Integration of GHPs into Energy Action and Spatial urban Planning

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Terminology and Abbreviation

4GDH	4th Generation District Heating Networks
5GDH	5th Generation District Heating Networks
AHU	Air Handling Unit
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATES	Aquifer Thermal Energy Storage
BHE	Borehole Heat Exchanger
BHE	Borehole Heat Exchanger Systems
BTES	Borehole Thermal Energy Storage
(CDD)	Cooling Degree Days
COP	Coefficient of Performance
DEM	Digital Elevation Model
EN	European Norm (technical standards)
FAU	Friedrich-Alexander-University Erlangen-Nuremberg
G.POT	Geothermal Potential (specific methodology)
GHP	Geothermal Heat Pump
GIS	Geographic Information System
GWHP	Groundwater Heat Pump
GWHE	Groundwater Heat Exchanger
GWHEs	Groundwater Heat Exchanger Systems
IEA	International Energy Agency
ILS	Infinite Linear Source
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
NECP	National Energy and Climate Plan
ÖNORM	Austrian Standards
RED II	Renewable Energy Directive II
RED III	Renewable Energy Directive III
RES	Renewable Energy Sources
TAP	Thermal Aquifer Potential
TC	Thermal conductivity

TRT	Thermal Response Test
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
VHC	Volumetric Heat Capacity

1. Introduction

1.1 Overview of the deliverable 3.2 framework and objective of the report

The 'GeoBOOST' project aims to overcome market barriers of geothermal heat pumps (GHPs) implementation by improving awareness, reducing upfront costs, enhancing data collection, developing business models, and harmonizing regulations. Work Package 3 focuses on i) analysing the current legal framework and procedures for GHPs promotion, ii) addressing energy planning tools and incentive policies iii) evaluating the legal and policy framework to propose measures for creating a supportive environment for GHPs.

This deliverable addresses the main aspects of Work Package 3 with the ambition to integrate Geothermal Heat Pump Systems (Open and Closed loop systems) into Energy Action and Spatial City Planning. This guideline will simplify and foster the integration of Geothermal Heat Pump (GHP) energy in spatial planning processes, close the knowledge gap of regional and local authorities about embedding it in the procedures and hence support decision makers for the implementation of Renewable Energy Systems (RES).

The main objectives of the deliverable are the following:

- Present and describe the policy and requirements framework for spatial energy planning.
- Propose a workflow for the integration of geothermal heat pump systems into energy actions and spatial city energy planning.
- Expose methods of shallow geothermal potential analysis and Good Practice implementation of GHPs into Spatial Urban Planning.

1.2 Motivation

1.2.1 Climate goals

Growing concern about climate change and its environmental, social and economic impact has led to implementation of global climate goals. The Paris Agreement supported by 196 countries and adopted in 2015, marked a milestone in committing nations to limit global temperature rise to less than 2 °K and to make efforts to limit it to 1.5 °C above pre-industrial levels (Agreement, 2015; Rogelj, 2020). The European Union has committed to achieving climate neutrality by 2050, a key effort in its decarbonisation strategy known as the European

Green Deal (2019) and the Fit for 55 legislative package that pushes for a 55% reduction in emissions by 2030 (Siddi, 2020). The European Green Deal aims for climate neutrality by 2050, reducing greenhouse gas emissions by at least 55% by 2030. A key strategy is accelerating cost-effective and energy-efficient renewable heating and cooling technologies, such as geothermal heat pumps (GHPs).

1.2.2 Heat transition from global to Local

Climate targets not only drive decarbonisation but also emphasise the transition to renewable energy sources and improved energy efficiency.
The global energy transition seeks to transform fossil fuel energy systems towards clean and sustainable and renewable sources. In Europe, the "Green Deal" promotes a transition to renewable heating systems, such as geothermal heat pumps and heat networks, along with the promotion of low-carbon and circular economies. National Energy and Climate Plans (NECPs), required by the EU, set out national strategies to meet Green Deal targets (Fetting, 2020). At the local and regional scale, heating and cooling solutions require adaptation to specific contexts, and the implementation of energy policies must be complemented by a bottom-up approach, where strategies are tailored to the characteristics of each territory (e.g. geothermal resources, existing infrastructure and socio-economic characteristics). This approach allows for efficient development tailored to local needs (Ferroukhi et al., 2020).

1.2.3 Energy planning and its role in the Renewable of Heating and Cooling transition

Energy planning is a structured process that aligns technological, human and financial resources with climate objectives. It enables the assessment and sustainable use of available resources, the design of sustainable infrastructures and the prioritisation of investments. With a detailed planning process, it is possible to identify barriers, optimise the integration of technologies such as heat pumps and ensure that climate targets are met efficiently and equitably. Although standard resource planning can be applied in many cases, geothermal energy requires additional planning to avoid unintended interactions between users, which may affect system performance and restrict access for new users. Planning not only serves as a strategic tool but also facilitates informed decision-making for key stakeholders and it a rapid implementation of sustainable energy systems on a broad scale (Ferroukhi, et al., 2020).

1.2.3.1 Energy planning on different scales

- European and national scale

At the European and national scales, energy planning objectives aim to establish a coherent vision for the use of renewable technologies and the decarbonization of heating and cooling (Aszódi et al., 2021). These objectives include creating regulatory frameworks that promote the integration of renewable energy, improving energy efficiency, and reducing emissions. General information to be included are emission projections and policy analysis, sectoral energy analysis and large-scale infrastructure planning, such as heat networks (Zell-Ziegler et al., 2021).

- Regional and Local Scale

At regional and local scales, energy planning requires detailed and spatially distributed data. This data includes information on the availability of renewable resources, energy consumption patterns, underground characteristics (e.g. geothermal) and local socio-economic factors, the assessment of the technical and economic feasibility of technologies and the integration of these solutions into urban development (Stoeglehner and Abart-Heriszt, 2022). These analyses enable efficient design of systems such as geothermal heat pumps, optimisation of district heating networks and local energy transition planning (Brandoni and Polonara, 2012).

1.2.4 Integration of energy planning in spatial urban energy planning

1.2.4.1 Description of spatial urban planning in the city

Spatial urban planning is a holistic approach that integrates land use, infrastructure, and resource management to optimize urban development (Albrechts, 2004) at local and regional scale. It ensures that cities grow sustainably while addressing environmental, social, and economic needs. In energy planning, this involves aligning the design and location of energy systems—such as electricity grids, heating and cooling networks, and renewable energy installations—with urban layouts to maximize efficiency and minimize environmental impact and to achieve sustainable, efficient, and resilient cities (Cities, 2014).

1.2.4.2 Spatial urban energy planning objectives at different scale

- European and national scale

Spatial urban planning at these scales focuses on achieving principal policy goals related to energy and climate. It emphasizes: i) climate neutrality by aligning with European Union targets, such as the European Green Deal and the Fit for 55 initiative, which aim to reduce emissions by 55% by 2030 and achieve net-zero emissions by 2050 (Siddi, 2020); ii) energy security by strengthening energy independence through diversified sources, robust grids, and cross-border energy networks; iii) establishing common frameworks to support sustainable energy systems across member states (Steiner, 2022); and iv) promoting the large-scale adoption of renewables (Al-Shetwi et al., 2024).

- Regional and local scale

At this scale, planning becomes more detailed, focusing on the specific energy and urban needs of cities and regions. Localized energy mapping utilizes GIS and other tools to identify energy demand, supply, and potential, such as pinpointing high-demand areas and those suitable for renewable energy installations like solar panels or geothermal systems (IEA, 2020). Building stock assessment involves evaluating energy efficiency and retrofitting needs in residential, commercial, and industrial buildings (Müller & Haller, 2012). Community energy projects support local energy cooperatives and small-scale renewable initiatives while fostering community engagement (Droege, 2008). Additionally, integrating transport and urban planning aligns transport infrastructure with energy planning, promoting electric mobility and reducing emissions. Finally, enhancing resilience to climate change ensures cities are prepared for climate impacts through adaptive energy infrastructure, such as decentralized systems and renewable microgrids.

1.2.5 Link between Energy planning and Spatial Urban Planning

Energy planning and spatial urban planning, although distinct disciplines, have an important overlap. In the context of energy planning, the goal is to determine how to supply the necessary energy to a city, which involves integrating renewable energy sources and planning for the electrification of transportation. Meanwhile, spatial planning in the urban context directly influences the location of energy infrastructure such as solar plants, wind parks, and distribution networks. Both disciplines work together to i) supports sustainable development by ensuring cities grow in a way that aligns energy systems with land use, mobility, and housing. his reduces resource consumption and promotes the use of renewable energy sources, as well as the efficient use of available resources, such as surface water and waste heat, ii) improve efficiency by synchronizing urban design with energy planning, which minimizes inefficiencies in resource distribution and infrastructure development, iii) save the cost, as early integration helps avoid expensive retrofits and ensures cost-effective investments in energy infrastructure. Moreover, integrated planning enhances resilience and adaptability, allowing energy systems to be designed to adapt to future needs and environmental challenges, iv) aids in achieving policy goals, as incorporating energy considerations into urban plans enables cities to contribute directly to national and international climate and energy objectives and iv) enhance stakeholder collaboration by coordinated planning, promoting cooperation between governments, the private sector, and communities, ensuring equitable access to energy and shared decision-making.

By embedding energy considerations into urban city planning cities can move towards sustainable, low-carbon urban environments that meet future demands while improving the quality of life for their residents.

2. Stakeholders / Framework

2.1 European and National Scale

2.1.1 Framework (Policies and Requirements)

Energy planning and spatial city planning at European and national scale is based on a robust regulatory framework that integrates climate policies, technical requirements and specific strategies to promote the use of sustainable technologies such as geothermal heat pumps. In this context, the **Renewable Energy Directive (RED II and RED III)** plays a key role in setting clear targets for increasing the share of renewable energy in the heating and cooling sectors. These targets commit Member States to implement support schemes, financial incentives and specific regulatory measures for renewable technologies such as geothermal systems (European Commission, 2020; European Commission, 2023).

The National Energy and Climate Plan (NECP), required by the European Union, strengthens these objectives by detailing national strategies that include the integration of geothermal heat pumps to achieve decarbonisation targets. Each Member State is responsible for identifying legal and administrative barriers, designing local solutions and ensuring significant progress in the implementation of sustainable systems (European Commission, 2023). This is complemented by the **Energy Union Governance Regulation,** which ensures transparency and monitoring of progress on climate and energy targets, including the deployment of renewable technologies (European Commission, 2018).

The National Renovation Strategies and the Energy Efficiency Directive further strengthen the regulatory framework by encouraging the renovation of buildings and the implementation of technologies that improve energy efficiency (European Parliament and Council, 2018). Furthermore, the **Energy Performance of Buildings Directive** introduces mandatory measures to integrate renewable solutions in new and existing buildings, increasing the relevance of these technologies in the context of urban and architectural design (European Commission, 2018).

The European Green Pact and the RePowerEU plan complement this framework by providing a strategic and financial vision to accelerate the transition to renewable energy sources. These plans include the diversification of sustainable technologies and the strengthening of energy infrastructure, where geothermal heat pumps emerge as a key solution. In addition, funding initiatives such as Horizon Europe, LIFE and the Cohesion Funds offer financial support to overcome technical and administrative barriers (European Parliament and Council, 2018).

On the **technical side**, standards such as EN 17522 and EN 378 provide criteria for the design, installation and operation of geothermal heat pumps, ensuring safety, efficiency and sustainability. This framework is aligned with the Water Framework Directive and other environmental regulations that ensure the responsible use of geothermal resources, minimising environmental impact (Sanner, 2008).

2.1.2 Stakeholder Description

Main stakeholders at the European and national scale allow design the development and implementation of policies that promote the adoption of geothermal heat pumps.

2.1.2.1 Integrating Stakeholders into the Heating and Cooling Spatial Urban Planning Process at Regional Scale

Main stakeholders' groups include (García Gil et al., 2021):

- **National governments** are responsible for designing and implementing energy and climate policies within the regulatory frameworks established by the EU. Ministries of Energy, Environment and Economy support the adoption of new technologies and the alignment of national policies with European objectives.

- **Energy Regulatory Agencies or national energy regulatory authorities** are responsible for setting technical standards for the integration of renewable energy systems into the energy grid, ensuring that heat pump installations are safe, efficient and sustainable. They also regulate licensing processes, fiscal incentives and subsidies at the national scale.

- **National urban planning institutions** define the overall framework for urban development in a country, ensuring sustainability, equity and coherence between different scales of planning through the development of guidelines for land use and urban organisation. These entities have responsibilities and functions that typically include aspects such as policy making, coordination between levels of government, and promotion of sustainable development strategies.

- **Energy companies or renewable energy providers**, especially those operating at the national scale, ensure that geothermal heat pumps are integrated into the energy system. These companies should collaborate with governments to establish regulatory frameworks that facilitate the adoption of renewable energy systems across the country.

- **Research institutions and universities** support investigation into the feasibility and benefits of renewable energy systems, developing new technologies and integration methods. They also help identify regulatory and technical barriers to the adoption of these technologies.

- **Industry associations and sustainability-related non-governmental organisations (NGOs)** can influence policymaking by providing data, case studies and best practices, as well as advocating for the adoption of policies that promote renewable energy systems.

2.1.2.2. Target Group

Main target groups include (McCorry & Jones, 2011; Goodman et al., 2010):

- **Government Ministries and Authorities** are responsible for the formulation and implementation of policies that directly affect renewable energy. Their support allows create an enabling environment for the adoption of renewable energy systems.

- **Energy Companies and Energy Service Providers** are directly involved in energy supply and distribution and must ensure that renewable energy systems are effectively integrated into the national energy infrastructure. Their participation in policy formulation helps ensure the technical and economic viability of renewable energy systems.

- **Technology Developers and Technology Providers** supply renewable energy systems and technological infrastructure components. Their ability to develop innovative, cost-effective and efficient solutions is key to increasing the adoption of renewable energy systems.

- **Energy Consultants and Technical Advisors** provide technical and policy advice to governments, businesses and consumers. They help assess the feasibility of renewable energy systems and integrate these technologies into national energy planning, spatial

- **Local and regional real estate developers** are responsible for transforming land-use plans into physical, tangible projects, managing everything from land acquisition to the construction and sale of properties. Their work directly impacts the structure of cities and the way inhabitants interact with urban spaces.

Final Remarks

Although there is an overlap between the two groups, it is important to consider that stakeholders have a more strategic and regulatory role, while target groups are more focused on the adoption and application of geothermal solutions.

2.2 European and Regional Scale

2.2.1 Framework (Policies and Requirements)

At the regional and local scales, integrating geothermal heat pump systems into energy planning requires a regulatory framework that combines national regulations with strategies tailored to specific municipalities. Local governments play a key role in adapting **National Energy and Climate Plans (NECPs)** to urban contexts, ensuring that decarbonisation policies for the heating and cooling sector are effectively implemented (Kastelein, 2024). To achieve this, many cities have developed strategic energy and climate plans that set targets for emissions reduction and the promotion of renewable energy in heating and cooling systems.

Regional and local regulations establish specific requirements for the installation and operation of geothermal systems, covering technical, administrative, and environmental aspects (European commission, 2019). These include regulations for obtaining drilling and operational permits to ensure project safety and sustainability. Additionally, some cities **(Stockholm, Amsterdam, Münich, Viena)** require an assessment of thermal impact on the subsurface before granting authorisations, particularly in densely populated urban areas where thermal interference between systems could become an issue (Gehlin & Andersson, 2018).

From a **technical perspective**, municipalities have begun to develop planning tools that facilitate the integration of geothermal systems into urban infrastructure (Bayer et al., 2019). One such tool is thermal zoning, which helps identify areas with high geothermal potential and establishes restrictions to minimise negative impacts (Bian et al., 2024). In some cities, this information is complemented by geothermal potential maps that integrate data on subsurface composition, water resource availability, and the energy demand of different urban sectors (Halilovic et al., 2024).

Thermal monitoring and modelling have also become a tool for ensuring the optimal performance of geothermal systems. By using temperature and flow sensors, it is possible to monitor subsurface thermal stability and adjust the operation of heat pumps according to demand (Vienken et al., 2019). Some municipalities have implemented environmental monitoring networks that allow for real-time detection of thermal interference, facilitating the optimisation of geothermal resource use and reducing risks associated with subsurface overexploitation (Farr et al., 2019).

In terms of **incentives**, local administrations have developed financial support programmes to encourage the adoption of geothermal systems. These include grants for installing heat pumps in residential and commercial buildings, as well as public-private financing schemes that facilitate investment in district heating networks based on geothermal energy (IRENA, 2021). Additionally, some municipalities have established regulations requiring the inclusion of renewable energy sources in new urban developments, thereby promoting the integration of geothermal technology into sustainable construction projects (Vandevyvere & Stremke, 2012).

2.2.2. Stakeholder Description

2.2.2.1 Integrating Stakeholders into the Heating and Cooling Spatial Urban Planning Process at local scale

Main Stakeholders groups include (UN-HABITAT, 2020):

- **Municipal and City Departments** ensure the integration of geothermal heat pumps (GHPs) into city development, zoning, and urban design. Environmental departments assess environmental impacts, focusing on groundwater protection and soil thermal balance. Building code authorities enforce energy-efficient construction policies compatible with geothermal systems, while climate and sustainability offices promote renewable energy adoption in line with local climate goals.
- **Regional Local Energy Providers** facilitate the integration of geothermal energy into existing networks. They collaborate with municipalities, providing energy demand data and assessing technical feasibility.
- **Local Urban Planners** often collaborate with independent urban planners, architects, and landscape designers to design and implement urban development projects.
- **Technology Experts and Consultants** (Engineers and geologists) conduct feasibility studies, analysing subsurface conditions, thermal storage capacity, and interference risks. Decision-support specialists optimize system placement and sizing for improved efficiency.
- **Universities and Research Institutions** provide cutting-edge research, data analysis, and pilot projects to advance geothermal technologies. They also support local governments in evaluating long-term impacts and benefits.
- **Community Organizations** represent public interests, ensuring concerns about environmental impact, costs, and benefits are addressed. They also bridge communication between policymakers and citizens, fostering awareness and participation in renewable energy planning.

2.2.2.2. Target group

Main target groups include (Šadl, 2024).

- **Municipal governments** are responsible for local policies and sustainable urban development.
- **Citizens, as end-users and promoters of renewable technologies** participate and are involved in the success of the initiatives.
- **Energy suppliers** are responsible for supplying renewable energy and integrating new technologies into their grids.
- **Energy communities** act as catalysts for energy decentralisation through collaborative projects.
- **Energy planners** design strategies that maximise the use of local resources in a sustainable manner.
- **Regional and local companies** are involved in projects related to urban development and services.
- **Real estate developers** focused on maximising land use and economic benefits.

Final Remarks

Although there is an overlap between the two groups, it is important to consider that stakeholders have a more strategic and regulatory role, while target groups are more focused on the adoption and application of geothermal solutions.

3. Workflow for Spatial Urban Planning Procedure

3.1 General Structure

Effective spatial urban planning for heating and cooling requires a systematic and adaptive approach. The workflow for planning procedure outlines key steps (Figure 1) to ensure shallow geothermal solutions are effectively implemented at regional and local scale, addressing both current energy demands and long-term sustainability goals.

The process begins with a comprehensive analysis of heating and cooling demand, using spatial and quantitative data to identify specific needs in targeted areas. This is followed by a detailed assessment of the current energy supply, including the performance of existing systems, and the collection of relevant data for modelling and scenario development.

Building on this foundation, the workflow analyses and evaluates shallow geothermal energy, and their capacity to support energy security and sustainability. By overlaying demand, supply, and renewable potential, planners can identify areas requiring action, such as system upgrades or the integration of high-potential renewable solutions including geothermal.

The next step focuses on defining goals and scenarios, identifying priority areas for geothermal development. These priorities are based on key factors such as demand density, land use compatibility, and accessibility to renewable (geothermal) resources. Strategies are then developed to translate these goals into actionable measures, including energy consulting services, incentives, and infrastructure upgrades.

The development of the transition in the regarded area should be monitored and analysed to proof the status of the goal. Real-time data collection and performance tracking ensure that systems remain efficient and compliant with evolving regulations. Periodic reviews allow adjustments to align with energy transition goals and respond to changing operational conditions or community needs.

This workflow not only supports immediate planning and implementation but also establishes a replicable framework for continuous improvement, ensuring that shallow geothermal systems contribute significantly to economic, environmental, and social development in diverse contexts.

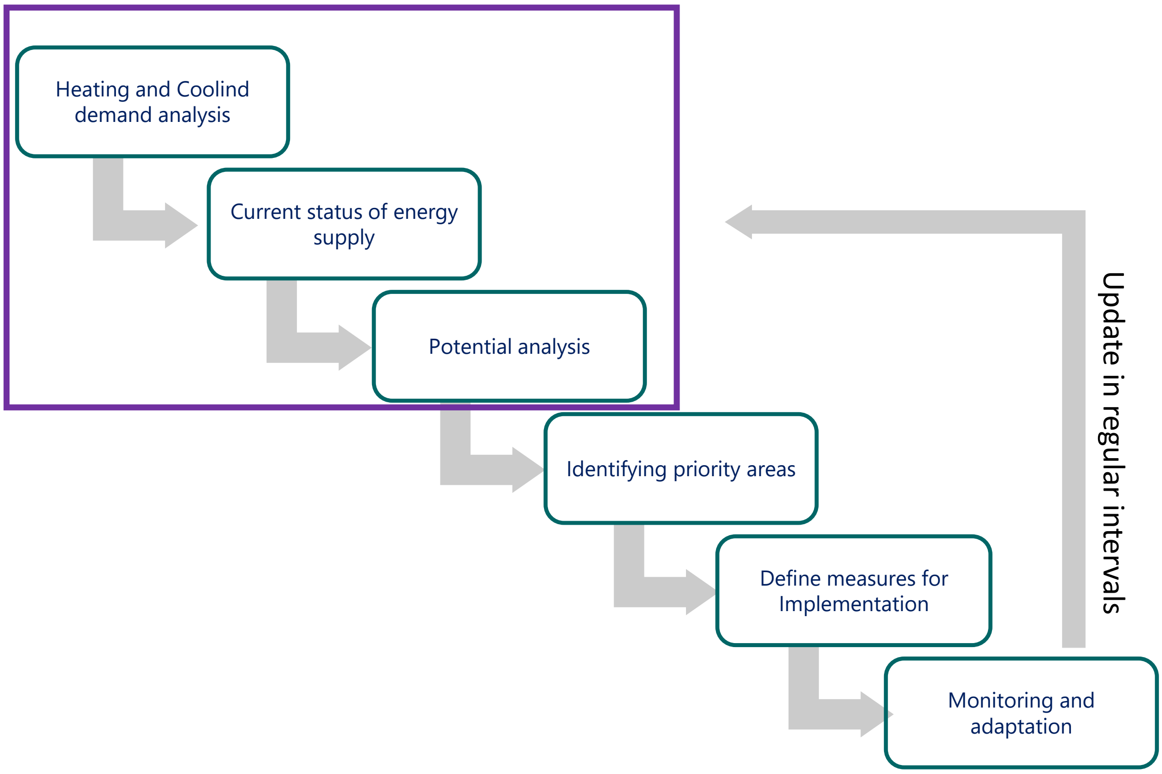


Figure 1: Workflow for spatial urban planning procedure

3.2 Heating and Cooling Demand Analysis

3.2.1 Purpose and Aims

Detailed analysis of heating and cooling demand help to support energy transition efforts and spatial urban planning at multiple scales. At the regional scale, it aims to coordinate and optimise available resources, ensuring effective implementation of national and European energy policies. At the local scale, the focus shifts to ensuring the operational efficiency of heating and cooling systems while meeting energy demands adequately, considering both current and future impacts of climate change.

This analysis encompasses understanding, managing, and projecting energy needs at building, areas, or regional scales. The goals include planning energy infrastructure (International Energy Agency, 2020), optimising energy consumption, and reducing greenhouse gas emissions (European Commission, 2021). To achieve this, it involves:

- Determining the energy requirements of heating and cooling systems across different sectors and regions.
- Identifying seasonal, diurnal and part-load patterns in energy use (National Renewable Energy Laboratory, 2019).
- Developing demand management strategies tailored to these patterns.

When integrated into spatial urban planning, this analysis serves as the foundation for optimising renewable energy sources, including shallow geothermal energy systems. Specifically, for geothermal heat pumps, demand analysis contributes to:

- Assessing the feasibility of geothermal resources at the regional scale (Omer, 2008).
- Optimising the design and integration of infrastructure to maximise efficiency (Curtis et al., 2015).
- Evaluating environmental impacts and ensuring sustainability (Rybach and Eugster, 2010).
- Supporting economic planning and investment decisions (Lund et al., 2010).

Thus, while heating and cooling demand analysis is a cornerstone of broader spatial energy planning, its application to shallow geothermal systems provides relevant insights for the development, optimisation, and sustainability of these renewable energy solutions.

3.2.2 Methods at Regional and Local Scale

3.2.2.1 Method at regional scale

3.2.2.1.1 Heating demand methods

Regional heating demand is generally assessed by considering factors such as outdoor temperature, type of buildings, energy consumption habits and efficiency of heating systems. The most common methods are (For more details on the methods, see Appendixes 6):

- Energy Balance Method

  This method establishes a balance between heat gains and heat losses in a region. Heat losses are calculated based on the characteristics of the environment and buildings (such as thermal envelopes and ventilation losses), while heat gains are calculated from internal sources such as solar radiation, human activities and electrical equipment. The balance between these factors gives an accurate estimate of the heating demand across the region (European Commission, Eurostart, 2023)

- GIS (Geographic Information Systems) based modelling

  GIS-based models integrate spatial data with energy modelling to estimate heating demand in different areas within a region. These models use spatially explicit data such as building footprints, land use and population density (Schwanebeck et al., 2021; Gils, 2012; Ruiz et al, 2007).

- Statistical Analysis of Consumption Data

  The use of historical energy consumption data (obtained from billing, smart sensors or specific measurements) coupled with variables such as temperature, humidity, building characteristics and socio-economic factors allows time series analysis to forecast trends in heating demand in the region. This approach can help detect seasonal and annual consumption patterns, as well as modelling the impact of exceptional events such as extreme cold spells (Schüler et al., 2019).

3.2.2.1.2 Cooling demand methods

The analysis of cooling demand at regional scale considers rising temperatures and the need to cool buildings and open spaces in the warmer months. The most common methods are:

- Cooling Degree Days (CDD) calculation

The Cooling Degree Days (CDD) calculation measures the number of degrees where the average daily temperature exceeds a predefined threshold, usually 18°C. CDDs are used to estimate the cooling demand during the summer, so that the necessary infrastructure can be planned and the impact of cooling technologies such as geothermal systems can be estimated (Scoccimarro et al., 2023).

- Building Energy Simulation Models

Model approaches that simulate the cooling demand of individual buildings or groups of buildings consider factors such as building design, insulation, occupancy, internal heat gains and local climate (Werner, 2017).

- GIS (Geographic Information Systems) based modelling

GIS-based models combine spatial data with energy demand models to estimate the cooling demand in a region. These models consider factors such as building density, land use, urban heat islands and socio-economic data (Lai et al., 2024).

