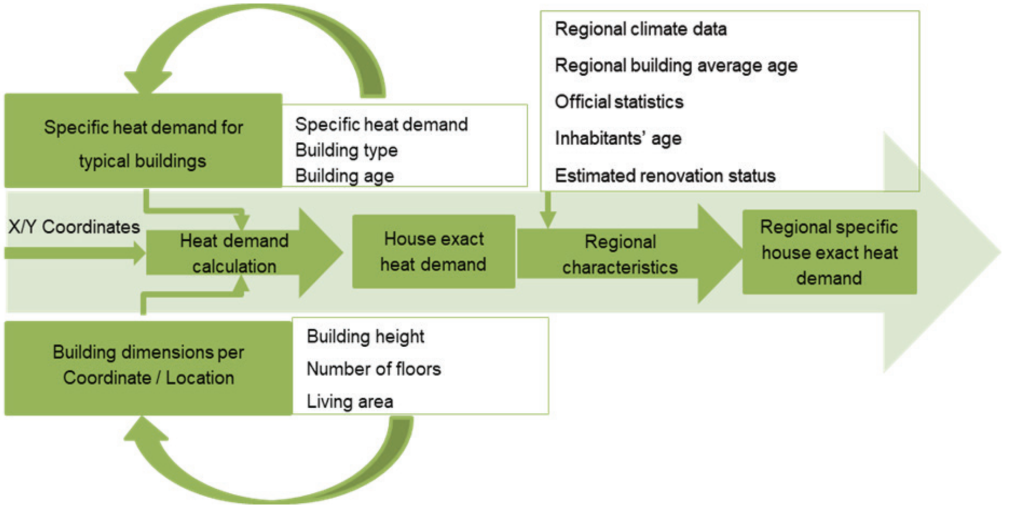

***Figure 1** Algorithm to predict address-specific heating demands based on geospatial and statistical data*

On the one hand, for example, information on building dimensions such as building height, floor area, etc, are necessary. On the other hand, specific heat requirements per square meter, which are determined depending on local characteristics such as building type or building age, should enrich the geodata. It is important to emphasise the differences within residential and/or non-residential buildings as well as different building types. This guarantees as much accuracy as possible as the algorithm can consider the differences in heat demand for all different types of buildings automatically, e.g. a building with 13 or more households (apartements) will be treated differently from a house with seven to twelve households. Also detached houses and terraced houses can be separated, because geospatial analysis allows a check whether the building is detached or not based on its location. Once a specific heat requirement has been assigned to each type of building for a specific location, a heat demand for each building can be calculated using a self-programmed tool. In concluding the simulation, regional characteristics must also be considered. In particular, the renovation status and climatic factors play a decisive role in regionalization. The refurbishment rates reduce the required heat demand. In addition, a climate adjustment of the locations is carried out, whereby the heat demand increases (cold environment) or decreases (*warm environment*) depending on the location. For example, a building at a high altitude is exposed to different annual weather conditions than a building in the city. For this reason, the climate adjustment is carried out using the local and standardized degree day figures for each building. The first result is a heating requirement in kWh/a for each *residential building*. For *non-residential buildings*, specific heat demand values are also assigned based on the calculation for residential buildings, which are combined with one or more unique sector-specific values from the *DBI Building Atlas* (e.g. heat demand per bed and patient in a hospital, heat demand per pupil in a school, heat demand per m² of sales area in a store, etc.). The basic procedure is identical to the calculation of residential buildings, even though the specific values do not necessarily refer to a heated area as they are standardized to other reference units. After the first approximate heat demand prediction, the results will be validated based on building data from the *DBI Building Atlas* for non-residential buildings (e.g., building height, number of storeys). In a second step, the regionalisation will continue analogous to the residential building simulation. Topographical data plays a particularly important role here. The results are evaluated based on real consumption values as well as using relevant primary and secondary literature. Finally, for each building in the investigation area a simulated heat demand can be assigned.

Step 2: Spatial Analysis of nearby suitable renewable heat potentials

Supplying selected neighbourhoods with heat from mine water using an ATES-System causes the mine and the storage to cool down over the long term. To feed the system with more renewable heat, suitable heat sources for a seasonal feed-in the ATES will be identified, such as

I. *solar thermal potentials* in the case study area, especially roof solar thermal potentials,
II. *cooling demands* per building (residential / non-residential),
III. *waste heat potentials* from nearby industries (metal-, glass-, food- & paper industries) and
IV. *surpluses or curtailed renewable electricity potentials* (mainly photovoltaic and wind).