3.2.2.2 Methods at local scale

3.2.2.2.1 Heating demand methods

At the local scale, the analysis of heating demand focuses on the specific needs of individual buildings or small groups of buildings (e.g. neighbourhoods or districts). The most common methods are (For more details on the methods, see Appendixes 6):

- Building Energy Simulation Models

These models simulate the heating demand of individual buildings or groups of buildings by considering factors like building design, insulation, occupancy, internal heat gains, and local climate. They are highly detailed and provide precise estimates at the local scale (Dochev et al., 2020).

- Top-Down

Top-down methods utilize the estimate of total residential sector energy consumption and other pertinent variables such as, macroeconomic indicators (gross domestic product, employment rates, or price indices), climatic conditions, housing construction/demolition rates, and estimates of appliance ownership and number of units in the residential sector to attribute energy consumption to characteristics of the entire housing sector (Swan & Ugursal, 2009; Meha et al., 2020; Frayssinet et al., 2018).

- Bottom-Up

Bottom-up models calculate the energy consumption of individuals or groups of houses and then extrapolate these results to represent the region based on the representative weight of the modelled sample (Swan & Ugursal, 2009; Meha et al., 2015; Frayssinet et al., 2018).

3.2.2.2.2 Cooling demand methods

- Cooling Degree Days (CDD) calculation

  As with heating degree days, the cooling degree day calculation measures the number of degrees where the average daily temperature exceeds a pre-defined threshold, usually 18°C. CDDs are used to estimate the cooling demand during the summer, so that the necessary infrastructure can be planned and the impact of cooling technologies such as geothermal heat pump systems can be estimated (Sivak, 2009).

- Top-Down

  Top-down methods utilize the estimate of total residential sector energy consumption and other relevant variables such as, macroeconomic indicators (gross domestic product, employment rates, or price indices), climatic conditions, housing construction/demolition rates, and estimates of appliance ownership and number of units in the residential sector to attribute energy consumption to characteristics of the entire housing sector (Swan & Ugursal, 2009; Müller, 2015; Frayssinet et al., 2018).

- Bottom-Up

  Bottom-up methods calculate the energy consumption of individuals or groups of houses and then extrapolate these results to represent the region based on the representative weight of the modelled sample (Swan & Ugursal, 2009; Möller, 2015; Frayssinet et al., 2018).

Final remarks

Current methods for estimating energy demand and required capacity often tend to overestimate actual energy needs. This overestimation can lead to inefficiencies in the design and sizing of geothermal systems, affecting their overall performance and sustainability. However, despite this limitation, these methods remain valuable tools for estimating and determining heating and cooling demand at regional and local scales. They provide insights into energy requirements, which are essential for the planning and design of energy systems, including geothermal heat pumps. This factor should be carefully considered when applying demand analysis, but the methodologies still serve as important starting points for decision-making.

3.3 Current State Analysis of the Heating and Cooling Systems

3.3.1 Purpose and Aims of the Current State Analysis

The 'current state analysis' identify which heating and cooling systems are installed, where they are located, and how much demand they cover. This analysis allows for assessing the available energy resources and infrastructure within a specific area. It focuses on understanding the strengths, weaknesses, opportunities, and threats related to the existing energy supply.

By analysing this information, it is possible to:

- Formulate policies and strategies for sustainable energy management, ensuring a stable, sufficient, and secure supply (International Energy Agency, 2021).
- Asses the capacity of the infrastructure (Gielen et al., 2019) and its integration with other renewable energy systems (Lund et al., 2015).
- Align current energy policies with economic, environmental, and social objectives, guaranteeing the profitability of energy sources and technologies (Pachauri & Jiang, 2008).
- Identify areas for improvement and update needs.

Additionally, the Trias Energetical approach should be considered, emphasizing:

- Minimizing energy consumption through improved building efficiency and recovery systems.
- Using sustainable energy generation, such as geothermal.
- Reducing primary energy use, particularly from fossil fuels.

This holistic approach helps in formulating energy strategies tailored to regional and local needs.

3.3.2 Data and procedure at regional and local scale

3.3.2.1 Data and Procedure at regional scale

A detailed analysis of existing heating and cooling supply systems requires robust data collection and integration procedures to map and analyse the current installations. This foundational step provides a clear understanding of the status quo, serving as the basis for subsequent potential analysis.

This section outlines the types of data that need to be collected to conduct a comprehensive analysis of the current state of heating and cooling supply at the regional scale.

Table 1. Data Description

Data	**Description**
Energy Consumption Data	Data on the current energy demand for heating and cooling is collected from various sectors, including residential, commercial, and industrial. This data may include historical energy consumption, peak load demands, and seasonal variations. This information can be obtained from national statistical agencies, energy providers, and specific regional surveys (Eurostat, 2023).
Energy Production and Supply Data	Information on the current sources of heating and cooling supply, including fossil fuels, electricity, district heating, renewable energy sources, among others, is important. This data helps to understand the supply chain and identify the carbon intensity of the energy mix. The data can be obtained from energy providers and regional authorities (International Energy Agency, 2021).
Infrastructure	Data on existing infrastructure, such as the energy efficiency of buildings. The data also includes the age of the infrastructure, and the geographical distribution. This data can be obtained from regional energy agencies, infrastructure operators, and technical assessments (European Commission, 2016).
Environmental Data	Data on emissions, particularly greenhouse gases and other pollutants emitted by current heating and cooling practices, will enable the assessment of their environmental impact (IPCC, 2014).

The proposed procedure for conducting the regional analysis involves several key steps:

- Data Validation**:** All relevant data from the sources mentioned in the data collection section should be compiled. The accuracy of the data is necessary to validate the information by cross-referencing multiple sources. For example, data on residential energy consumption should be compared with national statistics and utility records to ensure its accuracy.

- Data Mapping and Geospatial Analysis: Geographic Information Systems (GIS) are used to spatially map the distribution of heating and cooling demand, and renewable energy resources within the region. This helps identify areas of high energy consumption and potential sites for new renewable energy installations. GIS tools are also helpful for visualizing data and detecting patterns and disparities in energy distribution (Longley et al., 2018; Omusotsi, 2019).

- Capacity Assessment: The current capacity of the heating and cooling infrastructure should be evaluated, focusing on district systems and the integration of renewable energies. This includes assessing the age, efficiency, and potential for expansion or modernization of the existing infrastructure.

- Efficiency Assessment: Inefficiencies in the energy supply infrastructure should be identified, such as heat losses in distribution networks or outdated equipment. Additionally, the existing emission system temperature should be considered, as GSHPs require low-temperature emission systems, despite the use of higher temperature heat pumps. This can be accomplished using data from energy audits or technical assessments from organizations like Euroheat & Power (Euroheat & Power, 2020).
- Stakeholder Consultation: Engaging stakeholders, including energy providers, government agencies, and the public, for validating data and ensuring that the analysis reflects conditions and priorities. This step also helps to identify potential barriers to implementation and opportunities for collaboration (IRENA, 2020).

3.3.2.2 Data and Procedure at local scale

The data to be collected and the procedure to be carried out to analyse the current state of the energy supply (cooling and heating) at the local scale are like those at the regional scale. However, the focus and the data scale vary significantly.

Table 2. Data Description

Data	Description
Energy Consumption Data	Understanding current patterns of energy consumption for heating and cooling is essential. This data should include residential, commercial, and industrial energy use, segmented by fuel type (natural gas, electricity, oil, etc.) and seasonal variations. Local utility companies often provide this data, and in many cases, it is available through government energy departments.
Building Data	Data on the types, sizes, and energy efficiency ratings of buildings, as factors such as proximity to other infrastructures and accessibility for drilling need to be considered. Additionally, the analysis may include detailed case studies exploring how geothermal heat pumps would perform in a very specific environment. This data can be obtained from municipal records or specialised surveys.
Infrastructure Data	Details of existing heating and cooling infrastructure, such as district heating networks, individual heating systems, and cooling technologies. Reports from local utility companies or municipal energy departments are typical sources of this data (Rezaie and Rosen, 2012).

The proposed procedure for conducting the local analysis involves several key steps:

- Data Collection: Collaborating with local governments, building owners, and energy companies is relevant for collecting accurate data. These entities can provide insights into existing heating and cooling systems, their locations, and their energy demand coverage. Such collaboration also helps in understanding how buildings utilize energy, and which systems are in place (Mathew et al., 2015).

- Data Analysis: Once the data is gathered, it must be analysed to assess the current energy supply and demand situation. This analysis will establish a baseline of energy use, identifying inefficiencies, gaps in demand coverage, and opportunities for optimization (Mathew et al., 2015).

- Mapping and Simulations: Using geospatial mapping tools, energy demand across urban and rural areas can be visualized. Such maps are powerful tools for both planning and communication, helping stakeholders like local governments make informed decisions on energy management (Chen et al., 2024).

- Report Generation: Finally, the results of these analyses and simulations should be compiled into detailed reports for each area under review. These reports should not only summarize findings but also offer actionable insights for decision-making and strategic planning (Chen et al., 2024).

3.4 Potential Analysis

3.4.1 Purpose and Aims

The potential analysis aims to evaluate the capacity of different energy sources to meet the energy needs of a region or area (International Energy Agency, 2022) and to contribute to sustainability and energy security goals (World Energy Council, 2020). This analysis considers both renewable and non-renewable energy sources, leading to effective long-term energy planning (United Nations, 2021).

In the context of geothermal heat pumps, the energy potential analysis focuses on assessing the viability, impact, and benefits of this technology at different scales. The analysis involves estimating energy resources (Lund et al., 2010), adapting them to local conditions, and evaluating how geothermal heat pumps (GHPs) can diversify the energy mix and reduce reliance on fossil fuels (Lund and Toth, 2021). As a result of this analysis, the realizable potential to meet demand with a shallow geothermal system or a combination of systems is determined.

Within the analysis, the term "potential" should be clearly defined, along with the aspects to be included and the limitations for determining it. This helps avoid misinterpretations of the calculated potential values. It is recommended to establish a practical, quantitative, and realizable potential, considering the legal, technical, ecological, and economic framework conditions of shallow geothermal energy systems. It is important to mention that the energy potential assessment should be conducted independently from the demand analysis to ensure a clear differentiation between the available geothermal resources and the actual energy needs. For example, for estimating the potential definition in the Bavaria Region, the potential terms established in the Bavarian Energy Summit are considered (Figure 2).

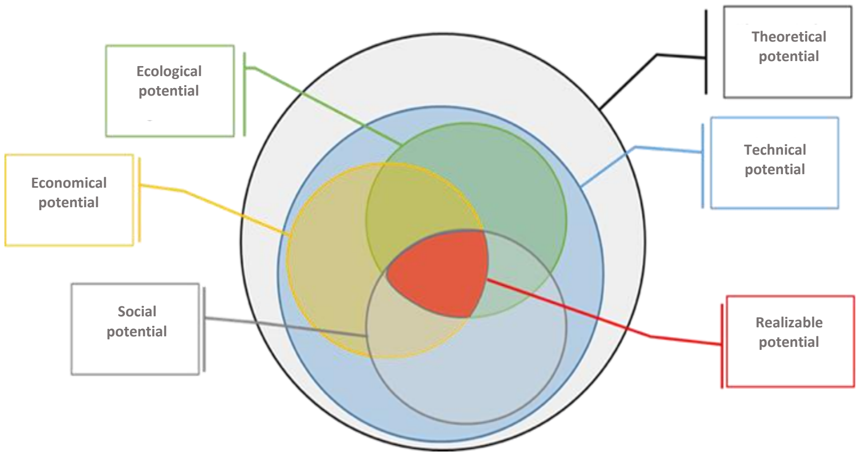


Figure 2: Potential terms from the results report of the 2018 Energy Summit (Bavarian State Ministry of Economic Affairs, Regional Development and Energy, 2019).

The **theoretical potential** comprises the absolute amount of heat/extraction or heating capacity available in the ground. It is first reduced by **technical limitations** and then limited to the **realisable potential** by ecological, economic, and social conditions.

The **realisable potential** is intended to provide a statement on the initial feasibility of a shallow geothermal plant at a location. In particular, the determined potential must be reliable, conservative (i.e., realisable in any case) and consistent. For this purpose, technical, ecological, and social constraints are considered. Economic constraints are considered separately, as they are complex to assess and highly dynamic.

The framework for **ecological compatibility** and **social acceptance** is provided by the currently existing, country-specific regulations for the utilisation of shallow geothermal energy. These include, for example, distances between geothermal wells, volume-related and thermal injection and extraction limits and drilling depth limits. In addition, areas that legally and/or ecologically exclude utilisation are considered in the potential analysis, as these areas have no potential.

Economic viability should be considered within the definition of potential. However, a very volatile market due to the current energy crisis, as well as the dynamics of the financing environment, would contribute to the potential results only being reliable for a short period of time.

The results of the potential analysis are commonly represented through geothermal potential maps, feasibility reports, and spatial decision-support tools, which facilitate the visualization and communication of findings to planners and stakeholders.

In summary, a robust potential analysis is essential for informed decision-making in urban and energy planning, as it enables stakeholders to identify the most suitable areas and strategies for deploying shallow geothermal systems, thus maximizing both economic and environmental benefits.

3.4.2 Methods used for each system at regional and local scale

3.4.2.1 Methods used for each system at the regional scale

Methods used for each system at the regional scale are presented below.

3.4.2.1.1 Potential Analysis for Open Loop Systems

- Method proposed by Arola et al., 2014

This proposes a method for calculating the geothermal potential of groundwater heat pump systems (GWHP), combines hydrogeological data with land use information to create a database for assessing geothermal potential in a detailed manner adapted to regional conditions. This is then explained in the document analysed through the step expose in the table 3:

Table 3. Methods steps.

Steps		Description
1	Groundwater Flow Estimation (F)	The groundwater flow in an aquifer is determined. This is calculated based on the estimated natural recharge of the aquifer and the percentage of the area of urban or industrial use of the aquifer. Groundwater data were collected from The Hertta Database (2012), and land use data from the Corine 2006 Database (2006)
2	Calculation of Extractable Energy (G)	The amount of heat that can be extracted from moving groundwater is calculated using the formula: $G(W)=F \cdot \Delta T \cdot Svcwat$

		Where, F: water flow (kg/s) ΔT: temperature difference between heat pump inlet and outlet (3 K in this case). Svcwat: heat capacity of water (4,200 J/kg-K).
3	Calculation of the Total Heat Load (H)	Using a typical coefficient of performance (COP) of 3.5, the thermal power that can be transferred to the heating system is calculated, applying the formula $H\ (J)=G\cdot(1-1/COP)$
4	Design Power Simulation	The design power of residential buildings (W/m^2) is evaluated as a function of local climatic conditions and construction characteristics. This allows the calculation of the total area that can be heated by groundwater energy.
5	Energy Adequacy Assessment	With the values obtained for H and the design power, the area of buildings that can be heated by the energy potential of the groundwater is estimated.

- TAP Method

The method for calculating the geothermal potential in the thermal utilisation of groundwater by means of heat pumps is based on the Thermal Aquifer Potential (TAP) Method (Böttcher et al., 2019). The method includes the following steps (table 4):

Table 4. Step Descriptions

Steps		**Description**
1	Assessment of Available and Pumpable Flow	The calculation of the available groundwater flow depends on natural factors and engineering conditions, including: - Thickness of the aquifer - Depth of the water table - Thickness of the aquifer. - Conditions of extraction and injection wells
2	Calculation of Potential in Plots and building block	Three key equations are established to determine the system constraints; i) Drawdown at the Extraction Well; ii) Injection Constraints and iii) Hydraulic Short Circuit Prevention.
3	Determination of Maximum Extraction Flow Rate	The maximum abstraction flow rate is obtained as the minimum value between the flow rates determined in the previous steps.
4	Calculation of the Thermal Extraction Capacity	The extractable thermal capacity is obtained from the maximum allowable flow rate and the temperature variation.

For more information on this method go to section 4.1.3.1.

3.4.2.1.2 Potential Analysis for Closed Loop Vertical Systems

- Method proposed by Previati and Crosta 2021

This method takes an approach that ensures a balance between technical feasibility and environmental and regulatory constraints, providing tools for sustainable planning and management of geothermal resources. The method includes the following steps(table5):

Table 5. Step Descriptions

Steps		**Description**
1	Hydrogeological and thermal data collection	Stratigraphic records, soil thermal and hydraulic properties, and subsurface temperature data are collected (physicochemical datasets and multi-temporal vertical temperature profiles). A spatial interpolation approach is used to map these parameters in the study area.
2	Thermal potential estimation with analytical equations	For BHE (closed loop) systems, the ASHRAE equation is applied to calculate the required borehole length as a function of heat transfer from/to the subsurface. $P=(T_g-T_f) / R_b+R_s$ Where: P: Thermal power transferred. T_g: Temperature of undisturbed soil (◦C). T_f: Average temperature of the fluid in the system (◦C). R_b: Thermal resistance of the borehole (casing and backfill material) ((mK/W) R_s: Thermal resistance of the ground(mK/W). The formula integrates thermal resistance of the soil and the borehole, heat capacity of the fluid, and the temperature difference between the fluid and the soil.
3	Consideration of regulatory and environmental restrictions	Limits imposed by local regulations, such as maximum allowable drilling depth and thermal impact on aquifers, are assessed.
4	Numerical modelling and simulation	Simulations are performed to assess system performance under different operational scenarios, considering long-term heat fluxes and seasonal effects.
5	Generation of geothermal potential maps	Thematic maps (MW) are produced using GIS systems to identify optimal areas for geothermal installations.
6	Comparison with thermal demand	The results are compared with the energy requirements of buildings in the area to assess the coverage of the geothermal potential.

- VDI 4640 Method

The methodology for estimating the quantitative potential of geothermal heat exchangers (BHE) is based on VDI 4640, sheet 2, using geological and thermal subsurface data.

Table 6. Step Descriptions

Steps		Description
1	Evaluation of Thermal Extraction Potential	The thermal conductivity of the soil and the borehole depth limit are determined. VDI 4640 Tables are used to relate thermal conductivity to the extraction capacity per meter of installation. The number of hours at full load (1,200 - 2,400 h/year), the type of operation (heating only or heating + hot water), and the minimum temperature of the transfer fluid (-5 °C to 0 °C) are considered.
2	Determination of the Number of Boreholes on a Plots	Determination of the Number of Boreholes on a Parcel
3	Calculation of the Heat Extraction Capacity	The extraction capacity per installation is obtained by considering the maximum borehole depth.
4	Calculation of the Annual Energy Extracted	Calculation of the Annual Energy Extracted

For more information on this method go to section 4.1.3.1.3

3.4.2.1.3 Potential Analysis for Closed Loop Horizontal Systems

- Method proposes by Bertermann et al., 2014

The method for calculating the geothermal potential (MW)for utilisation of very shallow systems (vSGP) with horizontal collectors is based on an integrated approach that combines geological, climatic and ground property data and provides a detailed tool for planning and optimising the use of very shallow geothermal systems in different geographical areas. The method includes the following steps (table 7):

Table 7. Step Descriptions

Steps		Description
1	Definition of Depth Layers	The subsurface is divided into three layers: 0-3 m, 3-6 m and 6-10 m. These correspond to typical installation depths for horizontal collectors.
2	Exclusion and Limiting Factors	Areas with less than 3 m of soft soil, presence of consolidated rock, permafrost or water bodies are excluded. Limitations are identified such as slopes greater than 15° or protected areas, which may require additional studies.
3	Soil Properties	Soil texture, bulk density and water content, as also the average soil temperature are analysed using national maps and borehole surveys.
4	Hydrological Status	The soil moisture index is determined, considering precipitation and temperature.

		It is assessed whether the layers are saturated, unsaturated or influenced by groundwater.
5	Calculation of Conductivity and Heat Capacity	Thermal conductivity (TC) and volumetric heat capacity (VHC) are calculated using specific equations that include soil properties and their level of saturation.
6	Validation and Visualisation	Results are validated using laboratory samples and plotted on thematic maps using a WebGIS system.

- VDI 4640 and 4710 method

The methodology for determining the potential of horizontal collectors (HC) is based on the approach developed by the Friedrich-Alexander-University Erlangen-Nuremberg (FAU), integrating the VDI 4640 and 4710 standards with digital soil data and a digital elevation model (DEM). The key parameter for the calculation of the potential is the soil type and its physical properties, together with climatic data determining the heating degree days.

Table 8. Step Descriptions

Steps		Description
1	Determination of heating degree days	These are calculated according to ÖNORM B 8110-5, using a reference indoor temperature of 22 °C and the average outdoor temperature. This data is linked to DIN 4710 weather stations and altitude.
2	Calculation of the heat extraction capacity	These are calculated according to ÖNORM B 8110-5, using a reference indoor temperature of 22 °C and the average outdoor temperature. This data is linked to DIN 4710 weather stations and altitude.
3	Calculation of the extracted energy	It is obtained by multiplying the extraction power by the full load hours, which are estimated as a function of altitude.
4	GIS use	Geographic information systems (GIS) are used to visualise and spatially differentiate the geothermal potential based on DEM and soil data.

For more information on this method go to section 4.1.3.1.3

3.4.2.1.4 Potential Analysis for Geostructure Systems

- Method proposed by Kong et al., 2024

The method includes the following steps (table 9):

Table 9. Step Descriptions

Steps	Description

1	Suitability Zoning	A GIS analysis is performed to identify optimal areas, considering factors such as lithology, hydrogeological conditions, aquifer thickness and initial soil temperature. The analytical Hierarchy Process (AHP) or combined methods are applied to assign weights to indicators
2	Calculation of regional potential	A volumetric approach is used to estimate the thermal capacity of the soil as a function of its volume, porosity and thermal properties. $E_{geo}=V\cdot[(1-n)\cdot Cs+n\cdot C_w]\cdot\Delta T$ Where, E_{geo}: Thermal potential (J) V: Volume of the soil under consideration (m^3) n: Porosity of the soil (dimensionless) C_w: Specific heat capacity of the soil and water, respectively (J/m^3-K) ΔT: Temperature change in the soil layer (K) Thermal interference between nearby geostructures is considered and empirical models are used to assess the long-term impact. To evaluate the interaction between structures the formula is used: $Q_{regional}= (\lambda/R_b+R_s)\cdot\Delta T$ Where, R_b: Thermal resistance of the geo-structure (m-K/W) R_s: thermal resistance of the soil (m-K/W).
3	Simulation of energy scenarios	The interaction between building energy demands and available geothermal potential is simulated. Strategies to mitigate thermal imbalances in dense urban areas are identified.
4	Visualisation and decision making	Maps of geothermal potential distribution ($kW\cdot h\cdot(hm^2)^{-1}\cdot a^{-1}$) and areas suitable for implementation are generated. The results are used to plan large-scale developments, optimising the use of the resource.

3.4.2.2 Methods at local scale

Methods used for each system at the local scale are presented below.

3.4.2.2.1 Potential Analysis for Open Loop Systems

- Method proposed by Tissen et al., 2019

This author proposes a method for calculating the geothermal potential utilisation of groundwater heat pump (GWHP) systems, which designs scenarios that include different system configurations, such as depth limitations, groundwater flow rates and heat extraction rates, to compare the feasibility of each configuration.

This approach ensures that GWHP systems are optimised both technically and environmentally, complying with local regulations and maximizing system efficiency. However, it is primarily applicable to porous media, where groundwater flow can be reliably estimated. Its applicability to fractured media would depend on local hydrogeological conditions, as water availability is less predictable due to the discontinuous nature of fractures.

Table 10. Step Descriptions

Steps		Description
1	Energy flow approach	The geothermal potential is estimated from the groundwater flow through aquifers. Using Darcy's law, the volumetric flux of water is calculated considering parameters such as hydraulic conductivity, hydraulic gradient and cross-sectional area of the aquifer.
2	Thermal plume approximation	This method analytically simulates the thermal plume caused by the re-injection of cooled water into the aquifer. It uses equations that consider thermal advection and conduction to estimate the maximum dimensions of the thermal plume, ensuring that it does not interfere with other nearby geothermal systems.
3	Evaluation of geothermal potential	Theoretical extractable geothermal energy is calculated using parameters such as groundwater flow, volumetric heat capacity of water and temperature difference before and after extraction. The applied formula includes the efficiency of the system represented by the coefficient of performance (COP).
4	Spatial analysis	Geographic information system (GIS) tools are employed to identify areas available for well installation, considering constraints such as maximum drilling depths and the location of underground infrastructure.
5	Evaluation scenarios	Scenarios that include different system configurations, such as depth constraints, groundwater flow rates and heat extraction rates, are designed to compare the feasibility of each configuration. The approach ensures that GWHP systems are optimised both technically and environmentally, complying with local regulations and maximising system efficiency.

- TAP Method

The method for calculating the geothermal potential in the thermal utilisation of groundwater by means of heat pumps is based on the Thermal Aquifer Potential (TAP) Method (Böttcher et al., 2019). The method includes the following steps (Table 11):

Table 11. Step Descriptions

Steps	Description

1	Assessment of Available and Pumpable Flow	The calculation of the available groundwater flow depends on natural factors and engineering conditions, including: - Thickness of the aquifer - Depth of the water table - Thickness of the aquifer. - Conditions of extraction and injection wells
2	Calculation of Potential in Plots and building block	Three key equations are established to determine the system constraints; i) Drawdown at the Extraction Well; ii) Injection Constraints and iii) Hydraulic Short Circuit Prevention.
3	Determination of Maximum Extraction Flow Rate	The maximum abstraction flow rate is obtained as the minimum value between the flow rates determined in the previous steps.
4	Calculation of the Thermal Extraction Capacity	The extractable thermal capacity is obtained from the maximum allowable flow rate and the temperature variation.

For more information on this method go to section 4.1.3.1.3

3.4.2.2.2 Potential Analysis for Closed Loop Vertical Systems

- rOGER Method

The method for calculating the geothermal potential for utilisation of Borehole Heat Exchanger (BHE) systems is proposed by Baralis and Barlas, 2024. This method, designed for urban areas, considers the thermal and hydraulic conditions of the subsurface, integrating numerical modelling and geographic information systems (GIS). The key steps are (Table 12):

Table 12. Step Descriptions

Steps		**Description**
1	Georeferenced database	Data on hydrogeology, subsurface infrastructure, thermal-hydraulic regime, and the built environment are collected. The data are organised in a GIS system with resolution suitable for urban areas.
2	Numerical modelling	The thermal and hydraulic behaviour of the area is simulated using three-dimensional transient models. This step allows to evaluate the distribution of temperatures and groundwater flows, fundamental for the calculation of the geothermal potential.
3	Calculation of the local geothermal potential	An improved version of the G.POT formula is used to assess the technical potential considering advective and dispersive heat transfer components. This formula includes factors such as thermal conductivity, thermal dispersity and groundwater flow velocities.

4	Spatial and temporal optimisation	The best location for BHE installations is identified through indicators such as geothermal potential and capacity to meet energy demands. Strategies to optimise the use of geothermal resources in relation to the heating and cooling needs of buildings are evaluated. This method combines the accuracy of numerical modelling with GIS tools to provide detailed maps of geothermal potential, enabling developers and environmental managers to plan geothermal installations and minimise interference in densely populated areas.

- G.POT method

The G.POT (Geothermal POTential) method (Casasso & Sethi, 2026) is a quantitative methodology to assess and map the shallow geothermal potential associated with vertical borehole heat exchangers (BHE). The general procedure follows these steps (Table 13):

Table 13. Step Descriptions

Steps		**Description**
1	Definition of the shallow geothermal potential	The amount of heat that can be exchanged sustainably with the ground without causing excessive cooling or heating of the carrier fluid is calculated
2	Key parameters	Thermal properties of the soil: thermal conductivity(W/mK), thermal capacity (J/m^3K)and initial temperature of the soil(°C). BHE characteristics: depth(m), radius(m) and thermal resistance of the heat exchanger(mK/W). Operational parameters: limiting temperature of the carrier fluid(°C), duration of the heating/cooling season (days)and simulated lifetime of the system(years).
3	Heat transfer model	A model based on the infinite linear source (ILS) theory is used to calculate the thermal alteration of the soil over time. The temperature variation at the exchanger wall is estimated by superimposing cyclic heat load effects. The heat transfer inside the BHE is modelled by an equivalent thermal resistance
4	Development of an empirical equation	Numerical simulations of heat transfer are performed by varying the soil and BHE parameters. From the results, an empirical equation is fitted to calculate geothermal potential as a function of BHE depth and site thermal conditions. $Q_{BHE}=a(T_0-T_{lim})\lambda L t_c(-0.619 t_c \log u_s+0.532 t_c-0.962)(\log u_c-0.455 t_c-1.619)+ 4\pi\lambda / R_b$ Where, $us=rb^2/4\alpha t_s=$ is a dimensionless parameter related to the lifetime of the system, $uc=rb^2/4\alpha t_c=$ is a dimensionless parameter related to the duration of the heating/cooling season, a=8 if Q_{BHE} is **W** o 7.01×10^{-2} if is in **MWh/year**.

5	Application for large-scale mapping	It is integrated into a GIS (Geographic Information System) to generate geothermal potential maps at regional scale. Geological, hydrogeological and topographical data are used to define the spatial variability of input parameters

3.4.2.2.3 Potential Analysis for Closed Loop Horizontal Systems

- Method proposed by Tissen et al., 2019

The method for calculating the geothermal potential of closed loop horizontal systems includes the following steps (table 14):

Table 14. Step Descriptions

Steps		Description
1	Spatial Analysis	A GIS system is used to identify areas available for installing horizontal collectors, excluding areas with infrastructure, vegetation or sealed surfaces.
2	Calculation of Geothermal Potential	The formula is applied $E_{hGSHP}=q_{hGSHP} \cdot t_h \cdot A_{hGSHP}/(1-1/COP)$ Where: q_{hGSHP}: heat extraction rate, typically 33 W/m^2 t_h: annual operating time. A_{hGSHP}: area available for collectors(m^2) COP: coefficient of performance of the system
3	Validation of Results	The calculation is adjusted according to soil conditions, such as type, moisture, and thermal properties. Possible efficiency reductions due to shading by buildings or trees are considered.
4	Energy Coverage Estimation	The calculated geothermal potential is compared with the energy demand before and after building renovation. The method demonstrates how Closed Loop Horizontal systems can meet the heating demand after renovations, highlighting their suitability for areas where adequate space is available and in areas with drilling restrictions

3.4.2.2.4 Potential Analysis for Geostructure

- Method proposed by Kong et al., 2024

The calculation of the geothermal potential of geostructures at local scale considers detailed site parameters and specific operating conditions. Here are the main steps (table 15):

Table 15. Step Descriptions

Steps		Description
1	Evaluation of specific design parameters	Includes geometry and layout of geostructures (energy piles, tunnels, diaphragm walls). Thermal response tests (TRT) are performed to obtain local thermophysical properties (thermal conductivity, thermal diffusivity, initial soil temperature).
2	Detailed numerical modelling	Uses heat transfer models to estimate thermal efficiency, such as linear or cylindrical heat source model. Simulates specific system operating conditions and building energy demands.
3	Calculation of heat exchange capacity	Extractable energy is calculated based on parameters such as exchanger length, heat flow, and thermal resistance of the floor and structures. $Q_{local}=\lambda \cdot A \cdot \Delta T/R$ Where: Q_{local}: Thermal power (W) λ: Thermal conductivity of the soil (W/m-K) A: Geostructure contact area (m^2). ΔT: Temperature difference between the soil and the fluid (K). R: Thermal resistance of the system (m-K/W).
4	Validation and optimisation	Results validated with empirical data, such as in-situ tests and comparative simulations. Designs are adjusted to maximise thermal efficiency.

3.5 Identifying priority areas for energy sources

3.5.1 Purpose and Aims of Priority Area Identification

Identifying priority areas allows resources and efforts in initiatives that generate a significant and sustainable impact on economic, social, and environmental development to be maximised. This process should be based on rigorous criteria and thorough analyses that consider technical and economic feasibility (Lund et al., 2011), environmental impact, technological innovation (Bayer et al., 2012), social equity, and alignment with energy policies (United Nations, 2015). In spatial heating and cooling energy planning priority areas can be defined by overlaying of the heating and cooling demand, status of the used energy systems and the potential assessment (García-Gil et al., 2020). Based on these relationships priority areas for specific actions can be defined. For example, areas with a high potential for the use of shallow geothermal systems can be identified by comparing the assessed potential, including all requirements (like available space for the installation, etc), the heat energy demand of the buildings and the status (e.g. a high percentage of fossil-based energy source utilizations) where there is a high potential for renewable technology deployment and the need for building refurbishment to reduce the heat energy demand. Also, the potential for deployment of low temperature grids in some areas can also be identified as favourable due to the demand distribution (heating and cooling), the building structure and the energy source potential, etc (e.g. 5th generation grids using shallow geothermal energy as source) (García-Céspedes et al., 2022). The results of the prioritization process are often represented visually through thematic priority maps, which facilitate communication and decision-making among stakeholders and policymakers.

The identification of priority areas also involves comparing different shallow geothermal systems, such as borehole heat exchangers (BHE) and groundwater heat exchangers (GWHE). This comparison considers factors like soil thermal conductivity, groundwater availability and quality, environmental and regulatory constraints, and local thermal demand (Bayer et al., 2019). For instance, in regions with high-yield aquifers and suitable water quality, GWHEs may offer higher efficiency, whereas in areas with thermally conductive soils but limited groundwater access, BHEs might be the preferred alternative. The prioritization of these systems within a given area is determined by these factors in combination with existing infrastructure and energy needs.

Focussing on key priority areas with the greatest decarbonisation need and with promising potential, specific objectives for the deployment shallow geothermal energy-can be achieved. Such priorities include:

- Prioritising High Demand zones: in zones with high heating and cooling demands, allowing them to benefit more from geothermal technology (Lund et al., 2010).
- Selecting Areas with High Geothermal Potential: Identifying areas with the highest geothermal potential, thereby maximizing the impact of investment in geothermal systems.
- Facilitating Strategic Planning: Guiding decision-making by focusing resources on areas that offer the greatest benefits and returns (Rybach, 2003).

The implementation of these priorities indirectly enables:

- Identification of favourable areas: for low temperature grids by analysing their building structure and patterns, the demand distribution and the existing shallow geothermal potential to operate the grid.
- Integration into Renewable Energy Networks: to improve the stability and efficiency of the district heating or cooling. This includes the development of hybrid systems that combine geothermal energy with other renewable sources (Lund et al., 2011).

Focusing on these priority areas ensures that resources and efforts are effectively directed toward promoting sustainable and equitable energy development, maximizing the positive impact on society and the environment. This targeted approach also improves the efficiency of investments and increases the chance of successful project implementation by concentrating efforts where the potential benefits are greatest.

It is important to note that prioritization is a dynamic process that should be periodically updated as new data on demand, potential, and policy frameworks become available.

3.5.2 Defining Priority Areas for Shallow Geothermal Systems at Regional and Local scale

3.5.2.1 Defining Priority Areas for Shallow Geothermal Systems at Regional scales

The prioritization of areas at the regional scale focuses on identifying zones with high geothermal potential by considering technical (e.g., geological conditions, system feasibility), economic (e.g., costs, financial incentives), environmental (e.g., groundwater impact, sustainability), and social aspects (e.g., public acceptance, policy alignment). The outcome of this process facilitates strategic investments and promotes sustainable development.

Below are the Main criteria to consider when conducting the analysis to prioritise areas at the regional scale (For more details on Criteria, see Appendixes 7).

- *Main Criteria for the Regional scale*
    - Political Priorities: Incorporation of regional targets for reducing greenhouse gas emissions (UNEP, 2019).
    - Technical Potential: Analysis of the long-term sustainable extraction and use capacity of geothermal resources, considering user density and subsurface thermal recovery rates (García-Gil et al., 2015). Additionally, it includes an assessment of existing infrastructure, such as district heating systems (efficiency and capacity of district heating networks, the availability of cooling systems, technical specifications of heating and cooling equipment, age of the infrastructure, geographical distribution, etc), that can support the integration of geothermal systems must be collected (Bayer et al., 2019).
    - Energy Demand: Prioritisation of regions where geothermal systems can address existing energy deficits to balance supply and demand, thereby contributing to regional energy security (REN21, 2021).
    - Economic Feasibility: Analysis of initial development costs and expanding district heating/cooling networks compared to the long-

term benefits for communities and regional governments (Robins et al., 2021).

    - Economic Data: Data collection of available financial incentives or subsidies for GHPs. This includes information on local energy prices. (International Renewable Energy Agency, 2021).

    - Development a regulatory framework: development regulation that covers the entire region, establishes a common regulation and permitting, system fosters quality, promotes monitoring and data acquisitions. Sucha framework should be, tailored to the specific needs of urban and rural areas. New regulations must be consistent with national and European legislation, including compliance with the Renewable Energy Directive (RED II) and the European Green Deal (European Commission, 2019). The simplification of the licensing processes for the installation of geothermal heat pumps in a digital form should be implemented to remove administrative barriers to the deployment of shallow geothermal systems and to facilitate the accelerated deployment through reduced approval times (Euroheat & Power, 2021)

3.5.2.2 Defining Priority Areas for Shallow Geothermal Systems at Local scales

The prioritization of areas at the local scale requires a detailed and site-specific analysis, adapted to the conditions of each site. The goal is to optimize the use of geothermal resources while ensuring technical feasibility and social acceptance of the projects.

Below are the main criteria to consider when conducting the analysis to prioritize areas at the local scale (For more details on Criteria, see Appendixes 7).

- *Main Criteria for the Local scale*

    - Urban Constraints: Assessment of how geothermal systems can be integrated into urban redevelopment projects or new sustainable constructions (Figueira et al., 2024).

    - Economic Feasibility: Analysis of initial development or expanding district heating networks costs compared to long-term benefits for local communities and governments.

    - Local Regulations and Licensing: Review on the current regulatory environment and policies (including environmental impact assessments and land use authorisations), impacting the deployment of renewable systems (European Commission, 2019), geothermal heat pumps (GHPs). This includes building codes, environmental regulations, and local incentives or subsidies for renewable energy projects.

- Community Participation: Identification of perceptions and attitudes toward shallow geothermal systems by local communities through surveys, interviews, and public consultations (Hildebrand, et al., 2022). Ensuring transparency and fostering public participation throughout the prioritization process is necessary, as it builds trust, enhances the legitimacy of decisions, and increases the success of the project implementation at the local level.
- Joint Planning with Local Stakeholders: Collaboration with local governments, developers, landowners, and communities to design site-specific geothermal projects (Haf & Robison, 2020).

Final Remarks

To optimise the identification of priority areas with high shallow geothermal potential, it is recommended to integrate the key points in the design of a multi-criteria assessment methodology that allows weighing key factors, such as technical feasibility, environmental impact, socio-economic considerations and associated risks. It is important to note that the relative weight assigned to each criterion may vary depending on the specific regional or local context, highlighting the need for a flexible and adaptive assessment methodology.

In addition, the use of Geographic Information Systems (GIS) is suggested as a central tool to collect, analyse and overlay data from geological, environmental and social studies. These data can be presented through interactive maps highlighting priority areas, using advanced GIS platforms to facilitate both visualisation and access to information by relevant stakeholders.

3.6 Define measures for Geothermal Heat Pump Implementation

3.6.1 Purpose and Aims of Defining Measures

Once potential and priority areas are identified in any strategic process whether in environmental management, urban planning, public health, or other fields findings should be addressed by defining specific measures. These measures should directly respond to the identified priorities areas and ensure effective implementation. To maximize their impact, these measures should be specific, measurable, and adaptable to changing circumstances.

This process ensures that the strategy not only identifies problems but also implements concrete actions to achieve the desired outcomes (Behn, R. D., 2003).

In the context of geothermal heat pumps, after identifying potential and priority areas, measures must be defined to ensure that these systems are effectively implemented and meet the planned objectives. These measures should address:

- Optimization of available geothermal resources
- Facilitation of the planning and design of GHPs
- Regulatory and compliance adherence
- Definition of necessary technical specifications and quality standards
- Integration of GHPs into existing infrastructure
- Access to subsidies and support programs

Addressing these points when defining measures will allow regulatory and technical barriers to be overcome (Florides and Kalogirou, 2007), ensuring the proper integration of systems (Rezaie and Rosen, 2012), and promoting community participation. In addition, the measures provide a framework for continuous monitoring and strategy adaptation (Lund et al., 2021), thereby maximising the benefits of using this technology and optimising its contribution to emission reduction and energy savings. The identification of areas or neighbourhoods with high potential for energy transition as starting points is recommended. At these locations, support programmes, such as personalised energy advice, could be implemented, taking advantage of information from space heating and cooling energy planning.

The successful implementation of these measures also relies on strong coordination between public and private stakeholders, as well as the availability of sufficient financial and technical resources.

3.6.2 Framework for Defining Regional Measures in Shallow Geothermal Systems

3.6.2.1 Procedural Framework for Defining Measures at Regional scale

The objective of the regional framework is to develop a coordinated approach to maximise the use of geothermal resources over large geographical areas, optimising their potential to meet regional heating and cooling energy demands and to ensure that shallow geothermal resources are managed in a sustainable manner. This framework focuses on regional energy planning, not on the specifics of individual installations (For more details on procedures, see Appendixes 8).

The procedure for defining measures involves several key steps:

- Supportive Policies:

Put in practica new regulations that facilitate the implementation of geothermal systems, reduce administrative barriers, and promote best practices (Pasquali, & O'Neill, 2015; European Commission, 2020).

- Financial Incentives at Regional scale

Implementing regional financial incentives that encourage the adoption of geothermal projects (Dumas & Angelino, 2015). This includes the creation of regional subsidy programmes to support initiatives in areas with limited economic resources or high energy needs. In addition, establishing financing schemes that integrate the public and private sector, to facilitate investment in geothermal technologies (Polzin et al., 2019) should be considered.

- Integrated Regional Planning and Design

Integration of shallow geothermal system, specifically geothermal heat pump (GHP) with existing energy and water infrastructure (Akhmetzyanov et al., 2021), and to foster cooperation between government agencies for a coordinated implementation in the projects (Dumas & Angelino, 2015).

- Education and Training

Installers and technicians should be trained in the installation and maintenance of shallow geothermal energy systems in accordance with applicable EN and local standards, geothermal heat pump systems (European Geothermal Energy Council, 2023) and public awareness campaigns should be conducted to promote their adoption in homes and businesses (Global Geothermal Alliance, 2023).

- Evaluation Framework

Implement mechanisms for periodic assessment and reporting of regional progress in adopting and performance of GHPs, including the installed capacity, emission reductions, energy savings, energy supplied, systems replaced, systems installed, and socio-economic impacts, to refine strategies over time.

3.6.2.2 Procedural Framework for Defining Measures at local scale

At local scale, the framework aims to provide specific guidelines tailored to the unique conditions of each community or small geographic area. This scale seeks a practical and straightforward implementation of shallow geothermal systems, considering the local geology, heating and cooling needs, and the socio-economic characteristics of the end-users.

The procedure for define measures involves several key steps:

- Simplified Licensing Procedures

Implement simplify licensing through local guidelines to ensure the quality and safety of installations, and to adapt regulations for municipalities to adjust standards according to their needs. Additionally, ensure that facilities comply with technical and sustainability standards set by local, regional and/or national authorities (Kłonowski et al., 2020).

- Local Project Planning and Design

Carry out energy consultant strategies trough pilot projects to demonstrate the feasibility of geothermal systems, integrate them with local energy infrastructure and designate 'shallow geothermal energy zones' in areas favourable for their installation. Also, ensure that local projects contribute to the climate and energy objectives set at regional and national scale (Bosch & Rathmann, 2018).

- Citizen Participation and Community Management

Apply citizen participation strategies such as digital participation platforms, monitoring and evaluation committees, regular public consultations, face to face meetings, organisation of public information events, etc (Teladia & van der Windt, 2014).

- Incentives and Local Funding

Enforce local economic incentives to facilitate the installation of GHP systems, such as tax rebates and preferential financing. It also seeks to fund community projects that not only promote but also implemented the use of shallow geothermal energy systems in public buildings and community centres (Borge-Diez et al., 2015).

- Monitoring and Evaluation at Local scale

Establish and apply monitoring measures to quantify the GHP impact, as well as ongoing adaptation strategies to monitor the effectiveness of such measures. The strategies should be flexible, allowing for adjustments in regulations, financing, technical design, and promoting collaboration between municipalities to share lessons learnt and best practices. Regular publication of monitoring results is encouraged to promote transparency, facilitate knowledge sharing, and support continuous improvement among all stakeholders.

Final remarks

The success of these frameworks (at regional and local levels) relies heavily on effective coordination between different levels of government and across sectors, ensuring that policies, resources, and actions are aligned and mutually reinforcing.

Furthermore, all measures identified should be in line with national and European decarbonisation targets, such as those set out in the European Green Pact and the Renewable Energy Directive.

3.7 Monitoring and Adaptation

3.7.1 Purpose and Aims

The process of monitoring and adapting any project, strategy, or process allows for proactive and flexible management in response to challenges and changes that may arise. By gathering key monitoring, data on the performance, the effectiveness of the activities can be evaluated and the strategies adjusted or adapted based on these data. The outcome the evaluations will optimise resource use and minimise risks, ensuring that objectives are met effectively and sustainably as well as responding appropriately to the changing needs and circumstances of the environment (Murray and Marmorek, 2004; Salafsky et al., 2001).

Monitoring and evaluation are important to ensuring that strategic objectives are met efficiently and effectively, particularly in the context of integrating geothermal heat pump (GHP) systems into the spatial urban planning process. A clear process for periodic evaluation from the outset guarantees that responsibility for these critical steps is well-defined and intentional. By continuously tracking the actions taken, it is possible to assess the effectiveness of the implemented strategies and adjust as needed (IEA, 2021) and validate progress toward objectives (Self et al., 2013)

Furthermore, monitoring informs both the public and authorities about the progress and performance of integrating GHP systems into spatial urban planning, while allowing for adjustments to strategies based on performance data and changes in demand (Sanner et al., 2003). This process also ensures compliance with local and regional regulations (Banks, 2012).

Ensuring interoperability of monitoring systems across different regions and municipalities is necessary to enable data comparability, enhance collaborative learning, and support coordinated policy development.

3.7.2 Regional and Local Framework for Monitoring Shallow Geothermal Systems

3.7.2.1 Monitoring and Adaptation Procedures for Shallow Geothermal Systems at Regional scale

At the regional scale, the Monitoring and adapting the integration of shallow geothermal systems into regional spatial urban planning focuses on ensuring that measures taken to adopt the use of geothermal heat pumps (GHPs) are effective and aligned with regional energy objectives. This process should allow for continuous adjustments and improvements to ensure that sustainability and energy efficiency goals are met at the regional scale. The approach emphasizes high-scale policy coordination, economic incentives, and the optimization of geothermal potential across multiple municipalities or administrative zones.

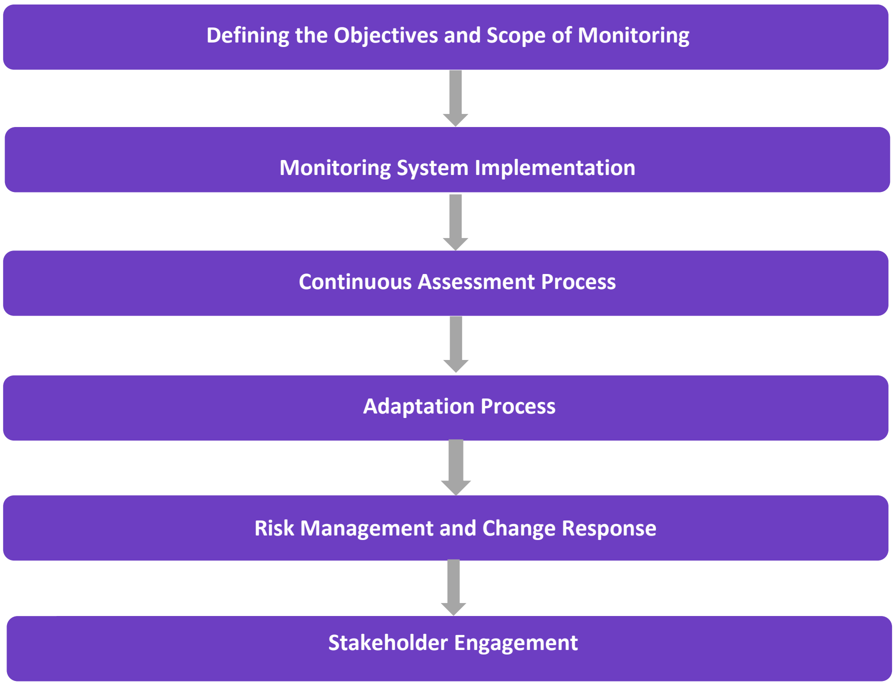


Figure 2. Monitoring and adaptation procedure at regional scale

The procedure for monitoring involves several key steps:

- Definition of Monitoring Objectives and Scope

Establish the objectives and KPIs for the effectiveness of the implementation of the measures defined in section 3.6 at the regional scale. This ensures that the systems not only operate efficiently but also meet the regional environmental and sustainability expectations (Tsagarakis et al., 2020; Clarke, 2022) (For more details on this step, see Appendixes 9).

- Monitoring System Implementation

Data collection and management for the efficiency of the implementation of defined measures through centralised databases (Julli et al., 2023), predictive analytics and IoT technologies to optimise performance and ensure a rapid response to any problems (Cheddadi et al., 2020) should be implemented. This allows an effective monitoring infrastructure to assess progress and effectiveness of measures (For more details on this step, see Appendixes 9).

- Continuous Assessment Process

The performance of Geothermal Heat Pumps (GHPs) should be continuously monitored and evaluated. Key performance indicators (KPIs) should be periodically reviewed, comparing operational data against predefined benchmarks to detect deviations and potential failures early. Monitoring results can be communicated through regular reports, automated deviation alerts, and recommendations for corrective actions (Miasayedava et al., 2020). Environmental and socio-economic impacts, as well as compliance with regulatory requirements, should be assessed as part of this continuous evaluation process (Miasayedava et al., 2020). Results should be presented to support decision-making, ensure transparency, and promote stakeholder engagement. Regular publication of monitoring data and clear communication with stakeholders are essential to build trust, facilitate informed decisions, and foster continuous improvement.

- Adaptation Process

The monitoring ensures the continuously adaptation of shallow geothermal systems to changing environmental conditions, energy efficiency requirements and current regulations. If it is necessary to adapt, three key steps need to be carried out: i) Identification of adaptation needs (Rybach and Eugster, 2010), ii) Implementation of adaptation measures and iii) Evaluation of effectiveness (Omer, 2008). Ensure the long-term performance, sustainability and regulatory compliance of geothermal heat pump (GHP) systems by identifying and assessing risk, developing mitigation strategies and responding to changes and continuous improvement and implementation to mitigate potential negative impacts (For more details on this step, see Appendixes 9).

- Stakeholder Engagement

Assessing the effectiveness of these strategies to adjust engagement and ensure continued collaboration between governments, businesses, communities, and universities enables informed decisions and fosters social acceptance, ensuring the sustainability and integration of GHPs (Wüstenhagen et al., 2007) (For more details on this step, see Appendixes 9). This can be achieved through participatory workshops, advisory committees, and transparent feedback mechanisms.

3.7.2.2 Monitoring and Adaptation Procedures for Shallow Geothermal Systems at local scale

Monitoring and adaptation at the local scale ensures that the measures for integrating shallow geothermal systems into spatial urban planning are effective and aligned with the specific needs of the community, geographic characteristics and urban/rural context. local monitoring directly considers factors such as local energy demand, groundwater conditions, urban-rural distinctions, and community acceptance. Adaptation strategies are highly customized to ensure compatibility with existing infrastructure and immediate environmental conditions.

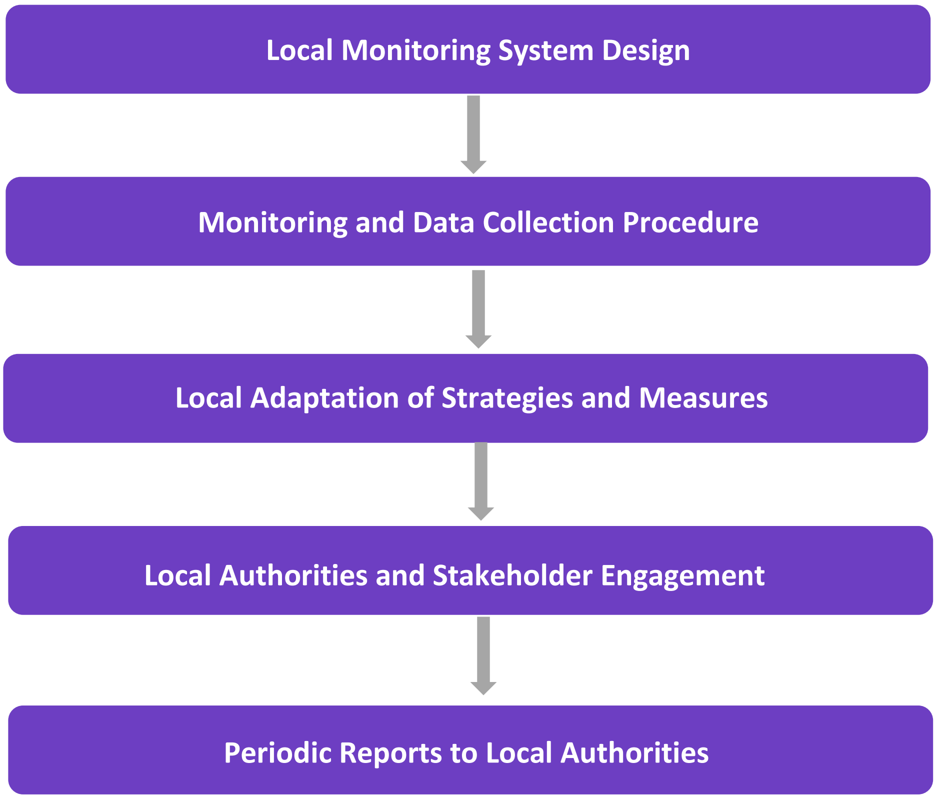


Figure 3. Monitoring and adaptation procedure at Local scale

The procedure for monitoring involves several key steps:

- Local Monitoring System Design

Design a monitoring system adapted to the local area. The objectives of the monitoring system should be tailored to the specific energy and environmental needs of the community or area. Some of the key objectives include optimising the use of local geothermal resources, maximising local energy efficiency, reducing energy costs, and adaptability to climate change and variable demand (For more details on this step, see Appendixes 9).