Many distinctions are made for each potential. For example, solar thermal energy will be utilised only on the roofs of buildings because the whole energy concept relies on a grid-based heating supply and the solar thermal yields can be fed directly into the grid and into the storage system. Also cooling demands arise directly inside each building, whereby a distinction must be made especially between the actual building's cooling demands and the actual installation of air conditioning systems. For the analysis of surpluses or curtailed renewable electricity potentials it is assumed that those are more likely located in open spaces. Industrial waste heat is also only available at the point of generation and should be distributed for use in the energy system. At this point, attention must be paid regarding cross-neighbourhood potentials in nearby building quarters. Currently, the algorithm for determining the solar thermal potentials (2-I) is under development, so this paper can discuss this in more detail. As the project progresses in 2024 and 2025, the other potentials (2-II up to 2-IV) will also be comprehensively modelled and evaluated for their systemic suitability for a stable and season-independent ATES energy supply.

Determining the solar thermal potential

To analyse the solar thermal potential for each roof in the area under consideration, it is necessary to know each roof area and orientation as well as the fluctuating local solar radiation. Due to a lack of data on roof geometry, it is assumed that the most common roof shape in Germany is a gable roof. These are pitched roofs with an angle between 20° and 50° from the horizontal (Scheffler 2002). The pitch angle is therefore assumed to be 35° (Kaltschmitt et al. 2020). The orientation of the roof is usually based on the nearest street. Therefore, it is assumed that the roofs slope downwards along the nearest street. Based on this information, the geographical orientation of the roofs can be estimated. This means that houses built along the east-west axis receive the full intensity of solar radiation on the south side of the building. On the north side there is no direct sunlight, so solar thermal energy should ¬¬be utilised on the south side of the building. In the case of buildings orientated along the north-south axis, however, the solar radiation does not reach the roof of the building in any suitable way. So, these buildings will be excluded from the analysis. Also, it cannot be assumed that the entire remaining roof area is available to use. Therefore, an approximate utilization rate of 75% of the south-facing roof area is assumed (Gaber 2014.). Also, from an angle of > 45° to the south axis, the yield of a solar thermal system decreases substantially. Roofs that exceed this orientation are further excluded from the analysis, too. To calculate the

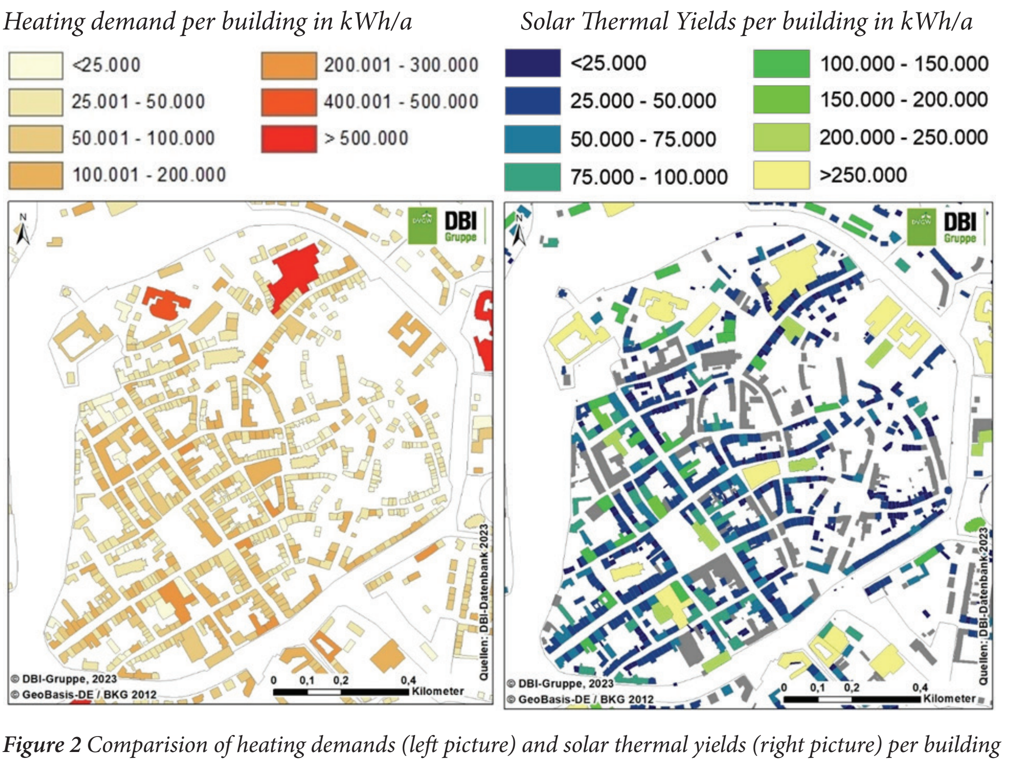

***Figure 2** Comparision of heating demands (left picture) and solar thermal yields (right picture) per building in the investigation area in the historic old town in Freiberg/Saxony*