- Monitoring and Data Collection Procedure

Establish a procedure to continuously and periodically monitor the systems to adjust the systems according to current conditions, collecting data automatically of the measures applied and allowing remote access in real time. Some of the key monitoring measures include technical aspects (subsurface temperature, groundwater quality, energy efficiency), replaced systems, local demand, regulation and economic aspects (For more details on this step, see Appendixes 9).

- Local Adaptation of Strategies and Measures

Based on the results of the monitoring and impact assessment, geothermal system integration strategies should be adapted at the local scale. This may involve adjustments in the density of installations, in energy distribution systems, regulations or economic incentives to encourage the adoption of GHPs in areas of high energy demand (For more details on this step, see Appendixes 9).

- Local Authorities and Stakeholder Engagement

Ensures municipal oversight, public participation, and collaboration with local businesses and authorities. Engagement is promoted through town hall meetings, citizen advisory panels, and participatory workshops, ensuring that adaptation strategies align with the specific needs and concerns of local stakeholders. This participatory approach also facilitates coordination of corrective measures in response to community feedback (For more details on this step, see Appendixes 9).

- Regular Reporting to Local Authorities

Submission of regular reports to the authorities and community, including monitoring results, adaptations made, environmental impact indicators and long-term projections. These reports help local governments to make informed decisions on energy and land use planning (For more details on this step, see

Appendixes 9). Regular publication of monitoring results and transparent communication with stakeholders are essential to build trust, enable informed decision-making, and foster continuous improvement.

3.8 GHP, UTES and District Heating/Cooling Networks – Integration in Spatial Urban Planning

Ground Source Heat Pumps (GHP) are active and decentralized solutions. They are typically designed for individual buildings, groups of buildings, or campuses, where they meet heating and cooling demands through shallow subsurface heat exchange, directly and according to currently demand (Casasso & Sethi, 2016; Soltani et al., 2019).

In contrast, Underground Thermal Energy Storage (UTES) systems, such as Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES), are mainly used for seasonal storage: mainly function as seasonal storage systems: they allow heat or cold to be stored during periods of low demand for use when demand is high (Bloemendal et al., 2014; Fleuchaus et al., 2018; Kallesøe & Vangkilde-Pedersen, 2019). For example, ATES systems typically operate with a warm well (storing heat rejected in summer during cooling) and a cold well (storing cold rejected in winter). However, UTES can also be used to store heat or cold from other sources, such as waste heat or deep geothermal, and can operate for short-term cycling (diurnal peak shaving) as well as long-term (seasonal) storage. In practice, both systems can complement each other: a UTES serves as an energy reservoir to optimize the temporal balance between production and demand, while the geothermal heat pump is used to adjust the temperature difference between the source and the building, when direct use of stored heat or cold is not possible. (Pellegrini et al., 2019; Wu & Ouyang, 2023).

However, incorporating these technologies into urban spatial planning requires consideration of different aspects. For GHPs, the proposed methodology involves, among other things, analysing the distribution of heating and cooling demand and the subsurface's extraction/injection capacity, ensuring a sustainable long-term thermal balance (Casasso & Sethi, 2016; Miglani et al., 2018).

In contrast, for UTES systems, the methodology should include estimating the total capacity for seasonal thermal energy storage and recovery, considering hydrogeological characteristics, land use restrictions, and energy demand at district or city scale (Duijff et al., 2023; Brown et al., 2024).

In regulatory and operational terms, GHPs are a bit more mature and consolidated technology for use at plot or building level. Their integration into urban plans is relatively straightforward, as they benefit from clear regulatory frameworks, established drilling permits, potential maps, and procedures for managing thermal interference. This allows municipalities to easily incorporate them into urban or building codes (European Parliament, 2023). Although technical and economic challenges remain in some countries, the deployment of GHPs is feasible and scalable to help meet Europe's energy and climate goals.

By contrast, UTES systems require complex hydrogeological and geological studies, multi-actor coordination, and large-scale planning. Furthermore, they do not respond to demand in real time but instead serve as supporting infrastructure for large-scale thermal networks Their stored energy is typically transferred to end-users through heat pumps or other technologies, which enable the necessary temperature adjustment and on-demand supply, even in small, scale networks such as campus or community-based systems. For example, BTES in Bradstrup (Sørensen & Schmidt, 2018) and ATES in Utrecht and Eindhoven (Drijver, 2019).

3.8.1 Why are District Heating and Cooling Networks Relevant?

District heating and cooling (DHC) networks are centralized infrastructures that supply thermal energy from one or more production points to multiple end users through a distribution network. Their relevance lies in enabling the use of local and energy efficient sources (such as deep geothermal, solar thermal energy, or industrial waste heat) in densely populated urban centres with older buildings requiring high temperatures for heating system. These networks also make it possible to integrate large-scale seasonal storage systems, helping to balance thermal energy production and consumption throughout the year (Frederiksen & Werner, 2013; Lund et al., 2018; García-Céspedes et al., 2022). Fourth and fifth generation networks (4GDH/5GDH) are specifically designed to facilitate this integration (Lund et al., 2014; Buffa et al., 2019).

3.8.2 Role of GHP and UTES in a DHC Network

In this context, GHPs are active producers of on-demand energy. They connect directly to the distribution network and operate when demand requires it, turning on or off according to the load. These heat pumps can be installed in a decentralized way for a single building or campus or integrated into a district heating and cooling network as a low-temperature source (Buffa et al., 2019). For example, centralized ground source heat pumps can be used to raise the temperature of fourth or fifth generation networks, which operate at low temperatures. In addition, local heat pumps can be installed on the delivery side to upgrade the temperature supplied by the network or UTES to the level required by the end user — for instance, using heat stored in ATES combined with building-level heat pumps to reach the desired indoor temperature. Their integration provides flexibility, helps reduce peak demand, and facilitates the combination with other technologies, acting as both producer and receiver nodes. However, they also have limitations, such as the inability to balance seasonal fluctuations, the need for underground infrastructure for each unit, possible competition for underground space, local regulation requirements, high initial drilling costs, and the need to oversize or include backup sources for high peak demands (Werner, 2017).

On the other hand, seasonal underground thermal energy storage (UTES) systems are large underground reservoirs that store surplus heat or cold for use when needed. These systems require an energy source for charging, such as solar thermal, waste heat, or large heat pumps, and they are integrated into the network or at exchange points to transfer energy effectively and balance seasonal peaks in supply and demand (Cabeza et al., 2018). For example, the network or the central plant can store heat in summer to extract it in winter, or store cold in winter for use in summer. Integrating UTES into heating and cooling networks helps balance seasonality, reduce production peaks, increase overall efficiency, and lower operating costs. However, they also pose challenges such as hydrogeological limitations, risks of thermal interference, and the need for robust planning and regulation (Marojević et al., 2025).

For all these reasons, the proposed methodology specifically focuses on the integration of GHPs into spatial urban planning, given their level of technological maturity, technical and regulatory feasibility, and compatibility with the municipal scale of intervention.

In contrast, UTES systems and district heating and cooling networks are considered complementary context, as their design, operation, and governance require broader territorial planning, multi-actor coordination, and solutions at district or city scale—elements that go beyond the technical and operational scope of this specific methodology.

Thus, this methodology prioritizes decentralised geothermal heat pump solutions that are easily integrated at local level and regional, considering UTES systems and district heating and cooling networks as supporting infrastructures that can strengthen the flexibility and efficiency of the urban energy system, provided that the technical, regulatory, and planning conditions are appropriate.

4. Best Practice Examples

4.1 Examples from Austria

4.1.1 Framework/Stakeholders

4.1.1.1 Framework/Stakeholders at local scale

4.1.1.1.1 Vienna Heat Plan 2040

The Vienna Heat Plan 2040 (*Wiener Wärmeplan 2040*) is a strategic initiative by the City of Vienna aimed at transitioning the city's entire heating and cooling supply in buildings to renewable energy by 2040 (https://www.wien.gv.at/umwelt/waermeplan-2040, accessed 20 January 2025). This plan forms a critical part of Vienna's overall ambition to achieve climate neutrality. It builds upon prior efforts including the *Wiener Klimafahrplan 2022*, the *Wiener Wärme Kälte 2040*, and implementation programs like *Raus aus Gas 1 (2023–2025)* and *Raus aus Gas 2 (2026–2040)*. At the federal scale, the Renewable Heat Act (*Erneuerbare-Wärme-Gesetz*) establishes a federal law prohibiting the installation of fossil fuel-based energy systems for space heating and hot water preparation in new buildings.

Decentralised gas-fired heating systems represent a major part of the challenge for Vienna (Table 16). Of ~608,000 fossil fuel systems, ~474,000 are decentralised units at the flat scale in mostly non-refurbished buildings. Of these, ~79,000 units are in buildings supplied with gas and district heating. This is due to district heating being installed at a later stage, but not all residential buildings are connected to it. Importantly, converting decentralised systems to renewable solutions will often require installing a central heat distribution system within the building. In addition, single- and two-family homes account for ~42,000 gas-fired systems, while multi-storey residential buildings have ~58,000 centrally installed systems. Beyond heating systems, there are circa 260,000 gas stoves that must also be replaced with renewable solutions. The city of Vienna's Energy Planning Department (Municipal Department 20 – MA 20) initiated the Vienna Heat Plan 2040 to accelerate this transition to renewable heating.

Table 16. Breakdown of heating systems in Vienna's residential buildings by building type, refurbishment status, energy source, and centralisation. Source: *Wiener Wärme Kälte 2040*.

Building Type	**Refurbishment Status**	**Energy Source**	**Centralised or Decentralised**	**Number of Units**
Apartment buildings and multi-storey	Not refurbished	Gas	Decentralised	306,000
	Not refurbished	Gas	Centralised	36,000

residential buildings	Not refurbished	Oil	Centralised	31,000
	Thermally refurbished/new and not refurbished	Gas and district heating	Centralised and decentralised	79,000
	Thermally refurbished/new	Gas	Centralised	22,000
	Thermally refurbished/new	Gas	Decentralised	89,000
Single- and two-family homes	Not refurbished	Gas	Centralised	36,000
	Thermally refurbished/new	Gas	Centralised	6,000
	Not refurbished	Oil	Centralised	3,000
	Total			608,000

A key feature of the Vienna Heat Plan 2040 is its energy spatial planning approach. Based on this approach, the plan maps the most suitable heating and cooling solutions for different zones within Vienna, considering the unique characteristics of each area. It thus gives a clear orientation for how buildings currently dependent on fossil fuels can transition to the best renewable options available.

Main aspects of the plan include:

- Transitioning all buildings in Vienna to renewable energy sources for space heating and hot water preparation by 2040.
- Guiding the most suitable heat supply options for buildings currently using oil or gas heating in different areas of the city.
- Expanding and decarbonising district heating, particularly in densely built-up areas.
- Promoting renewable low-temperature networks and building-specific renewable solutions in less densely built areas, emphasising heat pumps and some biomass usage.
- Developing "pioneering areas" where district heating expansion is proactively pursued and implemented.
- Offering information and services to support the transition, including consulting and guidance for implementation projects.

Accordingly, the main questions addressed by the plan are:

- District heating:
  - Where can buildings connect to existing district heating networks?
  - Where can district heating be expanded most effectively?

- Local heating networks & individual solutions:
    - Which areas are suitable for local heating networks other than district heating?
    - Which locations are best suited for individual solutions, such as air-source heat pumps and geothermal heat pumps?

Involved organisations

The primary organisations responsible for developing the Vienna Heat Plan 2040 are:

- Wien Energie and Wiener Netze:
    - Proposal of district heating areas, including urban densification.
    - Preparation of the decarbonisation plan for district heating.

- City of Vienna (Energy Planning Department, MA 20):
    - Validation of proposed district heating areas.
    - Definition, delineation, and designation of areas to be shown in the plan.

4.1.1.1.2 Geothermie-Atlas

The Geothermal Atlas (Geothermie-Atlas) is an interactive online tool designed to support the planning of shallow geothermal energy systems (https://geothermieatlas.geosphere.at/, accessed 20 January 2025). Launched in 2024, this platform provides detailed content covering the city of Vienna. Efforts are ongoing to expand its scope to other regions of Austria. The tool offers the following main features:

- Geothermal-relevant spatial data with query capabilities at specific locations for BHEs and GWHPs.

- Potential calculations for heating and cooling applications using individual borehole heat exchanger fields at property scale.

Currently, the potential calculations for BHEs on property scale can be conducted nationwide, though the user must input geodata for locations outside Vienna. Designed to offer a fast initial evaluation of geothermal energy potential, the Geothermal Atlas can serve as a valuable resource for a wide range of users. It intends to give a fast overview of possibilities to use shallow geothermal energy. The results can serve as an input for a more detailed feasibility study to be conducted in the following step by geothermal experts.

Involved organisations

The primary organisations responsible for developing the Geothermal Atlas are:

- GeoSphere Austria:
    - Development of the tool itself and implementation of the web portal.
    - Development of the methodology for and creation of the spatial data sets within the GEL-SEP project (Steiner et al, 2021).
- City of Vienna (Energy Planning Department):
    - Supported the work of GeoSphere Austria as co-commissioner of the GEL-SEP project.

4.1.2 Target groups

4.1.2.1 Target Group for Vienna Heat Plan 2040

The main target groups impacted by the plan and its outcomes are:

- Building owners and property managers: Both private and commercial property owners who need to transition their heating systems.
- **Residents of Vienna**: As the end-users, residents remain an important target group for the plan, which aims to inform and engage them, even though many renters are unable to directly modify their heating systems.
- City administrators and policymakers: Those responsible for implementing and overseeing the gas phase-out at the administrative scale of the city.
- Energy providers: Companies that are expanding district heating and implementing renewable energy projects such as low-temperature networks.
- Consulting companies: Firms offering services to support the transition, including advisory services, planning, and engineering.
- Renewable energy technology providers: Companies developing and installing solutions like heat pumps and other clean energy technologies.
- Construction and renovation companies: Businesses involved in retrofitting existing buildings with new heating systems.

- Research institutions: Organisations contributing to innovation in renewable heating and cooling technologies.

- Neighbourhood associations and community groups: They can play a role in coordinating local efforts and disseminating information.

4.1.2.2 Target Group for Geothermie-Atlas

The main target groups impacted by the Geothermal Atlas and its outcomes are:

- Home and property owners: Individuals considering the installation of a GHP system benefit from an initial feasibility check. By using the Geothermal Atlas, they can quickly gauge whether geothermal energy might cover a significant portion of their heating and cooling needs.

- Planners and engineers: Professionals working in building services, HVAC design, or renewable energy consultancy can benefit from efficient planning tools to compare different energy solutions. The tool allows planners to evaluate initial system dimensions, potential coverage ratios, and long-term fluid temperature stages. It can also serve as a starting point for detailed simulations performed with more specialised software.

- Authorities and energy agencies: Public offices responsible for building permits, energy guidelines, or local/regional development can use or test the tool to assess geothermal suitability at a strategic scale.

- Educators and students: Those teaching or learning about renewable energy technologies, environmental sciences, or geosciences can use the tool to demonstrate practical applications of hydrogeology and thermodynamics.

- General public and enthusiasts: Anyone curious about sustainability or planning an eco-friendly building project can explore the tool for basic insights on geothermal options. With minimal technical knowledge, users can understand how a geothermal system might fit into their property's energy concept, prompting further research or discussions with professionals.

4.1.3 Methods

4.1.3.1 Methods for Vienna Heat Plan 2040

The methodology for deriving the Vienna Heat Plan 2040 is based on three main pillars: the existing and expected heat demand up to 2040, the potential for renewable energy utilisation, and the availability of existing infrastructure. The methodological approach involved the following steps:

- Assessment of heat demand

The heat demand density per building block (in megawatt-hours per hectare per annum) was considered as a key parameter for determining the suitability of district heating networks. Heat demand data was derived from a detailed building data model at the building block scale, using results from the "Green Energy Lab – Spatial Energy Planning (GEL-SEP)" project (https://waermeplanung.at/). The data was validated collaboratively between Stadt Wien, Wiener Netze and Wien Energie.

- Analysis of renewable energy potential

The city of Vienna (Energy Planning Department, MA20) commissioned a study to evaluate the potential for shallow geothermal energy, more especially BHEs, for the whole city of Vienna (Steiner et al. 2023). Within this study, GeoSphere Austria and TU Wien identified unbuilt areas where BHEs could be placed and calculated the heating potential and the coverage of the heating demand on building block scale. The analysis accounted for constraints such as distances to buildings, vegetation and underground infrastructure. Streets were explicitly designated as available areas.

- Development of topology

A topology including a classification of the different heat plan zones was derived and GIS models were set up for the later integration of all input data sets. This step was done collaboratively with between City of Vienna, Wiener Netze and Wien Energie.

- Creation of the heat plan:

The various input data layers, including heat demand density, renewable energy potential, and existing infrastructure, were combined to create the Vienna Heat Plan 2040. The layers were overlaid to identify alignment and discrepancies. Minor refinements were made to adjust assumptions and factors where necessary.

4.1.3.2 Methods for Geothermie-Atlas

This section provides an outline of the instructions and methodology for calculating the potential of vertical ground loops (i.e., BHEs) on a specific property as detailed in the Geothermal Atlas. The developers note that the tool is not intended to replace detailed design or expert planning but rather serves as a preliminary resource assessment tool.

The user can select a plot of land (or draw a custom polygon) in the online map application. Then, the user receives automated borehole locations, considering the selected distance between the boreholes. This proposal can be refined interactively by modifying the number, individual location, or depth of boreholes. The user is then able to define the operational parameters for heating and cooling, expressed in annual full-load hours, and set the desired heating supply temperature. Once these parameters are entered, the tool calculates an approximate potential in terms of energy and power for both heating and cooling.

Although the tool draws on available underground data where possible, if no local geological data are stored in the application's database, the user is prompted to enter such data manually (e.g., thermal conductivity and ground temperature). This is currently the case outside the city of Vienna. The resulting output includes an overview of the potential energy flows for the configured BHE field, as well as an optional automated PDF report. This report details the system's performance over a 20-year period and includes a forecast of the fluid temperature in the borehole field.

The potential is largely influenced by parameters such as the size of the borehole field, the depth of the boreholes, and the annual operating hours. Hence, the tool serves to raise awareness about the importance of these parameters and helps users to account for their interdependence.

4.1.3.2.1 Using the Tool (instructions)

- *Access the tool*
    - Navigate to geothermieatlas.geosphere.at.
    - From the main page, click on "*Zur Potenzialberechnung*" ("To the Potential Calculation") or open the menu to select "*Erdwärmesonden*" and then "*Potenzialberechnung*."
- *Select a property*
    - To locate a specific property, the user can type an address in the "*Adresse und Ort suchen*" field or manually move around the map.
    - Standard map interactions apply: left-click to pan, use the mouse wheel (middle button) to zoom, and right-click to rotate.

- *Define the borehole field*
  - Once the desired zoom scale is achieved, borehole placement can be designated in two ways:
    - Arrow ("*Auswahl Grundstück / Bohrpunkt setzen*"): Clicking on the map automatically uses the official land registry to select the entire parcel.
    - Polygon ("*Sondenfeld zeichnen*"): Draw any polygon across one or more plots, allowing for a custom layout that may cross parcel boundaries. The polygon can be completed with a double click.
  - After defining this area, the application automatically proposes borehole locations arranged in a grid, based on a chosen spacing distance (e.g., 5 to 15 m). The user can adjust each point (delete, move, or add new ones) to suit preferences and site constraints.
- *Adjust borehole parameters*
  - The user can set the borehole depth (80–250 m) and the borehole spacing (5–15 m).
  - If the selected area is very large and more than 300 boreholes would be required to fill it, the tool will not generate any points automatically. Instead, the user can place each point manually.
  - Warnings are issued for boreholes placed outside the allowed area or closer than 5 m to each other, but the calculation can still be performed.
- *Specify underground data*
  - If local geological data (e.g., thermal conductivity, ground temperature) are not already available in the Geothermie-Atlas database, a prompt appears for manual entry.
  - If data are available, these values are locked in and displayed. The final PDF report lists the used subsurface parameters.
- *Enter operating parameters*
  - After selecting or drawing a borehole field, the user defines the annual full-load hours for heating and cooling. The application automatically provides an initial suggestion (called "*Norm-Jahresbetriebsstunden*") derived from Swiss standard SIA 384-6:2010 and the average ground temperature at that location.
  - Three default "heating system" options are available:
    - Floor heating (35°C supply): yields a typical heat pump COP of about 4.74.
    - Radiator (55°C supply): yields a typical heat pump COP of about 2.8.

- Custom supply temperature (30–65°C): the user sets a heating supply temperature manually, which modifies the system's performance accordingly.

- Users can optionally specify the building's required heating and cooling power (kW). If this is done, the tool calculates not only the total heating and cooling potential but also the % of this demand that the borehole system can cover.

- *Running the calculation and viewing results*

  - Clicking "*Berechnung starten*" starts the simulation. Within a few seconds, the tool displays an energy flow diagram and summary of results in a separate window.
  - If there are 5 or more boreholes and other specific conditions are met, the system may provide a comparison to an "automatically balanced operating mode," which aims for an equal amount of energy extracted (heating) and injected (cooling) into the ground over the year.
  - Users can download a PDF report containing all input data, results, the operational schedule, plus a 20-year temperature forecast for the circulating fluid in the ground loops.

4.1.3.2.2 Calculations

The tool's underlying methodology uses an analytical solution of the Finite Line Source theory to model conductive heat transfer around vertical boreholes in a homogeneous half-space (Eskilson, 1987). This approach is implemented via the Python library "pygfunction" (Cimmino and Cook, 2022), which computes thermal response factors (or g-functions) for multiple interacting boreholes. A homogeneous half-space is a simplified representation of the subsurface in thermal modelling. It assumes that:

- Homogeneity: The ground is made of a single, uniform material with consistent thermal properties (e.g., thermal conductivity, specific heat capacity, and density) throughout. This means there are no variations due to layers of different soil, rock, or groundwater.

- Half-space: The ground is modelled as a semi-infinite domain. This means it extends infinitely in the horizontal and downward directions but has a boundary at the surface (the interface with the air or another material). Heat transfer is considered only below this surface boundary.

These assumptions make the problem mathematically tractable and allow for the use of analytical solutions, like the Finite Line Source theory, to model heat transfer around boreholes. While it is an approximation, it is often reasonable for many applications, especially when variations in soil layers or groundwater flow can be considered negligible.

The main input parameters include:

- Borehole positions and depth.
- Annual full-load hours for heating and cooling.
- Heating supply temperature (to estimate the heat pump’s coefficient of performance);
- Optional building heating/cooling power requirements.
- Average ground temperature and thermal conductivity.
- Fixed simulation parameters (e.g., volumetric heat capacity of the soil, borehole diameter, grout thermal conductivity, fluid properties, etc.).

The output is the annual heating and cooling potential of the field, ensuring that at the end of the heating phase, the average fluid temperature does not drop below -1.5°C, and by the end of the cooling phase, it does not exceed 28°C. These limits reflect typical operating constraints for heat pump systems to yield reliable performance and prevent excessive temperature drift in the ground.

- **Optional building demand and coverage**

If a user enters specific heating and cooling demands (kWh/y), the tool compares the borehole potential with those demands. Several scenarios can occur:

  - If the system cannot meet either the heating or cooling requirement, the tool provides a result indicating the highest feasible potential within the given temperature limits and prompts that additional energy sources or sinks may be needed.
  - If only one of the demands is fully met (100% coverage) while the other remains partially uncovered, the system reduces utilization of the fully covered side (to exactly 100%) and recalculates how much potential is available for the other side.
  - If the borehole field is large enough to exceed both demands, the report may include a note that the field could be downsized while still covering 100% of the demand.

- **Automatically balanced operating mode**

For larger fields (more than 6 boreholes) and certain other conditions, the application computes an automatic balanced mode, seeking to distribute the heating and cooling loads so that total extracted and injected thermal energy remain equal over the course of the year. This involves:

  - Optimising the ratio of heat extraction to heat injection based on unperturbed ground temperature and the allowable fluid temperature limits (-1.5°C in heating and 28°C in cooling).

- Adjusting annual full-load hours so that the net energy balance is close to zero. If, for instance, the cooling operation is too low, it is increased up to a maximum of 4380 hours per year (half the year) to match the energy extracted during heating. The same logic applies if heating hours need to be adjusted.

- **Norm annual full-load hours**

When a user has not specified their own operating hours for heating or cooling, the tool auto-fills "*Norm-Jahresbetriebsstunden*", approximate typical annual hours taken from Swiss guidelines (SIA 384-6:2010) and adjusted linearly according to the local average ground-surface temperature. For many single-family houses, these Norm hours serve as a sensible starting point, but users with more precise data about their building's energy needs are encouraged to override them with custom values.

- **Fixed variables**

Certain simulation parameters are fixed and cannot currently be changed through the interface. These include:

- 20-year simulation time.
- Volumetric heat capacity of soil: 2.2 MJ/m^{3}K.
- Borehole radius: 0.075 m.
- Probe type: duplex 32 mm with 0.04 m pipe spacing.
- Grout thermal conductivity: 2 W/mK.
- Heat-transfer fluid: 15% ethanol solution.
- Mass flow per borehole: 0.4 kg/s.
- Minimal average fluid temperature (heating): -1.5°C;
- Maximum average fluid temperature (cooling): 28°C.

4.1.4 Results

4.1.3.1 Results from Vienna Heat Plan 2040

The resultant Vienna Heat Plan 2040 maps Vienna into the following areas (Figure. 4):

- District Heating Today (connected areas): Predominantly covered by district heating systems. Apartments not yet connected but within buildings already supplied by district heating can be retroactively connected.

- District Heating Today (connection possible): Areas with existing district heating infrastructure capable of connecting additional buildings, pending a technical evaluation by "Wien Energie." The focus is on maximising the efficient use of current systems.

- District Heating Future (expansion planned): Urban zones with high heat demand and limited renewable energy options are proactively pursuing and implementing district heating expansion, with gradual implementation plans under review.

- Pioneer areas (expansion in process): In these forward-thinking areas, the broad expansion of district heating is actively pursued and executed. Collaborative opportunities with other construction projects are leveraged, and the insights gained are integrated into the ongoing development of district heating systems.

- Local Collective Heating (heating neighbourhoods): Densely developed areas suited for collective heat supply through local networks using nearby energy sources. These networks can service multiple buildings, though building-specific solutions remain feasible.

- Local Individual Heating (heating individual buildings): Less dense developed areas where individual heating solutions using local renewable energy are recommended. Local networks may also be viable in some cases.