estimated solar thermal yields, the usable roof areas are multiplied with the solar irradiation values per hour. Hereby it is considered that a solar thermal module has an efficiency of approximately 50% (EnergieWerk Ost GmbH 2020). The input data of solar irradiation will be used hourly for both direct and diffuse solar radiation (DWD 2023). So, the solar thermal yields for all suitable buildings can be calculated hourly, too. All values enrich the geodata for each suitable roof to be a part of the GIS-algorithm. The results of the simulation are shown in Fig. 2. They are compared to the already modelled heating demands from algorithm step 1. The number of gray-colored buildings that are not available for solar thermal energy is striking, however, the remaining potential is still considerable compared to the heating demands.

Step 3: Local balancing with load profiles and initial results of the methods

To define the requirements for the ATES and estimate the seasonal fluctuations, the results of the heat demand and heat yield analyses are plotted and balanced over a year (Fig. 3). The analysis considers that heat is only fed into the storage if the yield from the solar thermal systems is not previously consumed by each building itself. The feed-in from the solar thermal systems is available directly in the building, which means that it offsets directly against the heat demands.

Additionally, Fig. 3 shows a draft for modelled cooling demands as another heat source as already alluded to. Even though the values are still subject to evaluation, it is already apparent that the influence on the overall system will not be very high. Only in the summer months, a cooling demand can be analyzed, however, compared to the solar thermal energy yields, it seems to be a very sensitive parameter for future grid-based system sustainability. For other feed-in options, such as industrial waste heat and surpluses/curtailed energy from renewable energy systems, the model will provide for feed-in upstream of the building.

However, a comparison of the two parameters *Heat Withdrawal* and *Heat Injection* under the mentioned boundaries, shows that already around half of the feed-out can be compensated by regeneration using the renewable heat considered. In total the heat withdrawal stays at 24.87 GWh/a, with a storage regeneration of 12.58 GWh/a (considering heat injection and natural geothermal heat transmission) in the area. In this first draft, storage losses are not yet considered.

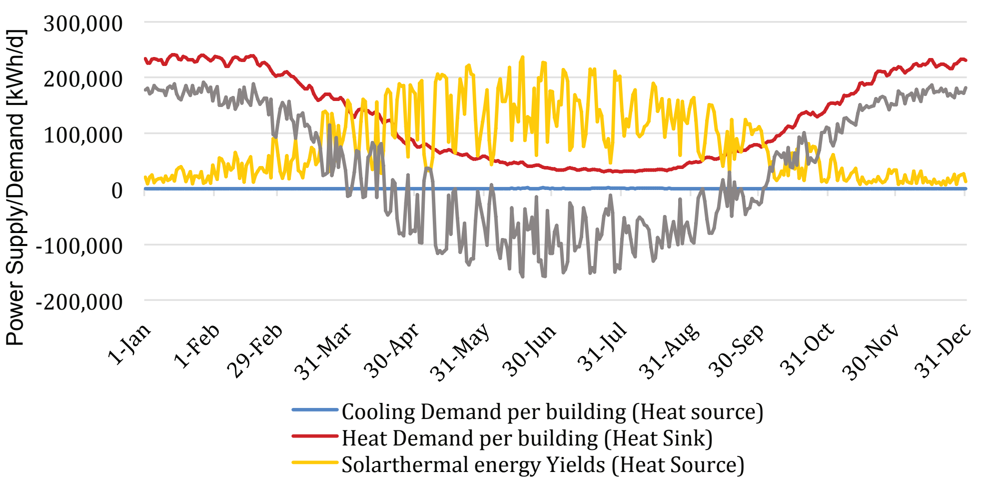

Figure 3 *Seasonal progression of cooling requirements, heating requirements, solar thermal yields and the resulting heat withdrawals / injections*

Next steps

The effects of the other heat sources (waste heat, cooling demands and electric surpluses/curtailed energy) will be analysed further in the project to gain a complete understanding of the necessity if a successful future ATES energy system design. To be able to estimate the potential of renewable heat for the year as a whole and simultaneously for hours or days, it will be necessary to define use cases for the heat supply considering all the applications for using renewable (waste) heat potentials. For the above-ground evaluation of the areas under consideration, the developed models need to be transferred to the remaining municipal areas and a suitable pipeline route of an energy supply network needs to be evaluated regarding their systemic feasibility. Finally, all the results of the sub-surface analysis in this project will be summarized and ranked due to their importance for a successful implementation of ATES-powered heating networks using (waste) heat potentials. The results should be prepared in such a way that they can be combined with the underground analyses from the MineATES project and give relevant criteria that should be fulfilled to suit ATES systems in heat supply concepts using excess heat at locations worldwide.

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