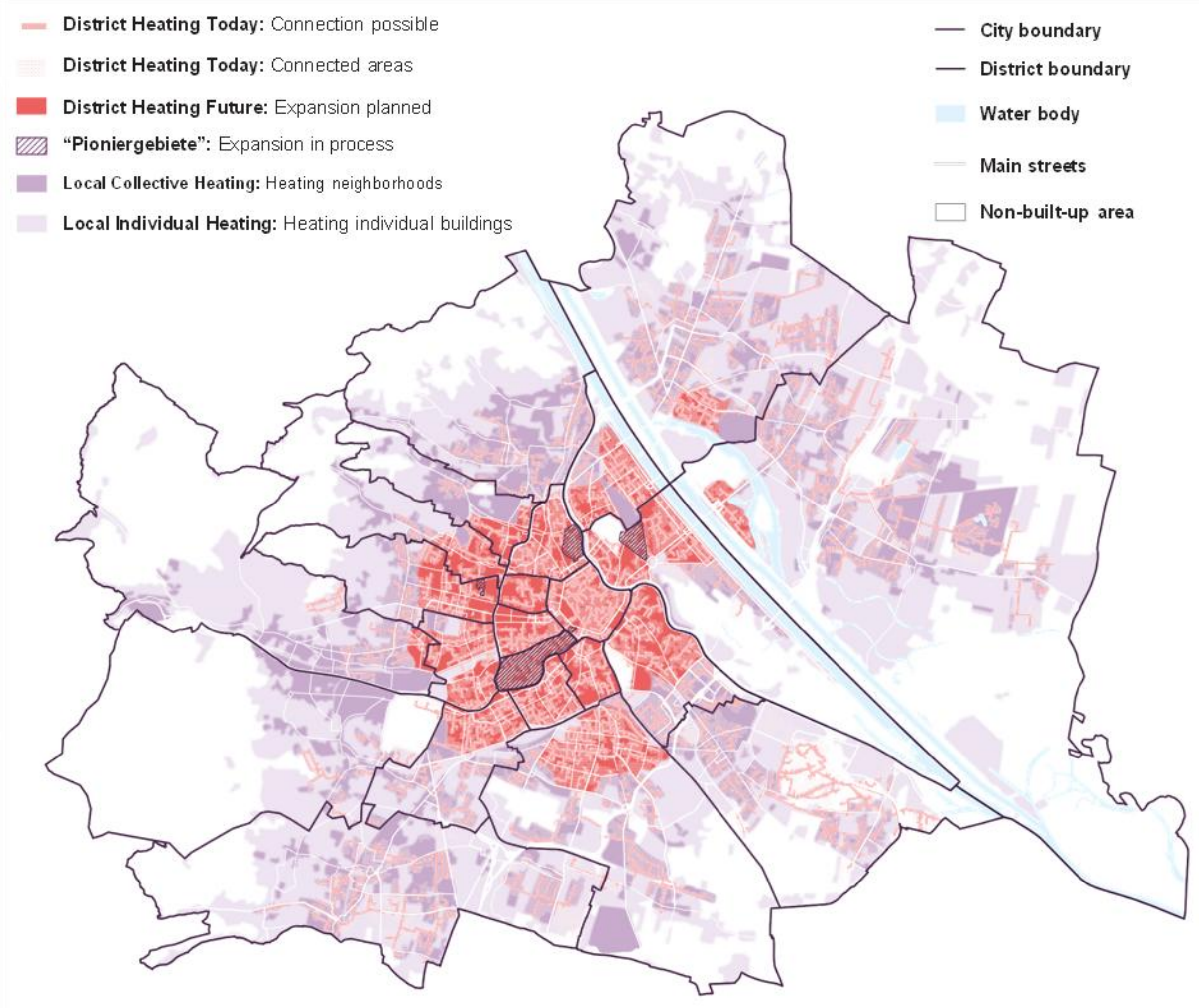


Figure 4. Different areas of the Vienna Heat Plan 2040. Underlying data: City of Vienna – Energy planning (MA 20), Wien Energie, Wiener Netze. Base map: City of Vienna – data.wien.gv.at

Final Remarks

The Vienna Heat Plan 2040 establishes a structured approach for transitioning to sustainable heating systems throughout the city. The plan emphasises district heating and the integration of renewable energy solutions, with geothermal energy identified as a central component of Vienna's decarbonisation strategy. Designated areas within the plan provide opportunities for integrating GHPs, making them suitable for regions categorised under "Local Collective Heating" and "Local Individual Heating." Additionally, deep geothermal energy and large-scale heat pumps are recognised as important elements in decarbonising Vienna's district heating network.

Several technical aspects and considerations for integrating GHPs are discussed. For example, to overcome space limitations in densely built-up areas, the use of public spaces for drilling boreholes such as sidewalks or courtyards is proposed. This facilitates the installation of GHPs in locations where buildings do not have sufficient private space to accommodate the system. Moreover, in dense urban environments, air-source heat pumps face challenges due to noise from fan operation. GHPs are preferred as they operate with minimal noise while offering higher operational efficiency compared to air-source heat pumps. Finally, a key advantage of GHPs is their dual functionality: they can cool buildings in the summer as well as heat them in the winter. Unlike conventional cooling systems, GHPs do not release warm air into the urban environment. Instead, they transfer excess heat to the ground, storing it for use in winter and avoiding further urban heat build-up.

In summary, the Vienna Heat Plan 2040 implements a layered strategy to decarbonise the city's heating and cooling systems, accommodating specific built-up characteristics and energy demands of the different areas. Within this framework, geothermal energy plays a critical role in contributing to sustainability and energy efficiency.

The Vienna Heat Plan 2040 will be updated and developed further according to feedback from stakeholders and international experts. Additional analysis on the role of district heating in the decarbonisation of cities and lessons learned from the implementation of other municipal programs (e.g., *100 Projekte Raus aus Gas*) will also be included.

4.1.3.1 Results from Vienna Heat Plan 2040

When a calculation is completed, the tool presents the estimated heating and cooling potential for a selected borehole field over a 20-year horizon. This section describes the main outputs and how to interpret them, which is also illustrated in Figure 5:

- Energy flow diagram
  - The tool automatically generates an energy flow diagram, accessible via a pop-up window on the map screen. By clicking on the diagram, a larger view in a separate browser tab is displayed.
  - The diagram visualises the annual heat extracted for heating (in winter) and the heat injected for cooling (in summer). By comparing both, users can quickly see whether the borehole field’s heating and/or cooling contributions meet their expected energy requirements.
- Summary of key performance indicators
  - Below the energy flow diagram, the tool displays summary values such as:
    - Heating potential (kWh/a or MWh/a): The maximum energy that can be extracted from the ground annually under the specified operating conditions.

- Cooling potential (kWh/or MWh/a): The maximum amount of heat that can be injected into the ground for cooling without exceeding the set fluid temperature limit.
- Coverage Ratio or "*Deckungsbeitrag*" (optional): If the user has entered building energy demands for heating and/or cooling, the tool estimates what percentage of those demands can be covered by the proposed geothermal solution.

- *Borehole details*
    - The tool lists the total number of boreholes used, their individual depths, and the chosen spacing. This overview helps users assess how changes in the number, arrangement, or depth of boreholes influence the potential outcomes.
- *Operating mode comparisons*
    - If certain criteria are met (e.g., more than 5 boreholes, the user's initial heating and cooling demands do not balance the ground energy extraction and injection), the tool provides a second set of results for an automatically balanced operating mode. This additional scenario seeks to balance annual heat extraction with reinjection so that the subsurface is neither overexploited nor overly loaded.
- *PDF report*
    - Users can download a detailed PDF report that lists all input parameters along with the simulation outputs.
    - This report includes a 20-year projection of the average fluid temperature within the boreholes. It shows how repeated heating and cooling cycles affect long-term ground temperatures.
- *Interpretation and next steps*
    - The summarised results serve as a first assessment of the potential feasibility of a geothermal system. Actual values will depend on more precise site data and specific equipment configurations.
    - Users are encouraged to iterate on their inputs (adjusting borehole layouts, depths, or operating parameters) and recalculate to see how the potential changes.

- Where coverage ratios show that the system could surpass both heating and cooling requirements, the result may indicate that the system is over-dimensioned. Likewise, low coverage may suggest that additional heat sources or sinks should be considered.

Together, these results enable a quick and very informative overview of how a BHE-based geothermal solution might perform at a given location. By considering both heating and cooling requirements alongside geological data, users can gain insight into the interplay between system configuration, thermal load balancing, and potential for long-term sustainable operation.

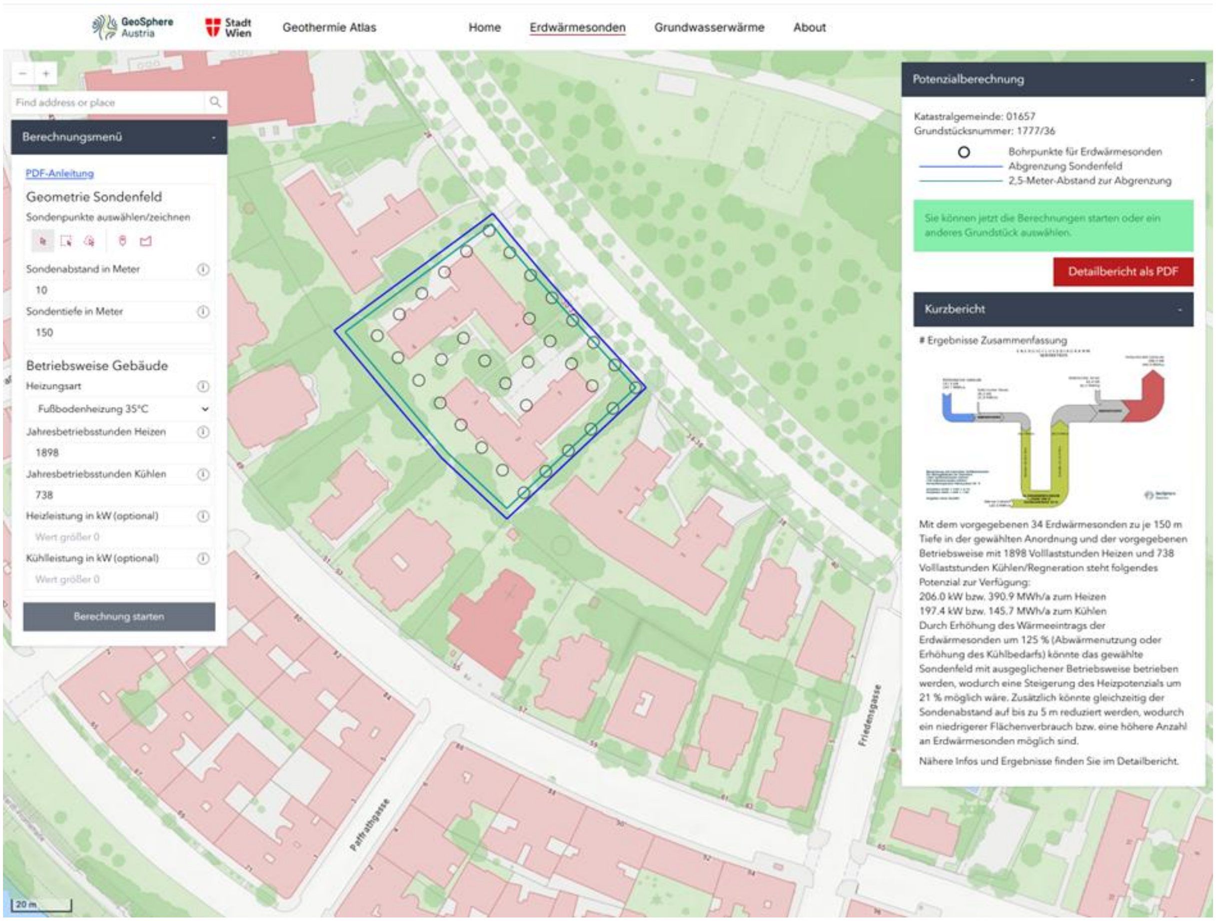


Figure 5. Screenshot showing the main functionality and BHE potential results provided by the Geothermal Atlas (*Geothermie-Atlas*). Source: https://geothermieatlas.geosphere.at/.

Final remarks

The main takeaways of the Geothermal Atlas are:

- The Geothermal Atlas offers multiple geospatial datasets including thermal conductivity, subsurface temperature, groundwater temperature, aquifer parameters, and heating and cooling potential estimates.
- Traffic light maps help users quickly identify restrictions or special considerations for shallow geothermal installations.
- The application is a user-friendly platform that allows initial planning and comparison of vertical BHE and GWHP systems for heating and cooling.
- The ability to dynamically adjust the borehole layout, depth, and operating hours helps users understand the trade-offs between field size, energy potential, and fluid temperature limits.
- Balanced versus unbalanced operation is automatically analysed for larger borehole fields, illustrating how combined heating and cooling can enhance long-term sustainability.
- The detailed PDF report generated by the tool digests all inputs and outputs, including a forecast of the loop's fluid temperature over 20 years. This makes it easier to communicate preliminary results to stakeholders or move on to more detailed simulations and design phases.
- It is important to remember the tool's recommendations and limitations: it does not replace official permitting processes, geotechnical assessments, or professional design services.

Therefore, the Geothermal Atlas represents a comprehensive tool for estimating BHE potential for heating and cooling, leveraging well-established theoretical models while remaining accessible to non-experts. It demonstrates how varying operational modes, borehole configurations, and ground conditions all influence a project's feasibility and performance.

The features provided by the Geothermal Atlas, on the one hand city-wide maps showing geological and hydrogeological data as well as available thermal energy and power and on the other hand parcel-based analysis, adjustable borehole field designs with balanced operation scenarios, align well with the objectives of energy spatial planning. The tool serves as a practical example of how digital platforms can bridge the gap between city-wide (*top-down*) energy spatial planning and individual property planning (*bottom-up*) for renewable energy systems.

4.2 Example from Germany/Bavaria

4.2.1 Framework/Stakeholders

4.2.1.1 Framework/Stakeholders at regional scale

The Energie-Atlas Bayern (www.energieatlas.bayern.de) is a comprehensive online platform developed by the government of the State of Bavaria, Germany, focused on promoting the regional energy transition through informational resources and planning tools.

The Energie Atlas Bayern, specifically in geothermal energy, is an online tool designed to encourage the use of renewable energy sources in Bavaria, Germany. This platform provides detailed information on geothermal potential, including maps of zones suitable for the installation of shallow geothermal systems such as probes, collectors, and groundwater heat pumps, which facilitates access to critical information for citizens, businesses, municipalities, and geothermal project developers.

The main stakeholders in the geothermal field of the Energie Atlas Bayern include various public and private actors. Notably:

- Academic institutions such as the Technical University of Munich (TUM) and the University of Applied Sciences (HM), which are involved in researching geothermal potential in Bavaria.

- Private and technological companies (Bayerngas GmbH, SWM-Stadtwerke München, Erdwerk GmbH) through the Green Tech Cluster, which promotes cooperation between companies for the development of sustainable solutions in renewable energy.

- Local and regional authorities (Bavarian Ministry of Economic Affairs, Regional Development, and Energy, and municipal governments in Bavaria) that work on the planning and implementation of sustainable energy projects and are responsible for executing projects at the municipal scale.

- Developers and Planners which want to implement renewable energy sources

- Citizens and local communities, who benefit from geothermal projects, contribute to the acceptance of these energy developments.

4.2.1.2 Framework/Stakeholders at local scale

The integration of open-loop heat pump systems into the energy plan of the city of Munich is part of the ‘Central Resolution II Munich Climate Neutral’. The Department for Climate and Environmental Protection was commissioned to manage the development of a binding and spatially differentiated heating strategy as part of this resolution. In this context the GeoKW project was born, designed primarily to explore the potential of underground geothermal energy in urban environments and its integration into Munich's energy system. The project was led by the Technical University of Munich (TUM)-Chair of Hydrogeology- and involved various actors specialised in urban planning, geology and energy engineering such as:

- Authorities: Collaboration with authorities such as City of Munich, Department of Climate Protection and Environment, which is leading the heat energy transition of Munich, City Department of City Planning, City, City Department of Construction. Additionally, the Environmental Agency of Bavaria was involved which is responsible for legal, administrative and data transfer barriers. It facilitated the adoption of geothermal technologies in urban settings. In addition, the involvement of these entities ensures that the projects are aligned with the sustainability and energy efficiency goals of the region.

- Local utilities: Companies such as SWM-Stadtwerke München, Energy Supplier of Munich which manage the water and heating utilities in the city are interested in diversifying their energy sources and contributing to the supply of renewable energy for heating buildings and other urban services.

- Federal Ministry of Economics and Energy (Bundesministerium für Wirtschaft und Energie-BMWi): This German ministry finances and supports geothermal projects such as GeoKW, promoting research and development for the energy transition in Germany.

- Research and technology development institutions: This project works with additional academic partners or research centres that contribute with expertise in geothermal, digital modelling and sensor technology, such as TUM; Chair of Renewable and Sustainable Energy Systems; University of Stuttgart Institute for Parallel and Distributed Systems; Leibniz Supercomputing Centre of the Bavarian Academy of Sciences and Humanities.

4.2.2 Target Group

4.2.2.1 Target Group at regional scale

The target group of the Energie Atlas Bayern includes a wide range of users interested in the transition to renewable energy sources in Bavaria. These include:

- General Public: The atlas is designed for individuals seeking information on how to implement renewable energy solutions in their homes, such as geothermal heating systems, solar panels, or energy efficiency improvements.

- Businesses and Industrial Sector: Local companies and businesses aiming to reduce carbon emissions and improve energy efficiency can find guidance on renewable energy technologies and funding opportunities.

- Municipal and Regional Authorities: Local and regional governments use the platform for planning and decision-making in renewable energy and energy efficiency projects, as well as for managing permits and complying with energy regulations.

- Project Developers and Consultants: Companies and consultancies in the energy sector utilize the atlas to assess geothermal potential, identify suitable locations, and understand the regulatory framework for renewable energy project development.

4.2.2.2 Target Group at local scale

The target group mainly includes city authorities and city managers, as they are the main managers of the integration of geothermal systems into the city's energy plan. Other key target groups are:

- Energy and Utilities Companies: These companies are interested in integrating renewable energy sources into their operations and can benefit from the project's models and recommendations to adopt open loop systems in their energy networks, thus optimising their infrastructure and use of groundwater resources in a sustainable way.

- Building and Urban Development Sector: As new urban areas or renovations are planned, the building sector can take advantage of geothermal systems to provide sustainable heating and cooling solutions, increasing the energy efficiency of buildings.

- General Public and Property Owners: Disseminating knowledge about the benefits and feasibility of these systems can encourage property owners to consider geothermal solutions to reduce energy costs and contribute to sustainability.

4.2.3 Methods

In the context of planning and management of shallow geothermal systems in Bavaria, both at regional and local scale, there is convergence in the methods used for implementation and monitoring. This uniformity responds to the need to ensure a consistent approach that allows for technical compatibility, regulatory compliance and environmental sustainability, regardless of territorial scale.

4.2.3.1 Methods at regional scale

In order to determine the integration of geothermal heat pumps in the energy plan of the Bavarian region, it is necessary to determine the demand and the potential of geothermal energy to cover this demand.
The methodology and methods used are described below.

4.2.3.1.1 Design of the building model

A building model serves as the foundation for determining heat demand and analysing the heat supply potential of existing buildings through geothermal heat pumps. It is recommended to design the building model in a way that accurately reflects the essential characteristics of the real estate stock, including the geometry, use, and structural properties of the buildings.

The steps to be taken to design the building model are outlined below.

- An essential aspect of building modelling is the delimitation of the individual buildings, i.e., the building outline. Each building outlines is assigned a unique object ID (identifier), which is subsequently used in all models (heat register, potential model for geothermal heat pumps, etc). It is recommended that the object ID, as an autonomous property of the building, is not reassigned even after the building has been demolished. This would represent an essential basis for the future update or version of the building database to be created.

- Next, building geometry is determined using digital data. This model is made up of building components, which are differentiated according to roof surfaces, wall surfaces and the lower building surface (ground level). As a result of this procedure, each outline is assigned to a 3D model representing the enclosed volume (above ground) and the individual surfaces of the building components with their orientation and inclination.

- Then, the building's use is determined and assigned using the available database. The following illustration provides a basic overview of the approach used.

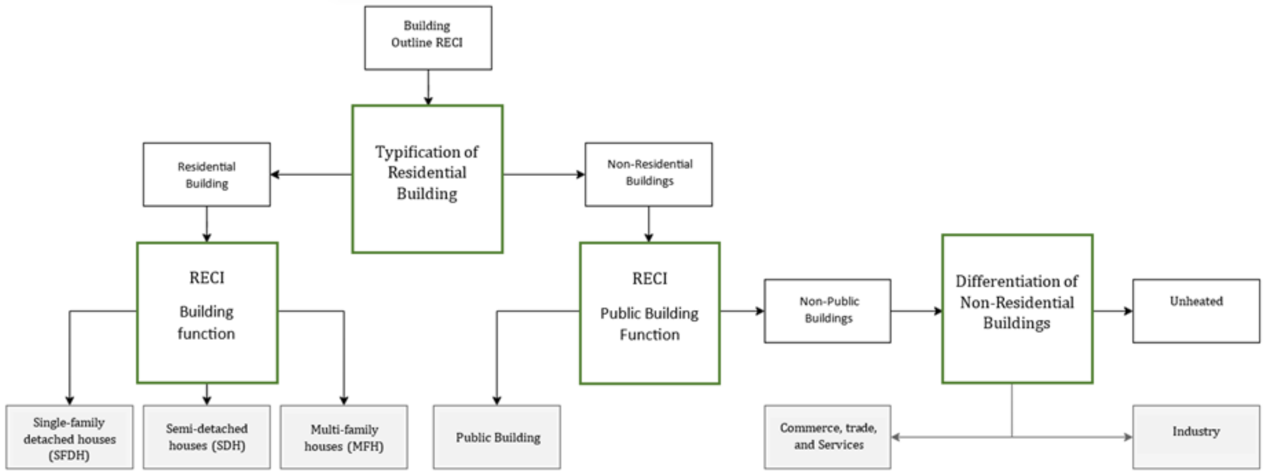


Figure 6: Flow chart for determining and assigning building use.

- In the following step is to assign an age to each building (building outline). If this information is not available, it is approximated using a combination of available data sources, such as Real Estate Cadastral Information (RECI), census data, etc.

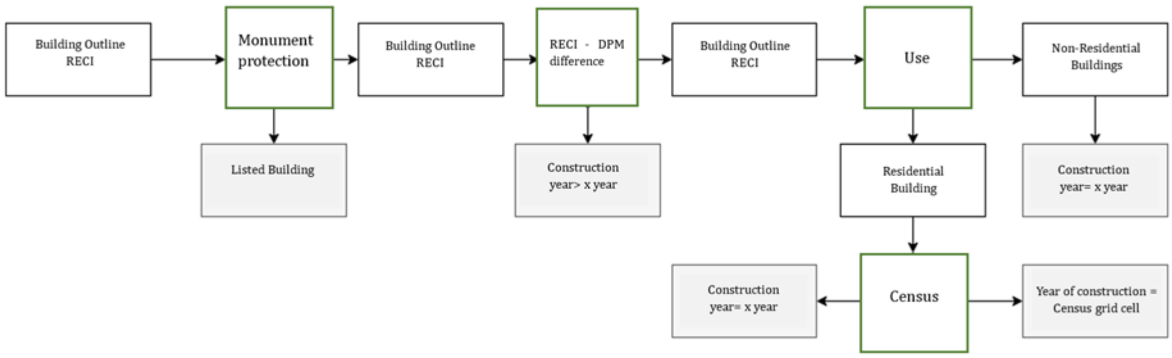


Figure 7: Flow chart for assigning the construction age for buildings.

- Finally, the relevant information on geometry, use and age of the building is extracted and assigned from the available data sources. The model is implemented in a building database that represents each building and forms the basis for all subsequent calculations and evaluations of the building stock. The transfer of the unique object identifier of the cadastre (ID) allows an easy update and historization of the model. The demolition of a building can be represented by adding an additional attribute "year of demolition" and the construction of a new building by adding updated cadastral data.

4.2.3.1.2 Structure of the heat register

The recommended methodology to use for creating the heat register is based on typologies.

- First, specific energy demand parameters are assigned to the buildings depending on their use and age. These specific parameters (determined for the calculation of the potential analysis) are related to the energy reference surface, which in turn is derived from the geometry of the building as a function of use.

- Then, the analysis of renovation potential must then be conducted based on building typology. For different types of use or building typologies, renovation maximums defined according to various renovation levels specified in each regulation should be established using specific energy parameters.

- Finally, the results obtained from these calculations, such as heating demand and renovation variants, are stored for each building in the building database as an extension of the existing model.

.4.2.3.1.3 Main method for determining the potential of GWHP, BHE and GHC

In this proposed methodology, the determination of the geothermal heat pump energy potential requires a large amount of geological and hydrogeological data for the whole area. These can be processed in databases or by means of geographic information systems.

The processing procedure proposed here is basically the same for all three technologies:

- Exclusion zones / Suitability zones: Exclusion zones must be examined, as the system in question cannot be used in them as a matter of principle. Furthermore, each technology, even if permitted, is not equally suitable everywhere.

- Database: Next, the necessary data sets must be collected for further processing and potential analysis. For this purpose, the datasets are checked and, if necessary, supplemented with other databases.

- Parcel-based calculation: For the calculation of the potential at plot scale, a potential value for each plot must be determined from the RECI databases of plots and buildings based on the heating demand.

- Raster-based calculation: For the grid scale representation, the potential is determined analogous to the plot-related calculation with a uniformly applied reference system for a 10 m x 10 m grid.

- **Methodology for determining the potential of groundwater heat pumps (GWHP)**

The calculation of the geothermal potential for the thermal utilisation of groundwater-by- heat pumps recommended is based on the Thermal Aquifer Potential method (Böttcher et. al., 2019).

The estimation of the available and pumpable flow rate of the groundwater well is of fundamental importance for the quantitative assessment of groundwater resources and depends on the natural parameters of aquifer thickness (distance from the aquifer top to the aquifer bottom), the depth to groundwater table (distance from the groundwater table to the surface of the ground), hydraulic permeability and groundwater flow velocity and direction, as well as on the engineering conditions of the well.

In this methodology, three fundamental questions arise during pumping and re-injection process:

i) At what maximum pumping rate may water be extracted from the production well?

ii) At what maximum flow rate can water be pumped into the injection well?

iii) At what rate, depending on the distance between the wells, is water not pumped between the absorption well and the production well?

which can be answered from the licensing practice based on the Bavarian regulations for the use of shallow geothermal energy (VDI 4640, BayWG and WHG)

- Parcel and grid potential calculation.

  Based on the considerations in the description of the TAP method, three equations can be established (below) to describe the limitations of the extraction rate, the injection rate and the thermal-hydraulic breakthrough.

  - Drawdown in the extraction well

    Equation (1) calculates the drawdown rate at the production well with a maximum drawdown of one third of the saturated aquifer thickness and the prevailing local hydraulic conductivity.

$$V_1 = 0{,}195\ k_f\ M^2 \qquad (1)$$

where,

V_1	$m^3 s^{-1}$	Flow rate at the drawdown threshold M/3

k_f	$m\ s^{-1}$	Hydraulic conductivity
M	m	saturated aquifer thickness

Injections constraints

The re-injection of groundwater shall not cause an excessive rise in the groundwater level that could result in surface or basement flooding. The groundwater level may rise to a maximum of 0.5 m below the ground surface (without surface flooding). Therefore, a maximum injection rate is determined, which is determined by the hydraulic conductivity, the hydraulic gradient, and the thickness of the saturated aquifer. The following applies:

$$V_2 = (s - 0{,}5)\ k_f\ M^{0{,}798}\ e^{(29{,}9\ i)} \qquad (2)$$

where,

V_2	$m^3\ s^{-1}$	Discharge rate for the Accumulation limit (s - 0.5)
k_f	$m\ s^{-1}$	Hydraulic conductivity
M	m	Saturated aquifer thickness
s	m	Depth to groundwater table
i	-	Hydraulic gradient

- Hydraulic short-circuit (or breakthrough).

The injection well returns the thermally altered water to the aquifer. For efficient use of groundwater heat pumps, it is essential that there is no thermal-hydraulic break between extraction and injection, as this would make sustainable and efficient operation of the thermal use of groundwater impossible. Therefore, the extraction rate is limited and depends on the separation between wells. The maximum extraction rate of a pair of wells without hydraulic short-circuit is further determined by the Darcy velocity and the saturated thickness of the groundwater. The following formula applies.

$$V_3 = \frac{\pi}{1{,}96}\ v_D\ M\ x_w \qquad (3)$$

where,

V_3	$m^3 s^{-1}$	Extraction rate without hydraulic short circuit.
v_D	$m\ s^{-1}$	Darcy velocity
M	m	Saturated aquifer thickness
x_w	m	Distance between production and injection wells.

The contained Darcy velocity of the groundwater is defined as

$$v_D = k_f\ i \qquad (4)$$

where,

k_f	$m\ s^{-1}$	Permeability coefficient
i	-	Hydraulic gradient

- Estimation of the maximum extraction rate

The three calculated volumetric flow rates in the well pair must be combined in a final step into the maximum realisable extraction rate. Therefore, the minimum flow rate as the dominant limiting factor determines the maximum achievable extraction rate.

The following applies:

$$V_{max} = \min\ (V_1, V_2, V_3) \qquad (5)$$

where,

V_{max}	$m^3 s^{-1}$	Maximum realisable extraction flow rate
V_1	$m^3 s^{-1}$	Flow rate for M/3 extraction limit
V_2	$m^3 s^{-1}$	Discharge rate for the accumulation limit (s - 0,5)
V_3	$m^3 s^{-1}$	Extraction rate without hydraulic short-circuit

- Calculation of the thermal extraction capacity and heating capacity

The maximum viable extraction rate is used to calculate the thermal capacity within the legally permissible temperature range. Calculating the extraction capacity using the allowable temperature range permits the potential to be estimated independently of the actual temperature (e.g. in Bavaria, normally 5 K). However, when installing the system, the absolute minimum and maximum temperatures must also be considered to ensure that neither the system freezes, nor the groundwater is contaminated by excessively high temperatures of the re-injected water. The following formula applies:

$$P_{th} = V_{max} \, c_{pw} \, \rho_w \, \Delta T \qquad (6)$$

Where;

P_{th}	W	Thermal extraction power
V_{max}	$m^3 \, s^{-1}$	Technically reasonable extraction rate
c_{pw}	$J \, kg^{-1} K^{-1}$	Specific heat capacity of water
ρ_w	$kg \, m^{-3}$	Water density
ΔT	K	Maximum temperature dispersion

According to VDI 4640, sheet 2, equation (6) and a specific heat capacity of 4,187 $J \, kg^{-1} \, K^{-1}$ of water at constant pressure and 10 °C can also be used to estimate the evaporator capacity of a water-to-water heat pump. Thus, only a rough estimate of the average efficiency is needed to calculate the final heat output that a heat pump can provide in the heating circuit. The estimate is made using the annual efficiency factor of the heat pump.

The Seasonal Coefficient of Performance (SCOP) indicates the ratio between the heating energy delivered throughout the year and the electrical energy consumed and includes the additional energy required for the auxiliary drives of the geothermal system. Therefore, the actual groundwater temperature is not necessary for estimating the heating capacity.

Thus, the average heating capacity results from:

$$P_t = \frac{P_{th}}{1 - \frac{1}{JAZ}} \qquad (7)$$

where,

P_{th}	W	Thermal extraction power
P_t	W	Average heating Power
$SCOP$	-	Seasonal Coefficient of Performance

- **Methodology for determining the potential of borehole heat exchangers (BHE)**

The present calculation for the estimation of the quantitative potential for borehole heat exchangers is based on data for the geological description of the subsurface. As a basis for the geological description of the subsoil and as a hydrogeological evaluated boundary, the thermal conductivity as well as the borehole depth limit are required.
The methodology for determining the potential of geothermal probes is based on VDI 4640, sheet 2. Several tables relate the average thermal conductivity of the surrounding subsoil to the expected extraction capacity per metre of installations. Values in between are interpolated in a simplified way. Thus, given the thermal conductivity of the soil, it is possible to calculate the extraction capacity per metre of borehole (W/m), considering the borehole depth limit, and the total extraction capacity of a borehole (kW).

The tables in VDI 4640, sheet 2, allow the calculations to be differentiated according to

i) Full-load hours/year assumed: 1,200 h/year, 1,500 h/year, 1,800 h/year, 2,100 h/year, 2,400 h/year.

ii) System operation with "heating only" and "heating and domestic hot water heating" and

iii) Minimum temperature of the heat transfer medium leaving the heat pump: -5 °C, - 3 °C, 0 °C

For the calculation of the potential per plot of borehole heat exchangers it is recommended to carry out the following procedure:

- Determination of the number of potential borehole heat exchangers

  The potential for the use of borehole heat exchangers is only calculated for suitable plots. Plots that do not offer sufficient space for the implementation of a borehole heat exchanger due to their size or building development are not considered in the quantitative analysis of the implementation potential.

For all suitable plots, the maximum possible number of probes is determined with the help of the legal separation regulations. The maximum possible number of Installations is calculated as follows.

$$Number_{Installations} = \frac{Area_{plot}}{Area_{installations}} \qquad (8)$$

where,

$Number_{installations}$ Maximum number of possible installations on the plot

$Area_{plot}$ m^2 Maximum available area after deduction of the building areas and consideration of the boundary distances

$Area_{installations}$ m^2 Required area/installations = 36 m^2

In the case of systems with several installations, it must also be considered that the installations influence each other, so that the extraction rate of each individual probe decreases.

Table B3 of VDI 4640 shows the corresponding decrease in the extraction rate with each additional probe for a maximum of five probes (see table 17).

Table 17: Conversion of thermal conductivity to extraction power per metre of probe as a function of the number of probes at 1,800 hours per year at full load.

Extraction power at turbulent flow (W/m).	**Thermal conductivity of the surrounding substrate (W/(m*K)).**			
Number of probes	**1,0 W/(m*K)]**	**2,0 W/(m*K)]**	**3,0 W/(m*K)]**	**4,0 W/(m*K)]**
1	24,5	36,9	45,4	51,8
2	22,0	33,6	42,1	48,5
3	20,3	31,5	39,8	46,2
4	19,1	29,9	38,0	44,4
5	18,4	28,9	37,0	43,4

For systems with several installations, it must also be considered that the installations influence each other so that the extraction capacity of each individual installation decreases. A corresponding decrease in extraction rate with each additional probe is given in Table B3 of VDI 4640 for up to five probes. The curve thus given is extrapolated in a simplified way for this study to up to 20 installations.

$$P_{installations} = -3{,}85 * \ln(n) + 24{,}55 \quad (9)$$

where,

$P_{installations}$	kW	Extraction capacity of a geothermal installations
n	-	Number of installations

It is recognised that this represents a strong approximation of the real conditions on the one hand, but on the other hand enables a large-scale Bavaria-wide assessment of the potential.

- Calculation of the heat extraction power

In order to obtain an average and conservative estimate, the relationship between average thermal conductivity and expected extraction capacity should be taken from the tables in VDI 4640 Table B3 (see Table 5 here). This also requires the following assumptions:

- Full load hours = 1,800 h/a,
- Minimum temperatura of the heat transfer fluid at discharge = -3 °C and
- System operating mode = 'heating only'.

Under the above conditions, the extraction capacity of an installation can now be calculated from the maximum possible depth of the borehole and the extraction power per metre of installation as follows.

$$P_{installations} = P_{installation\ meter} \frac{ddl}{1000} \quad (10)$$

where,

$P_{installation}$	kW	Extraction power of geothermal installations

$P_{installations\ meter}$	W m-1	Extraction power per probe meter
ddl	m	Drilling depth limit = maximum drilling depth

- Calculation of the energy extraction

The conversion of the thermal conductivity into extraction energy per metre of installations is based on VDI 4640 sheet 2, table B3 (see also table 14). This assumes an annual operating time of 1,800 hours. The extraction energy must therefore be calculated using equation (11).

$$E_{installations} = P_{installation}\ T \qquad (11)$$

Where,

$E_{\text{installations}}$	kWh/a	Extraction energy of geothermal installations.
$P_{\text{installations}}$	kW	Extraction power of geothermal installations.
T	h/a	Full load hours per year

- **Methodology for determining the potential for Horizontal Collectors (HC)**

it is proposed that the estimate of the quantitative potential of Ground heat collectors (GHC) and their special shapes be carried out based on the methodology developed by the Working Group Near-Surface Geothermal Energy of the Friedrich-Alexander-University Erlangen-Nuremberg (FAU). In this methodology, the designs of VDI 4640, Sheet 2 and VDI 4710 are linked to the digital surface data of the soil map and the DEM. The most important parameter for calculating the potential is the soil type with its characteristic physical properties. In addition, climatological data should be used to obtain the heating degree days to consider regional average temperatures.

Raster-and parcel calculation of the realisable potential

- Calculation of the realisable potential

In general, the extraction power and extraction energy should be derived from the data or information already available (see section 4.5.4.5) In the case of Germany table values for these parameters are in the VDI 4640. The VDI 4640 provides these for a selection of very near-surface geothermal systems (horizontal systems and their special forms), with the respective extraction powers and energies that are emitted for various climatic zones (specifically distributed in Germany: see Table x). Since these individual climate zones can cover very large areas, a more differentiated approach should be used to calculate the respective extraction rates.

- Linking climate zones through altitude

The information on the individual climate zones must be linked to the altitude of the respective reference locality. This link is the basis for further correlation with calculated heating degree days (example Table 18).

Table 18: List of climatic zones for Germany considered in VDI 4640 and listed in DIN 4710

NR	Locality	Altitude [m a.s.l.]	Climate zone
1	Bremerhaven / Norderney	18	(1) Bremerhaven
2	Rostock-Warnemünde / Heiligendamm	13	(2) Rostock-Warnemünde
3	Hamburg-Fuhlsbüttel / Hamburg-Sasel	31	(3) Hamburg-Fuhlsbüttel
4	Potsdam	81	(4) Potsdam
5	Essen / Gelsenkirchen / Bochum	134	(5) Essen
6	Bad Marienberg / Bad Lippspringe	355	(6) Bad Marienberg
7	Kassel	231	(7) Kassel
8	Braunlage	607	(8) Braunlage
9	Chemnitz	418	(9) Chemnitz
10	Hof / Zinnwald	722	(10) Hof
11	Fichtelberg	1213	(11) Fichtelberg
12	Mannheim	96	(12) Mannheim
13	Passau	409	(13) Passau
14	Stötten / Stuttgart-Schnarrenberg	526	(14) Stötten
15	Garmisch-Partenkirchen	596	(15) Garmisch-Partenkirchen

- Determination of heating degree days

To determine the heating degree days, the respective heating degree days must be calculated from the weather or temperature data of the individual weather stations, in this case from DIN 4710 (12):

$$Heating\ degree\ days_{22/14} = \sum(T_{in} - T_{out})\ d \qquad (12)$$

where,

$Heating\ degree\ days_{22/14}$	K d/a	Heating degree days
T_{in}	°C	Internal temperature
T_{out}	°C	Outdoor temperature
d	d/a	Number of days with average temperature < 14 °C

It is proposed that the calculation of the heating degree days be based on ÖNORM B 8110-5. In ÖNORM B 8110-5, the indoor temperature (Tin) for this function is defined as 22 °C, the outdoor temperature (Tout) is calculated using the corresponding average outdoor temperatures. The sum of the differences between the heating limit temperature and the average outdoor temperature on days (d) where the average temperature is below 14 °C is calculated. The heating degree days could be represented by the above link to the DIN 4710 weather stations as a function of the altitude above sea level (a.s.l.)

- Calculation of the heat extraction power

In addition, the soil type-specific and system-specific extraction performance must be correlated with the heating degree days of the same weather stations.

Thereby, a calculation basis (table x) is created for the groups of soil types sand, loam and silt and the geothermal systems (in this case listed in VDI 4640). The extraction power can be derived for each site from the heating degree days as surface information (e.g. Bavaria) and the soil- or system-specific correlations between the extraction power and the heating degree days. For the derivation of the current soil type group the provided soil estimation map should be used. After checking the soil type within each polygon, the extraction power can be calculated using formula in Table 19.

Table 19: Calculation model for determining the extraction power of various near-surface geothermal systems based on heating degree days.

Very close to the surface geothermal system	Soil type group	Calculation of the extraction power (P) on the basis of the heating degree days (x)
Horizontal Collector	Sand	$P=261.74\ e^{-0.0005667956x}$ (W/m²)
	Clay	$P=176.54\ e^{-0.0003992871x}$ (W/m²)
	Silt	$P=141.53\ e^{-0.0003357456x}$ (W/m²)
Capillary tube mats	Sand	$P=971.46\ e^{-0.0008099321x}$ (W/m²)
	Clay	$P=146.50\ e^{-0.0003352380x}$ (W/m²)
	Silt	$P=152.21\ e^{-0.0003090645x}$ (W/m²)
Geothermal basket 1	Sand	$P=81.67\ e^{-0.0003242691x}$ (W/m²)
	Clay	$P=87.27\ e^{-0.0002375047x}$ (W/m²)
	Silt	$P=77.37\ e^{-0.0001963163x}$ (W/m²)
Geothermal basket 2	Sand	$P=23.05\ e^{-0.0001750295x}$ (W/m²)
	Clay	$P=39.96\ e^{-0.0001807998x}$ (W/m²)
	Silt	$P=35.13\ e^{-0.0001341375x}$ (W/m²)
Trench-Collector	Sand	$P=49.76\ e^{-0.0001244829x}$ (W/m²)
	Clay and Silt	$P=76.23\ e^{-0.0000715544x}$ (W/m²)

Calculations of heating degree-days and subsequent site-specific extraction powers can be performed and visualised in interaction with the DEM 25 digital surface data and the digital soil estimation map with the help of a geographic information system (GIS).

- Calculation of the extraction of energy

In a further step, the extraction of energy can be derived from the extraction power and the full load hours. For this purpose, the following relation is used (equation 13):

$$E = \frac{P * T}{1000} \qquad (13)$$

where,

E	kWh/(a*m2)	Extraction energy
P	W/m2	Extraction power
T	h/a	Full load hours

For the calculation of the energy extracted, it is also considered that in colder regions a greater number of hours at full load is necessary to cover the greater demand for heating in these regions. To determine the representative full-charge hours of an area (in this case Bavaria), the full-charge hours should be correlated with the altitude of the weather stations.

This correlation (see equation 14) allows full-load hours to be calculated for all heights of the DEM 25.

$$Full\ load\ hours = 0{,}5779 \frac{h}{m} * Height + 1560{,}1\ h \qquad (14)$$

where,

$Full\ load\ hours$	h	Full load hours
$Height$	m	Altitude above sea level a.s.l

The area data on the required full load hours can be differentiated and derived as a function of the altitude in the GIS, whereby the site-specific extraction energy can be calculated.

In order to determine the extraction energy, the specific extraction power of the system and of the entire area can be used as a basis for determining the extraction energy.

4.2.3.2 Methods at local scale

- **Methodology for potential analysis of open loop systems**

This section describes the methodical procedure and relevant methods for calculating the potential of open loop systems, based on the requirements of municipal heating planning. The methodology is divided into three stages: (a) assessment of the technical potential for parcel and building blocks, (b) comparison of the potential with the needs, and (c) optimisation and determination of the spatial potential.

- Assessment of the potential for parcels and building blocks.

The first step involves examining aspects of the federal and state legal framework, as well as municipal statutes and ordinances related to the exclusion of adjacent areas. Specifically, this refers to restrictions due to natural areas, water conservation zones, and existing urban infrastructure. In this analysis, these elements are integrated into white zone mapping. In this way, unsuitable and unauthorized locations for well construction are initially excluded from the quantitative analysis. Specifically, the criteria summarized in Table 20 have been integrated into the white zone mapping.

Table 20. Criteria integrated into white zone mapping

Exclusion zones		
Drinking water protection areas	Bodies of water	Underground tunnels
Nature conservation areas	Ground monuments	Suburban railway tunnels
Landscape conservation areas	Natural monuments	Road tunnels
Natura 2000 areas	Floodplains	Underground car parks
Biotopes	Trees	Underground buildings
District heating pipes	Gas pipelines	Telecommunications network
Underground power lines		

The second step involves calculating the thermal utilization potential of groundwater using the TAP (Thermal Aquifer Potential) method (Böttcher et al., 2019) in the available area (not exclusion zone). This method aims to capture the advantages of numerical simulation within analytical formulas, enabling large-scale potential analysis in geoinformation systems.

In applying the method, aspects of the legal framework are reviewed and considered. Three relevant technical restrictions within the authorization practice are calculated in the potential analysis, based on Bavarian regulations for the utilization of shallow geothermal energy (VDI 4640, BayWG, and WHG).

Within the TAP method, the relationships between the previously defined restrictions and hydrogeological or operational parameters were analysed using numerical models. For this, models were constructed, allowing significant parameters (Table 21) to vary isotropically and consistently to simulate their influence on volumetric flow in the well pair.

Table 21. Parameters

Parameter	Unit	Maximum	Minimum	Cases
Groundwater thickness	m	30	1	6
Hydraulic permeability	m/s	5.8 10-2	2.1 10-4	6
Hydraulic gradient	-	0.01	0.001	6
Well spacing	m	variabel	10	5

The simulations that vary significant parameters relative to each other are conducted in idealized box models with the following characteristics:

- Vertically averaged flow was computed in 2D, according to the third level model reduction by Diersch.
- Unconfined flow and heat transport is simulated in steady state.
- The saturated groundwater thickness, the hydraulic conductivity and gradient are kept constant throughout the model domain.
- The pumping rates are constant, and the absolute values are equal for well doublets, while the wells are always fully penetrating the aquifer.

The estimation of the regression functions was performed individually for the three restrictions of withdrawal, reinjection and short-circuit described above. The corresponding equations for quantifying the technically shallow geothermal potential are explained in the section 4.1.3.1.3.

- Determination of the parcel-specific potential

The spatial hydrogeological basic data from previous projects are used as the basis for the potential analysis for thermal groundwater use. For this purpose, the parcel distance, groundwater-filled thickness, flow direction and gradient as well as the hydraulic permeability of the aquifer are used to calculate the quantitative potential. For this purpose, the median of all input parameters is determined for each parcel and the calculations are used to determine the technically feasible potential on a parcel-by-parcel basis (kW). The extraction rate and the discharge rate can be derived directly from the aggregated hydrogeological data using equations (1) and (2). To calculate equation (3) (Section4.1.3.1.3.), the well spacing that can be realised on the parcel is also required.

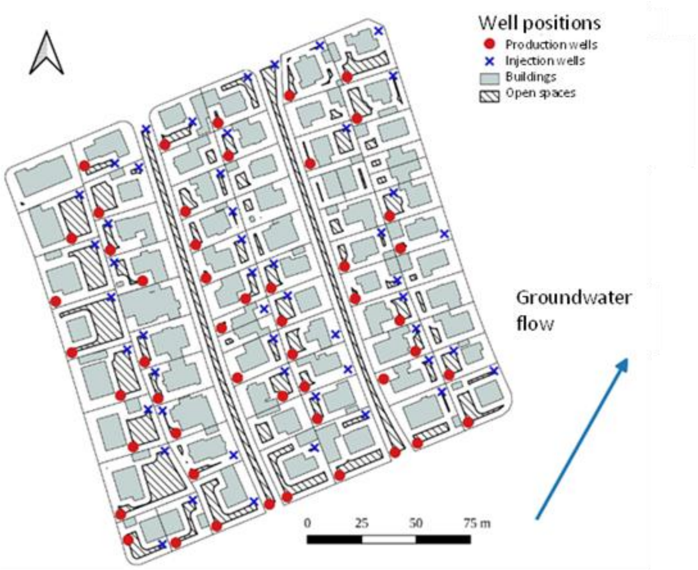


Figure 8: Example of arrangement of extraction and injection wells on parcels of land, considering the groundwater flow direction and the 3 m minimum distance to buildings and the parcels boundary.

To calculate the maximum possible distance between extraction and injection wells, both the groundwater flow direction for aligning the wells and the compliance with distance areas are considered. To designate appropriate open spaces for well construction, the minimum distance of 3 metres to existing buildings and property boundaries prescribed in Bavaria is first considered. The remaining open spaces are then used to place the production well at the point furthest upstream and the injection well at the point furthest downstream. If the resulting well spacing is less than 10 metres, the pair of wells is no longer considered. All values for the calculation of equation (3) are now available and the technically feasible extraction rate and the thermal output for each parcel can be calculated.

- Determination of the building block-specific potential

Similar to the parcel approach, the hydrogeological parameters are determined as a median for each building block and the calculations are then used to determine the technically feasible potential (kW). The open space available in the building block is also mapped for the positioning of the wells. In contrast to the parcel approach, only the 3 m minimum distance to buildings is considered here. The decision not to include any distance to building block boundaries was made in consultation with SWM, since as a municipal energy supplier they are also authorized to drill wells on public land or on streets. The potential on building blocks is used to assess the feasibility of interconnected solutions such as cold local heating networks, which are typically operated by an energy supplier.

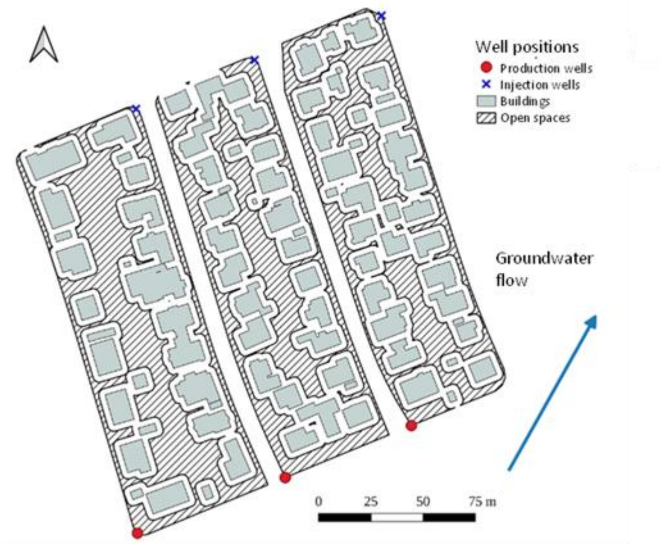


Figure 9: Example of arrangement of extraction and injection wells on building blocks, considering the groundwater flow direction and the 3 m minimum distance to buildings.

Since the wells can generally be located further apart from each other than with the parcel approach, the hydraulic breakthrough becomes less and less of a limiting factor for the technically feasible withdrawal rate. Limit states are more frequently reached in which the maximum drawdown or the maximum accumulation are decisive for the feasible extraction rate.

After calculating the potentials from the two aggregation levels, i.e. parcel and building block, the next step is to compare them with the building's heat demand.

- Comparison of potential and heat demand

In order to check the possible coverage of the heating demand by the locally available potential, a detailed comparison of the technically possible heating output with the heating demand on the respective parcel or building block is necessary. The technically possible heating output is calculated using equation (7). For this purpose, an average annual performance factor of 4 is assumed to be constant for groundwater heat pumps. In contrast to other shallow geothermal extraction systems, the decisive factor for thermal groundwater utilisation is not the annual energy quantity, but the output. Since no thermal short circuit occurs during extraction and injection in a pair of wells, even at the maximum operating point, continuous operation is ensured by a conservative design of the method. Consequently, it is not the duration of operation, i.e. extraction power, but the intensity, i.e. maximum extraction capacity, that is decisive.

The conservative assumption is always that the heat pump will operate monovalently and that the heat demand of the building will be fully covered. If the needs of one building can be met, it will be supplied, and the next smaller building will be considered. The supply of buildings accumulates until the potential is spent or all buildings are supplied. If the next smallest building cannot be supplied, but there are other buildings in the area, the test is continued, thus ensuring that the remaining potential is 'supply'. The result of the possible adjustment is an identification of the buildings that can be supplied and an indication of the possible coverage of the needs in parcels and building blocks. Particularly important here is the total installed heating capacity of the zones, as this is used to optimise the spatial potential.

In addition to checking whether the available potential on a parcel can meet the demand, in a second step, the economic feasibility of the construction of wells is considered. Depending on the depth of the water table (distance from the ground), the well construction costs for a system can vary greatly from place to place, whereas, for example, the costs for construction equipment, well pumps, permits, etc. are fixed. costs tend to fluctuate little for the same system size.

In practice, such high costs for developing the heat source are not economical, so a limit on the maximum final depth (expansion depth) of the well pair was introduced depending on the heating capacity of a groundwater heat pump. The larger the heat pump, the deeper the wells can be built. To determine the current costs for 2023, an expert survey was carried out among drilling companies, geo-offices and heat pump manufacturers. Based on the usual services for the installation of a groundwater heat pump, the variable items of well construction, such as linear metres of drilling and well construction, including risers and down pipes, were evaluated to adapt a cost function.

The function for calculating the cost is:

$$c_{limit} = \frac{5{,}6\, z + 6{,}9\, (2{,}25\, p_{hp})^{0{,}47}}{15\, p_{hp}^{0{,}7}} \qquad (15)$$

c_{limit}	-	Ratio of the variable investment costs of the well construction to the costs of the heat pump unit
p_{hp}	kW	Heat output of the heat pump
z	m	Depth of the well pair (extraction and injection wells)

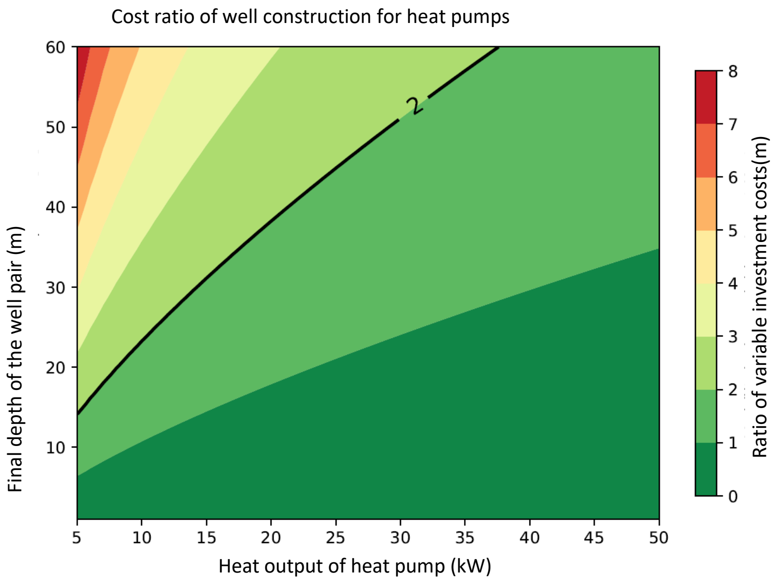


Figure 10: Development of the ratio of the variable well construction costs as a function of the final depth of the well pair to the costs of the heat pump as a function of the installed heating capacity with the defined economic limit of 2 (black contour line = well construction twice as expensive as the heat pump).

The limit of the cost factor (c_limit) in equation (8) was set at 2. This value was determined empirically in consultation with drilling companies.

It should be noted that the function given in equation (8) is the calculation of the cost factor (c_limit) is represented graphically by equation (8) for defined ranges of well depth (final depth) and heat pump heat output.

4.2.4 Results

4.2.4.1 Results at regional scale

- Design of the building model

Using the information for each building model constructed, the gross volume can be broken down, which provides a picture of the buildings identified. This analysis could also be extended to include the factor 'age of the buildings.

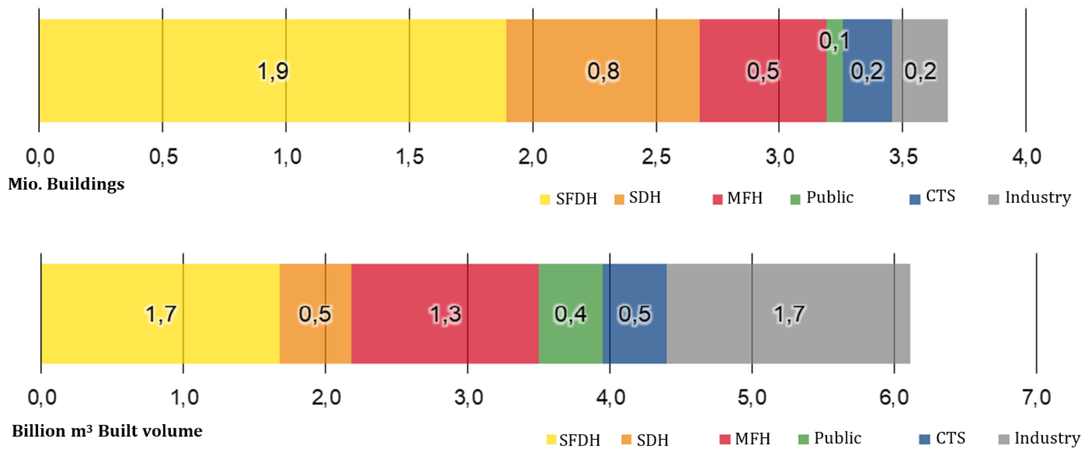


Figure 11: Example distribution of building use by number of buildings (top) and built volume (bottom) (Bavaria).

Table 22: Example of Gross volume differentiated by building function and age (Bavaria).

Mio. Buildings	1910	1933	1963	1970	1980	1982	1988	1993	1998	2002	2006	2010	2015
SFDH	91,36	63,85	598,87	311,07	44,9	137,43	35,1	67,83	71,58	37,24	27,26	7,71	184,34
SDH	29,32	28,32	200,32	23,32	2,14	56,11	18,38	27,3	30,63	18,17	13,93	4,78	47,66
MFH	236,5	61,25	442,64	201,93	23,75	74,77	19,96	47,5	32,55	15,9	12,89	4,9	144,84
Public	109,87	0	0	0	253,02	0	0	0	0	0	0	0	80,94
CTS	80,97	0	0	0	327,84	0	0	0	0	0	0	0	45,43
Industry	14,31	0	0	0	1295,29	0	0	0	0	0	0	0	404,41

Table 23: Example Number of buildings differentiated by function of the building and age of the building.

Number of buildings differentiated	1910	1933	1963	1970	1980	1982	1988	1993	1998	2002	2006	2010	2015
SFDH	105,49	77,46	671,09	336,69	45,2	147,26	39,27	76,52	83,57	45,3	33,81	9,73	221,22
SDH	42,02	43,31	316,42	32,65	2,44	87,73	29,44	42,7	49,46	30,37	23,34	8,22	76,99
MFH	90,86	26,65	169,17	81,02	12,2	29,73	8,11	18,37	13,66	6,61	4,91	1,68	51,29
Public	15,97	0	0	0	37,37	0	0	0	0	0	0	0	12,6
CTS	23,49	0	0	0	154,41	0	0	0	0	0	0	0	21,28
Industry	1,69	0	0	0	194,9	0	0	0	0	0	0	0	61,21

- Structure of the heat register

The heat registers for existing buildings and for the renovation variant should be calculated for each building stock model in the region. The results should be stored for each building in a database.

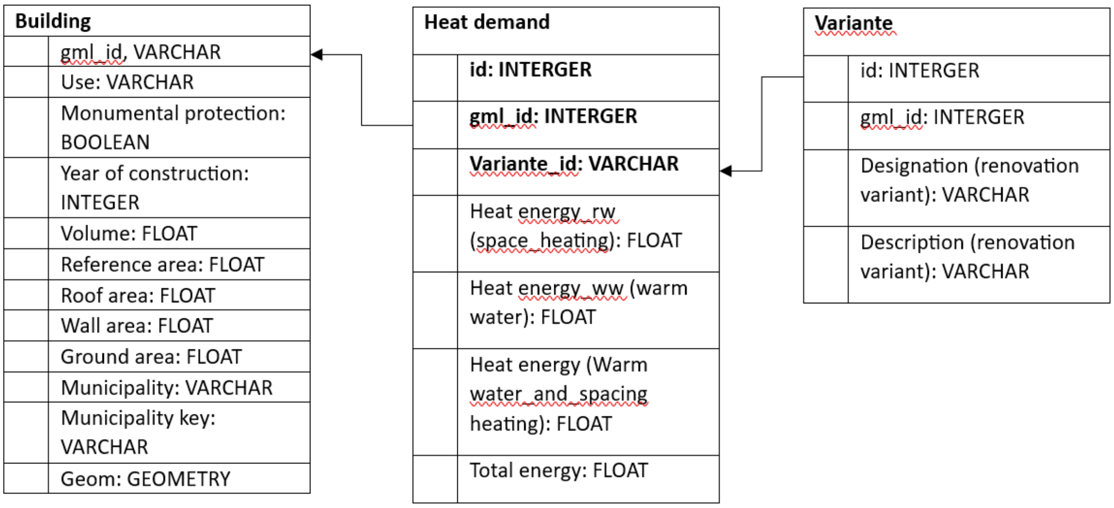


Figure 12: Example of Building-Specific Heat Record Data Model

The results of the renovation/ refurbishment and heat register are used to obtain the final energy demand and hot water demand differentiated according to the use and age of the building.

Table 24: Example values of Final Energy Demand in TWh differentiated by function and building age (Bavaria)

Final energy in TWh	1910	1933	1963	1970	1980	1982	1988	1993	1998	2002	2006	2010	2015
SFDH	4,73	3,07	29,51	12,77	1,74	5,33	1,46	2,81	2,62	1,05	0,77	0,13	3,06
SDH	1,36	1,19	7,92	0,64	0,08	2,23	0,61	0,91	0,87	0,47	0,36	0,08	0,8
MFH	10,72	3,05	19,27	7,26	0,93	2,93	0,8	1,9	1,02	0,36	0,29	0,09	2,46
Public	3,66	0	0	0	8	0	0	0	0	0	0	0	2,03
CTS	3,59	0	0	0	9,66	0	0	0	0	0	0	0	0,88

Results can be aggregated by municipality and district and presented as a prepared geodata set, as we can see in the following example.

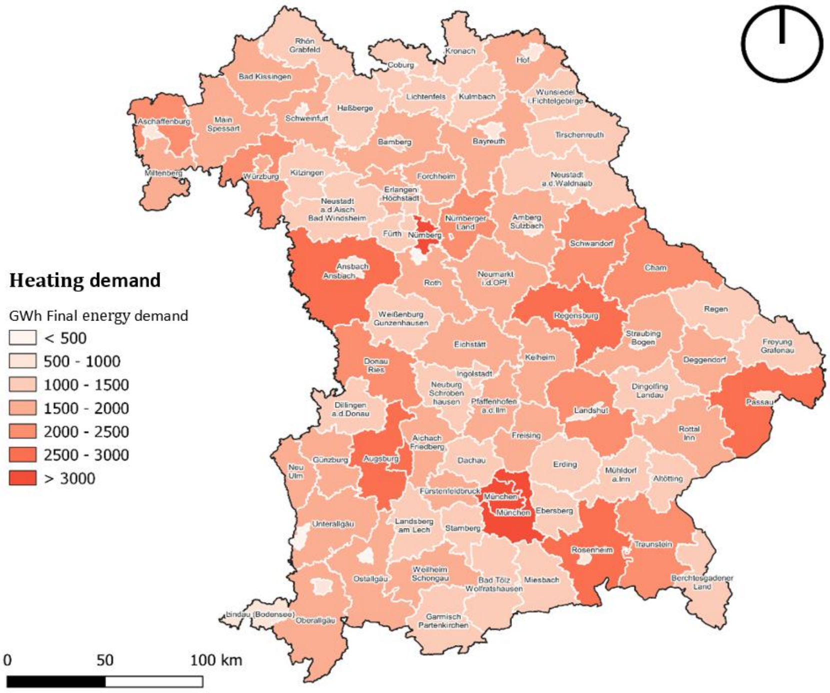


Figure 13: Example of a map with Aggregated Final Energy Demand by district in state of Bavaria.

The results of the thermal cadastre are processed into a thermal density map (Figure 14), which gives an overview of the heat demand distribution.

Figure 14: Heat density map for the state of Bavaria

- Grid calculation of realisable potential
    - Extraction capacity for GWP

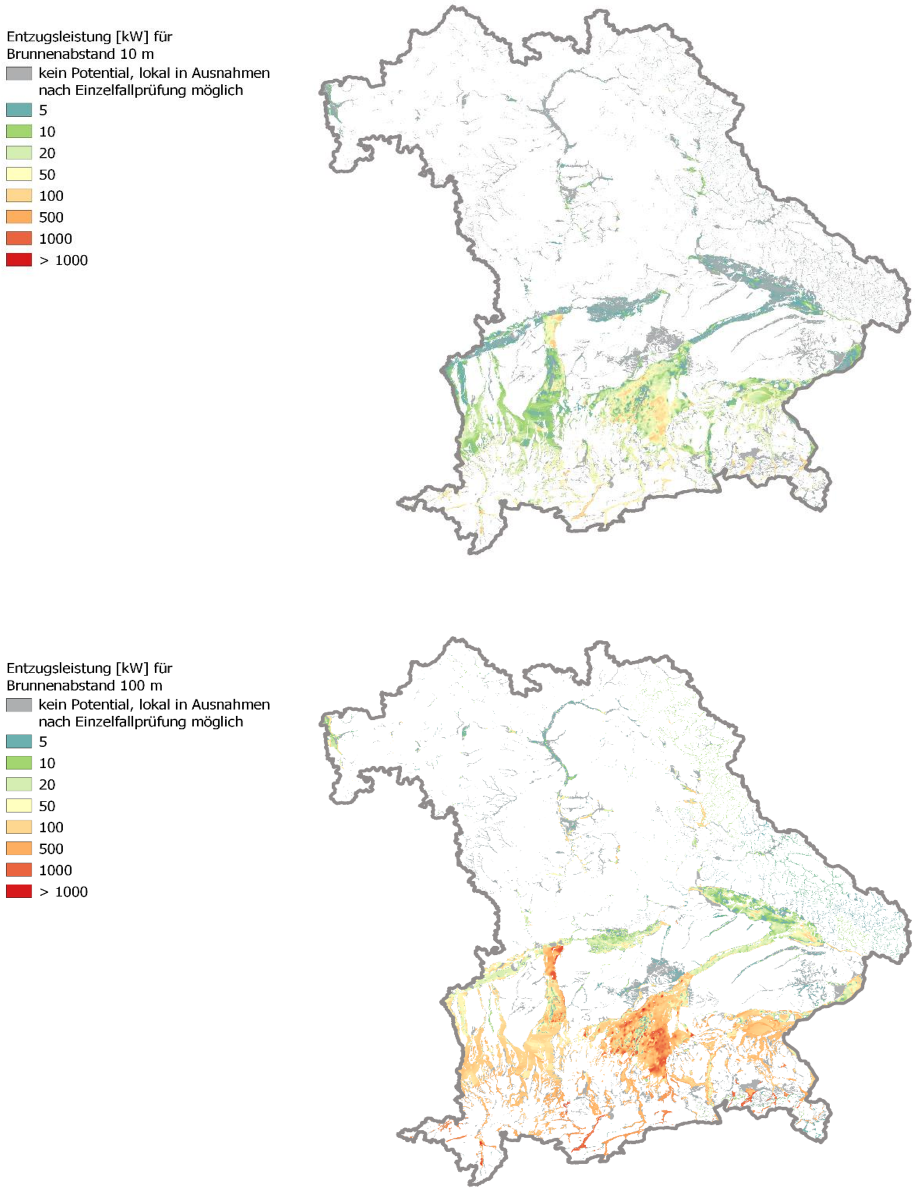
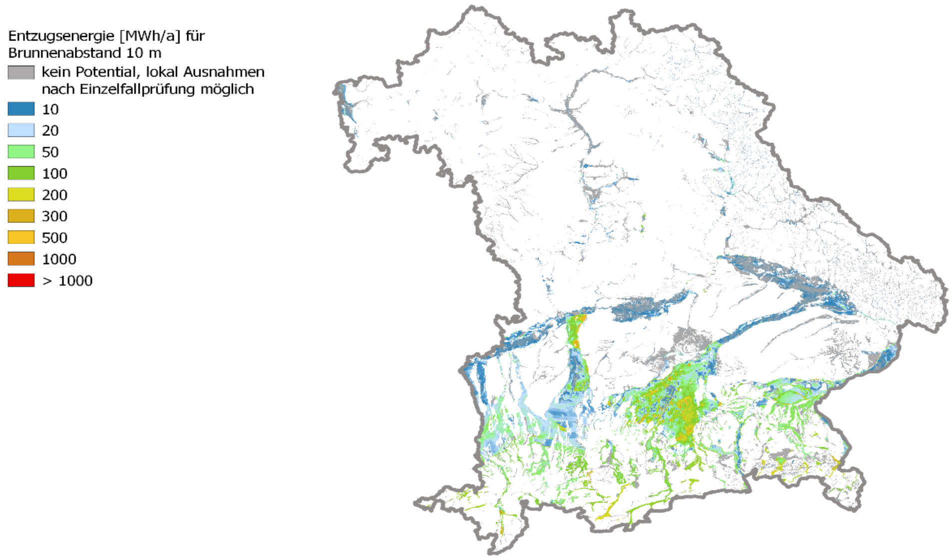


Figure 15: Extraction capacity (kW) for groundwater heat pumps. Top: Well spacing 10m, bottom: Well spacing 100m

- Extraction Energy for GWP



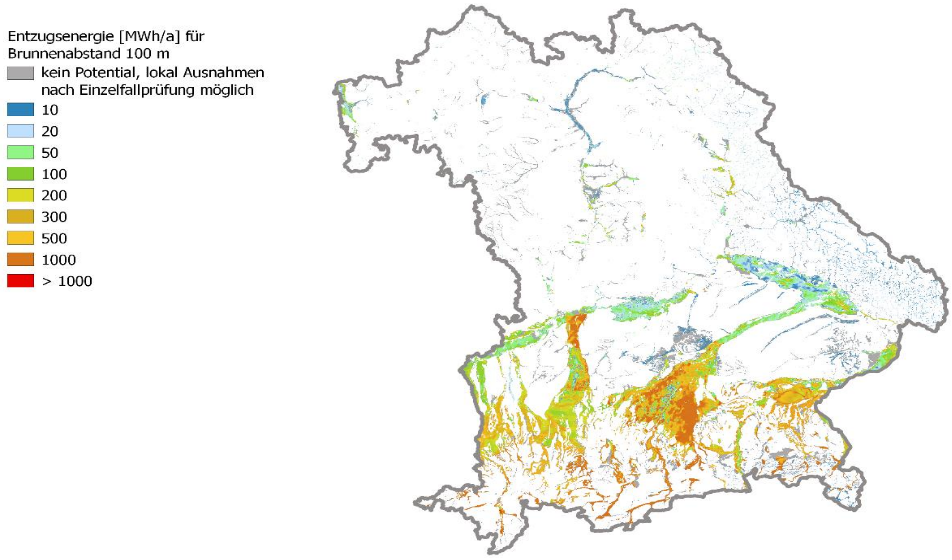
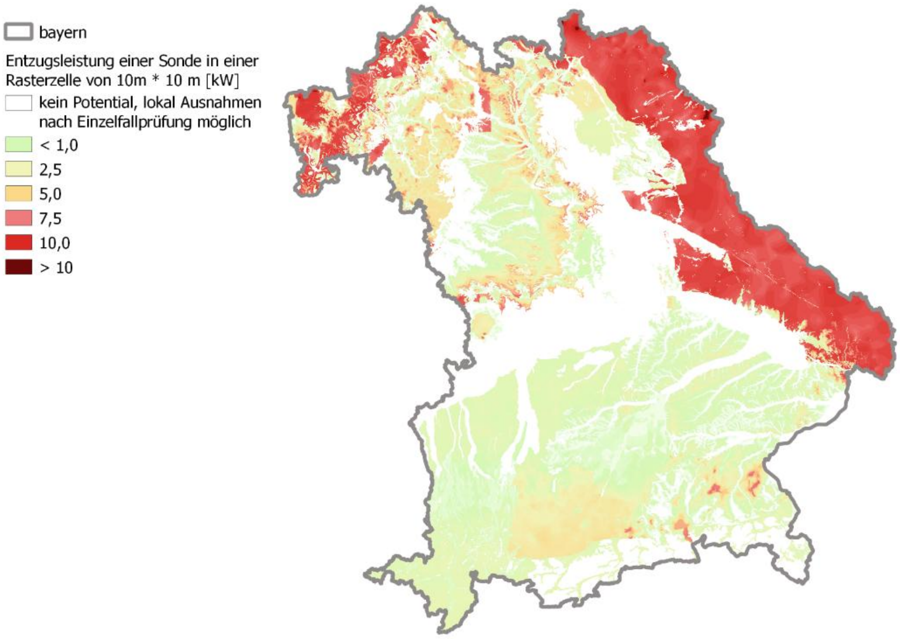


Figure 16: Bavaria-wide energy extraction (MWh/a) for groundwater heat pumps. Above: Well, spacing 10 m, below: Well, spacing 100 m.

- Extraction capacity for BHE



- Extraction capacity for GHC

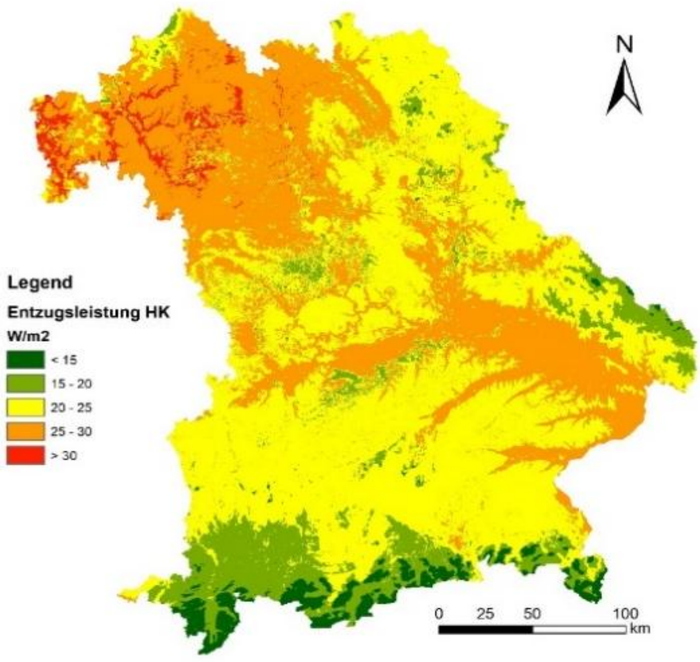


Figure 17: Calculated extraction capacity for horizontal collectors in Bavaria

- Extraction Energy for GHC

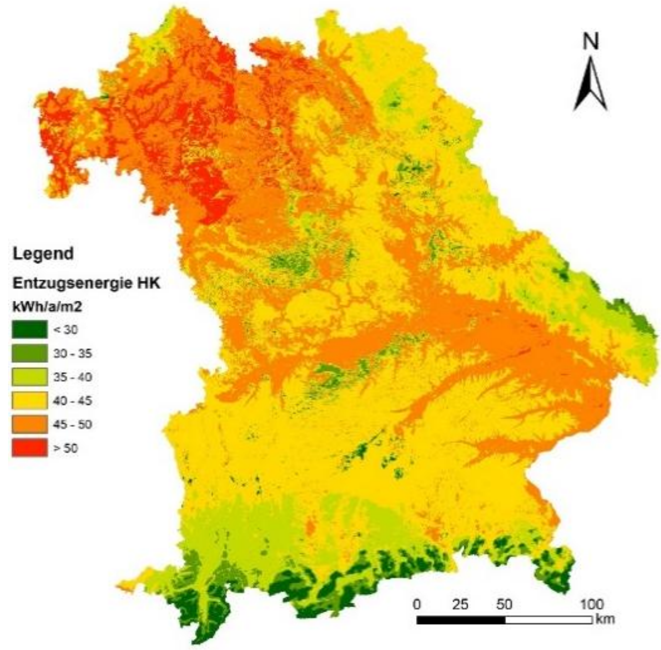


Figure 18: Calculated extraction energy for horizontal collectors in Bavaria

- Realisable potential of shallow geothermal energy

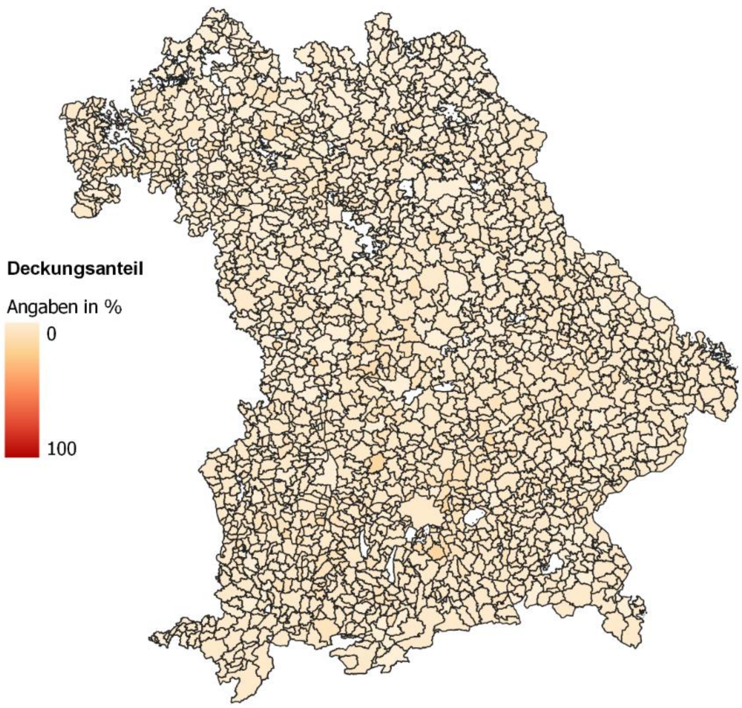


Figure 19: Bavaria-wide ONG potential per municipality with the assumptions made

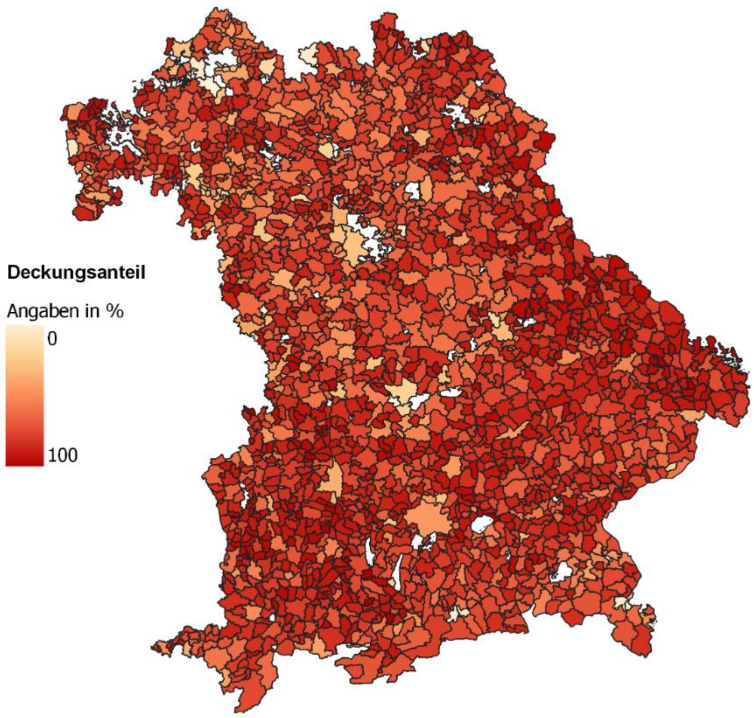


Figure 20: Bavaria-wide potential for shallow geothermal energy per municipality after energy-efficient refurbishment

4.2.4.2 Results at local scale

This section presents the results from each step of the potential analysis. The basis for calculating technically viable potential is white area mapping, which determines exclusion zones for the thermal use of groundwater. The results of the potential analysis are then provided for each parcel and building block.

- Results of White Area Mapping

As described above, the white area mapping considered relevant criteria for nature, monuments, and water protection, along with structural criteria. An overview of the spatial design of individual exclusion criteria can be seen in Figures 21, 22 and 23.

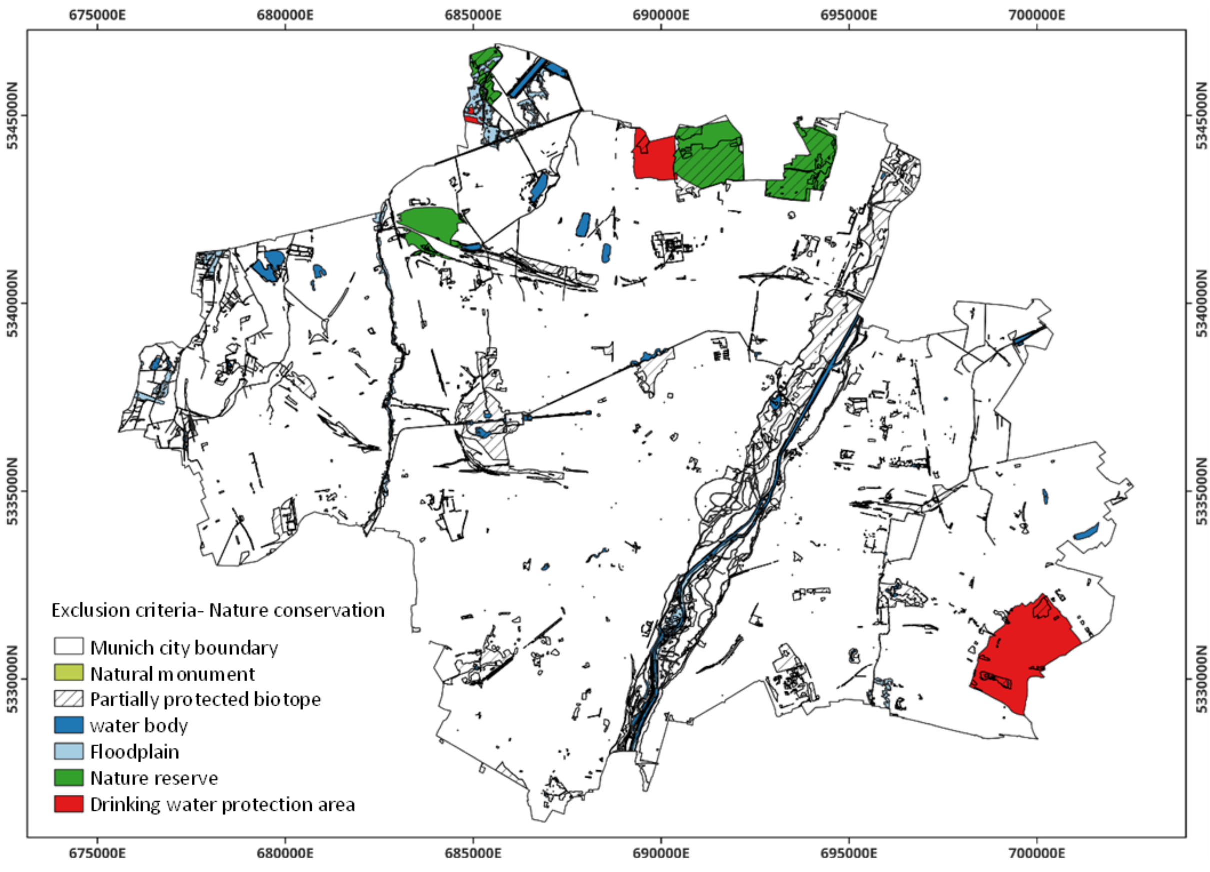


Figure 21: Exclusion areas specific for nature and water protection that are included in the white area map.

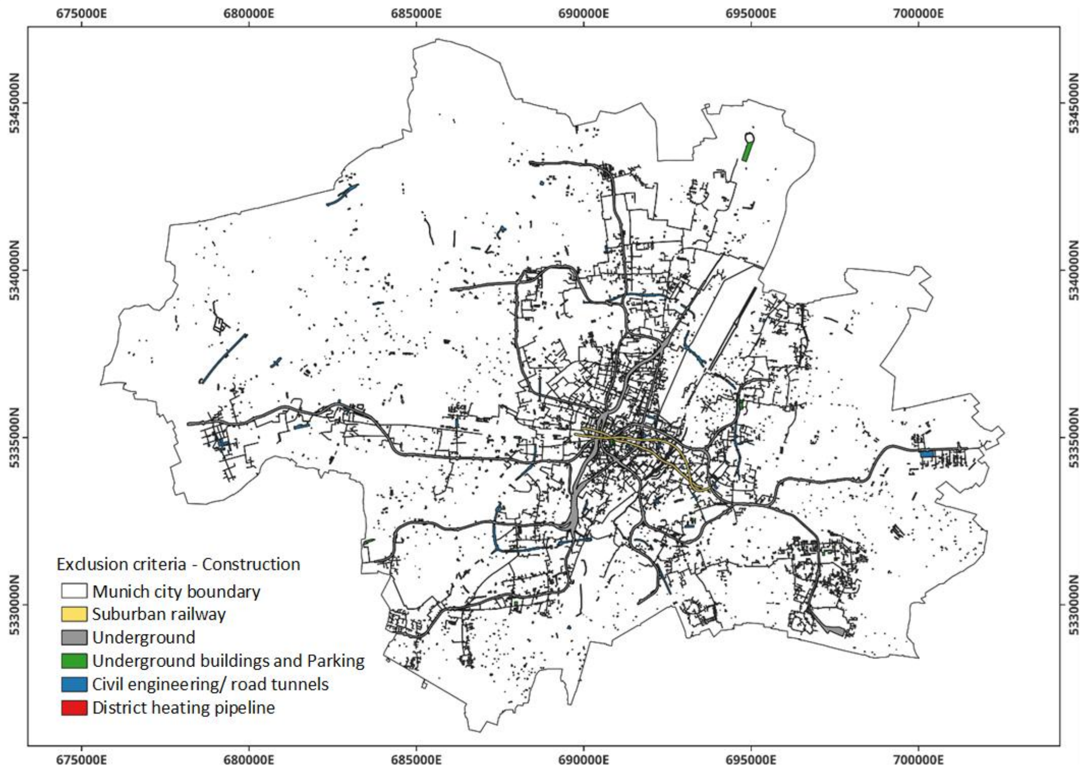


Figure 22: Exclusion areas specific for construction that are included in the white space mapping.

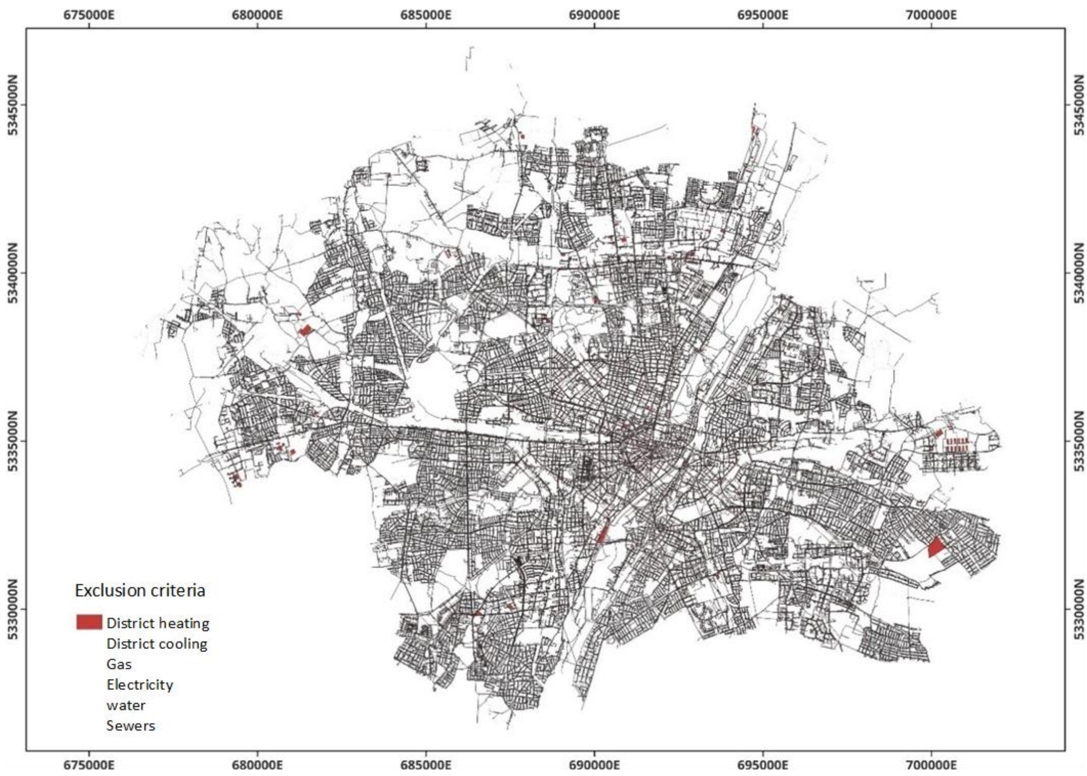


Figure 23: Exclusion zones of connections that are considered in the white zones mapping.

The white area mapping presented here represents a significant level of detail in further analysis of the technically feasible potential. With the help of high-quality urban datasets, most of the relevant criteria for identifying exclusion areas could be considered and the method could also be further developed with regard to its spatial integration.

- Results of Specific Parcel Potential Analysis

As previously mentioned, the specific potential of the plot for the thermal use of groundwater was calculated throughout the city based on the TAP method (see Böttcher et al., 2019). The result of the thermal extraction capacity, ultimately calculated using equation (6) with a typical temperature variation of 5 K, is shown in Figure 24. The blank space mapping results from the previous chapter indicate that high-potential areas are well separated from the urban heating area. Therefore, the thermal use of groundwater can be appropriately integrated into the strategic considerations of municipal heating planning in Munich and can provide a significant share of heating and cooling supply in decentralized zones.

As an approximate guide to interpret extraction benefits, the colour scheme in Figure 24 can be classified as follows. If no additional hydrogeological information is available, thermal use of groundwater should be avoided on plots with an extraction capacity below 5 kW. Areas between 5 and 25 kW can typically supply single-family homes and townhouses. Up to 100 kW can supply smaller apartment buildings, and from 100 kW, larger residential buildings. It should be noted that this provides the geogenic extraction yield of the groundwater heat source. The heating capacity of a heat pump in a building depends on the efficiency of the heat pump, which in turn depends on the temperature range between the heat source—groundwater temperature—and the heat sink, namely the heating circuit. Simplifying the assumption of an average operating point or an average efficiency of a hypothetical heat pump, the evaporator output of a heat pump can be calculated using equation (7) to estimate initial feasibility.

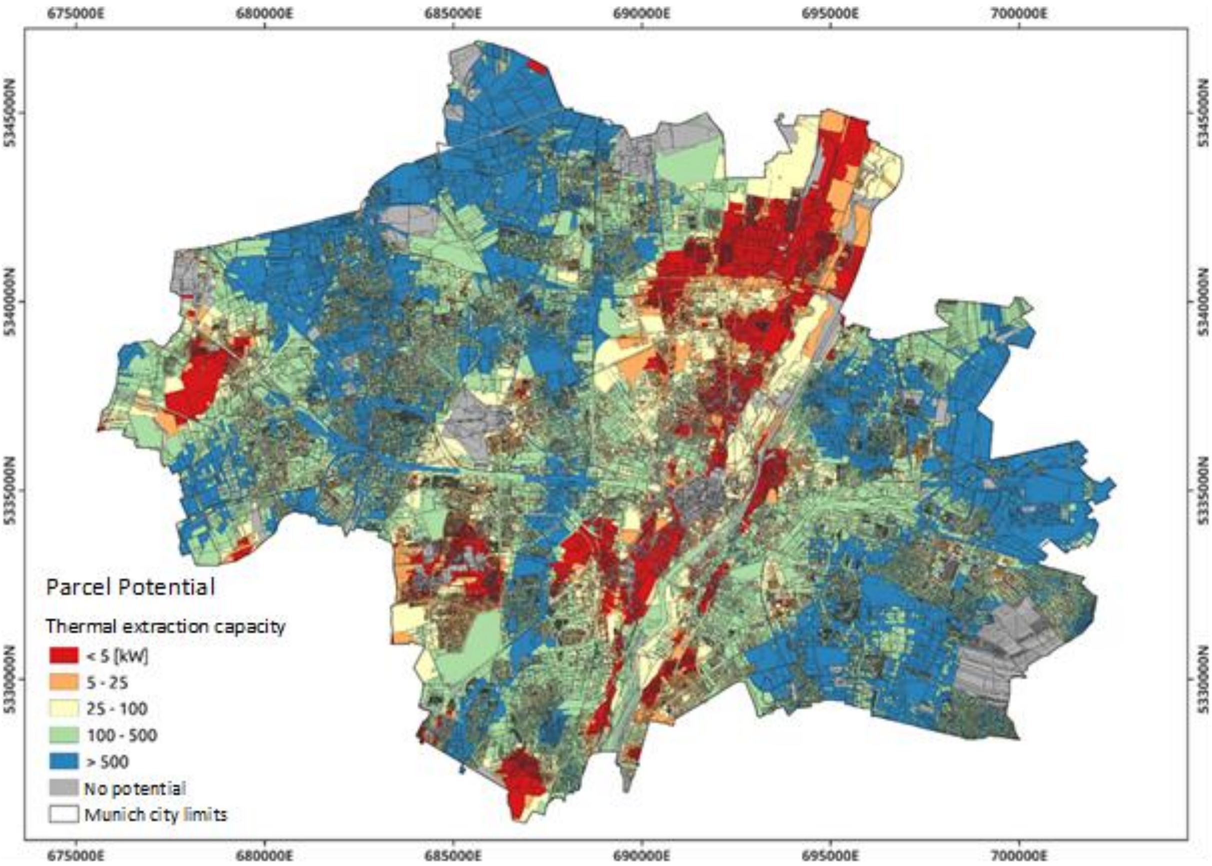


Figure 24: Result of the parcel-specific potential analysis, in which the technically realisable thermal extraction capacity on the respective parcel was calculated.

- Results of the block specific potential analysis

The block-specific analysis for the thermal use of groundwater was also conducted using the TAP method. Figure 25 illustrates the resulting thermal extraction potential across the city. This building block-specific potential serves as a solid foundation for assessing the feasibility of local heating networks powered by groundwater. In addition to decentralized groundwater heat pumps for individual use, local heating networks are an essential component of municipal heat planning and thermal transition.

In densely urbanized areas, the thermal use of groundwater can often only be achieved by connecting neighbourhoods through a local heating network, as existing developments frequently lack the space needed for thermal infrastructure, including individual extraction and absorption wells on separate plots. Like the plot-based analysis, high-potential areas within building blocks are also well separated from the urban heating area, making them ideal for complementing the urban heating expansion strategy in decentralized zones.

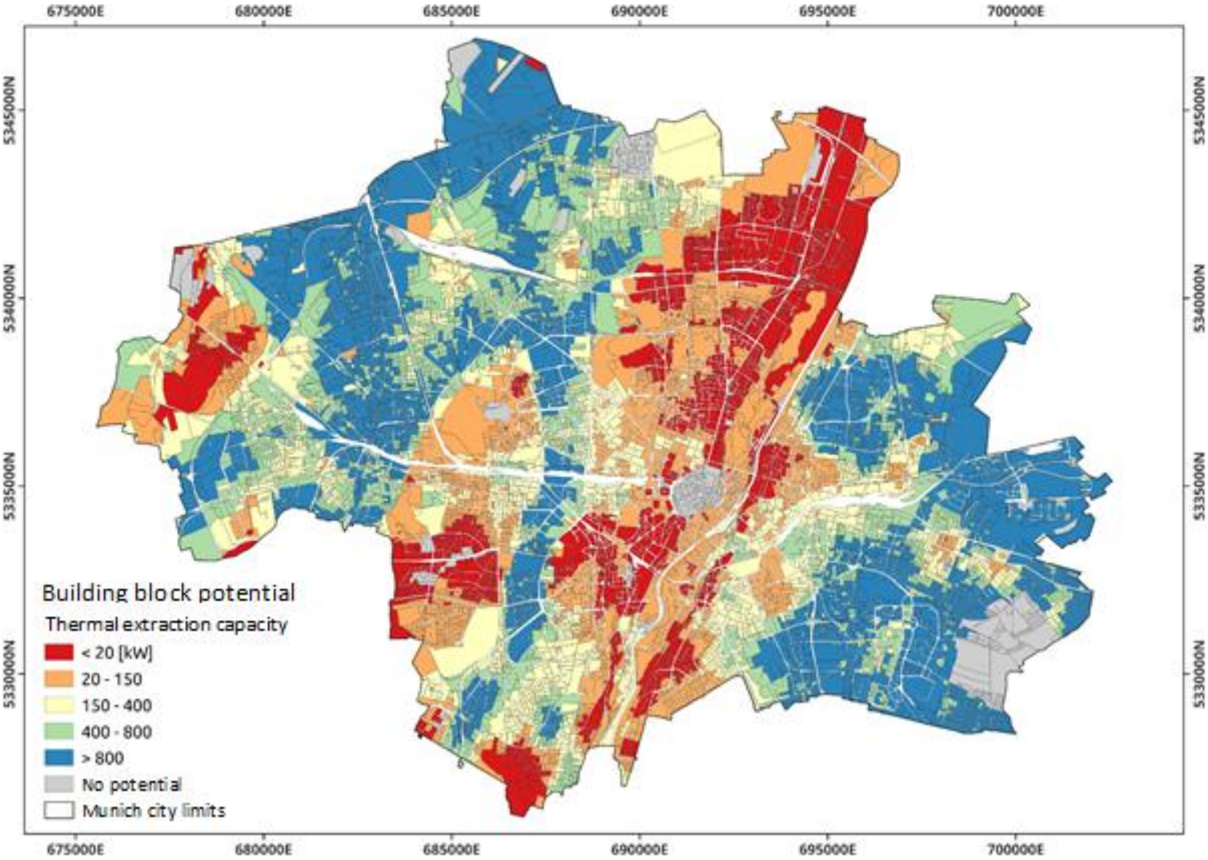


Figure 25: Result of the building block-specific potential analysis, in which the technically realisable thermal extraction capacity was calculated for the respective building block.

Final remarks

The analysis of fundamental components highlighted the potential role that groundwater-supported local heat supply can play, particularly in utilizing larger available spaces, positioned between urban heating systems and individual groundwater heat pumps. Generally, compared to individual groundwater heat pumps, the reduced number of wells required for local heat supply simplifies the task of finding open spaces for well construction. If larger areas had not been excluded through white area mapping, suitable well locations could still be identified by maintaining a 3-meter distance from existing developments.

Now that all relevant potential values have been established, the next step is to compare the available potential with the specific thermal needs of each building to assess the feasible degree of coverage for a groundwater-based thermal supply.

- Results of Potential Comparison with Existing Heat Demand

Following the calculation of technical potential by plot and building block, a comparison with the specific heating needs of each building was conducted. This comparison yields the technically feasible heating capacity that can be achieved either with groundwater heat pumps on individual plots or with a local heating network for an entire building. Both a maintenance scenario and renovation scenarios—Efficiency House (EH) 85, EH 70, and EH 55—were used as baseline criteria for this comparison. This approach allows for a comparison of the maximum expansion potential of the current state against the reductions in heat demand resulting from renovations.

The comparison also includes the economic feasibility threshold, represented as a vertical red line at a profitability index of 2. Results indicate that only a small proportion of groundwater heat pumps city-wide fall below this threshold. For most systems, the variable costs of well construction are actually lower than the heat pump unit costs, largely due to the shorter floor distances across much of the city. As the energy standard of the building is improved, heat demand and heating capacity requirements decrease, allowing for the installation of a smaller, more cost-effective heat pump. However, since well construction costs are mostly dependent on floor depth, they remain constant, increasing in relative proportion to heat pump costs.

After excluding parcel with an economic efficiency criterion greater than 2, it is possible to calculate the technically achievable degree of heat demand coverage for groundwater heat pumps on each plot. The result for the heat demand under the maintenance scenario is shown in Figure 26. Notably, there are clearly defined boundaries between coverage levels of 0–20% (red areas) and 80–100% (dark green areas).

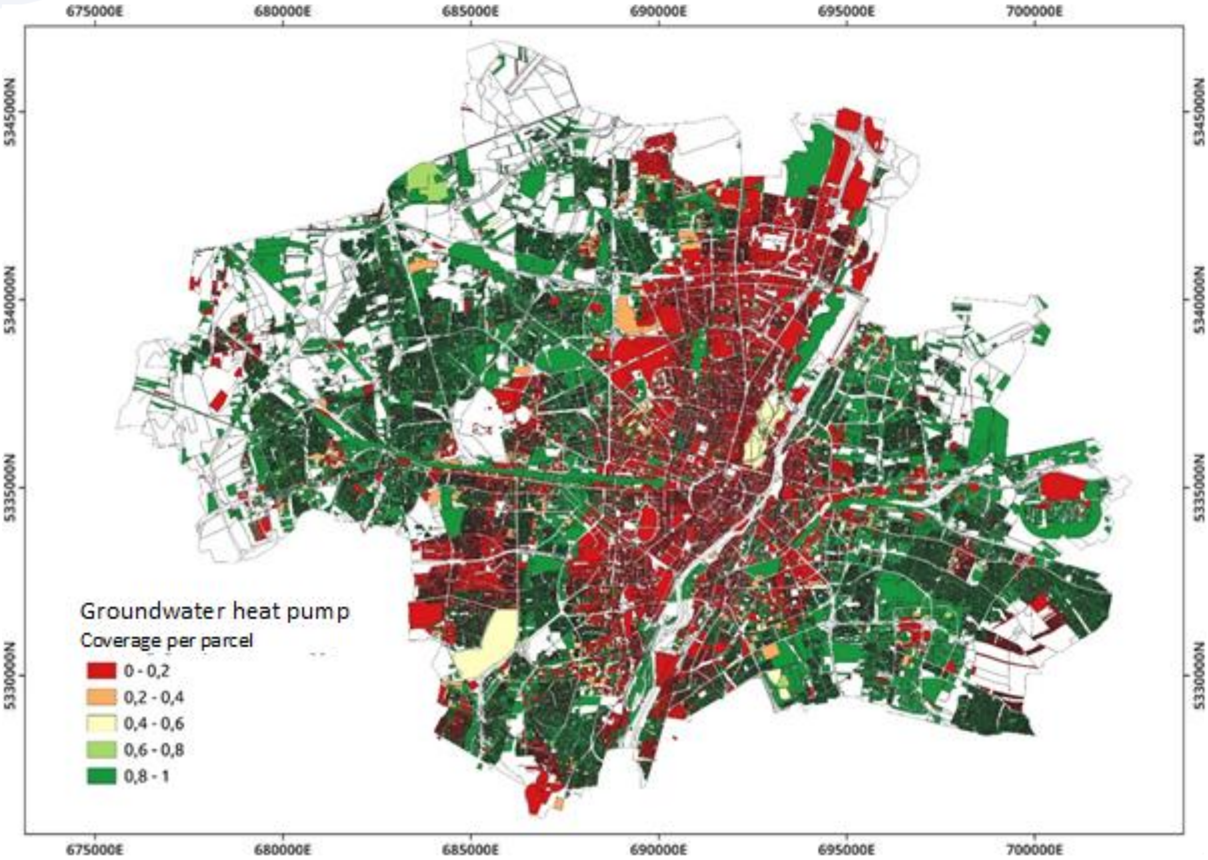


Figure 26: Coverage of the heat demand through a parcel-specific potential comparison, in which the required heating output for space heating and domestic hot water of the maintenance scenario of the individual buildings on a parcel was compared with the existing technical potential.

In addition to decentralized supply with groundwater heat pumps, the potential of local heating networks supported by groundwater was determined at the building block scale and also compared to the existing heat demand in each respective block. The result for the entire city is visualized in Figure 27. Since heating networks are particularly economical when a high connection rate is achieved, only building blocks with at least 80% coverage should be considered suitable.

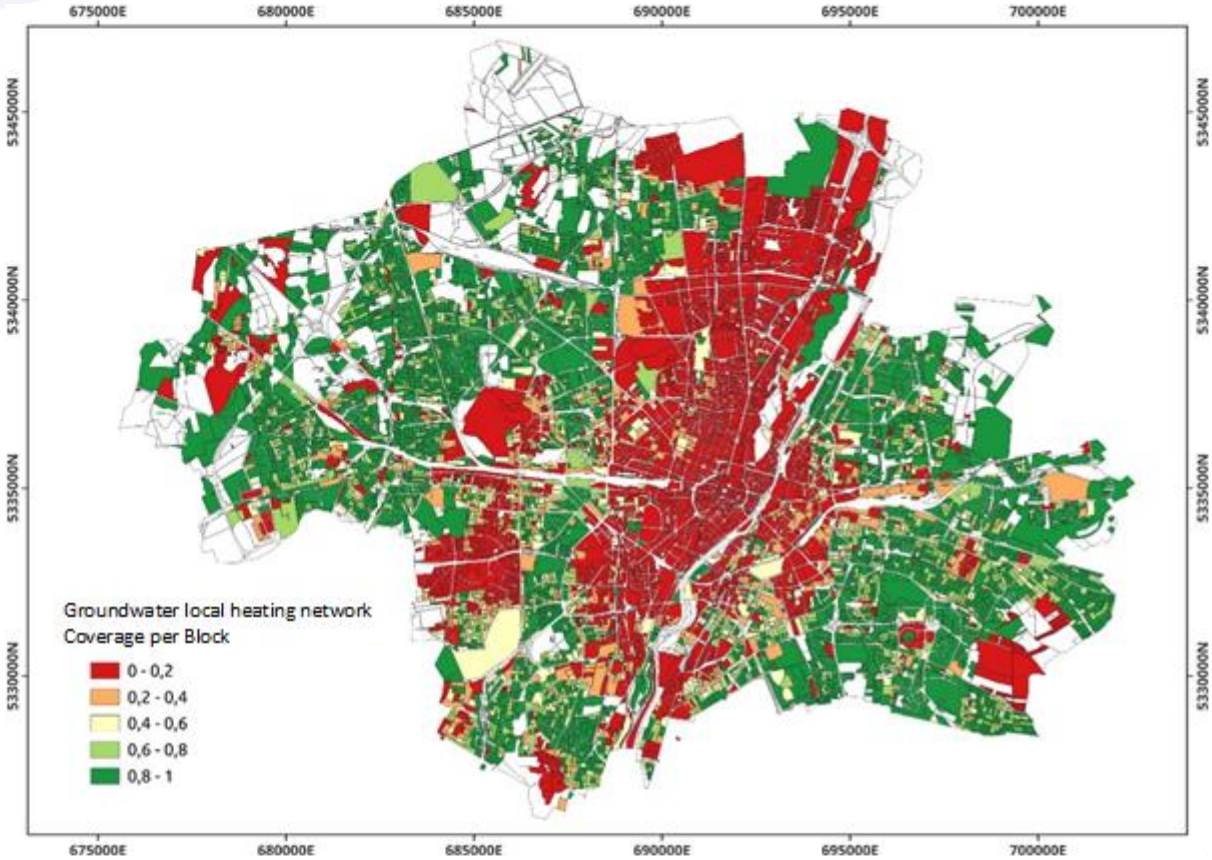


Figure 27: Coverage of the heat demand through a building block-specific potential comparison, in which the required heating output for space heating and domestic hot water of the maintenance scenario of the individual buildings on a building block was compared with the available technical potential.

When evaluating city-wide results, it can be stated that, regardless of the extraction system, almost 40% of the heat demand could be met through the thermal use of groundwater. In addition to the maintenance scenario, a potential comparison was also conducted using city-wide renovation scenarios based on EH 85, EH 70, and EH 55 standards. Figure 28 shows the proportion of heat demand that can be supplied by the two extraction systems across the different scenarios. For both extraction systems, it can be observed that the supply proportion increases with renovations, from approximately 38% to around 45%. In the renovation scenarios, heat demand decreases, meaning that the existing potential for buildings with improved energy standards is increasingly sufficient for supply.

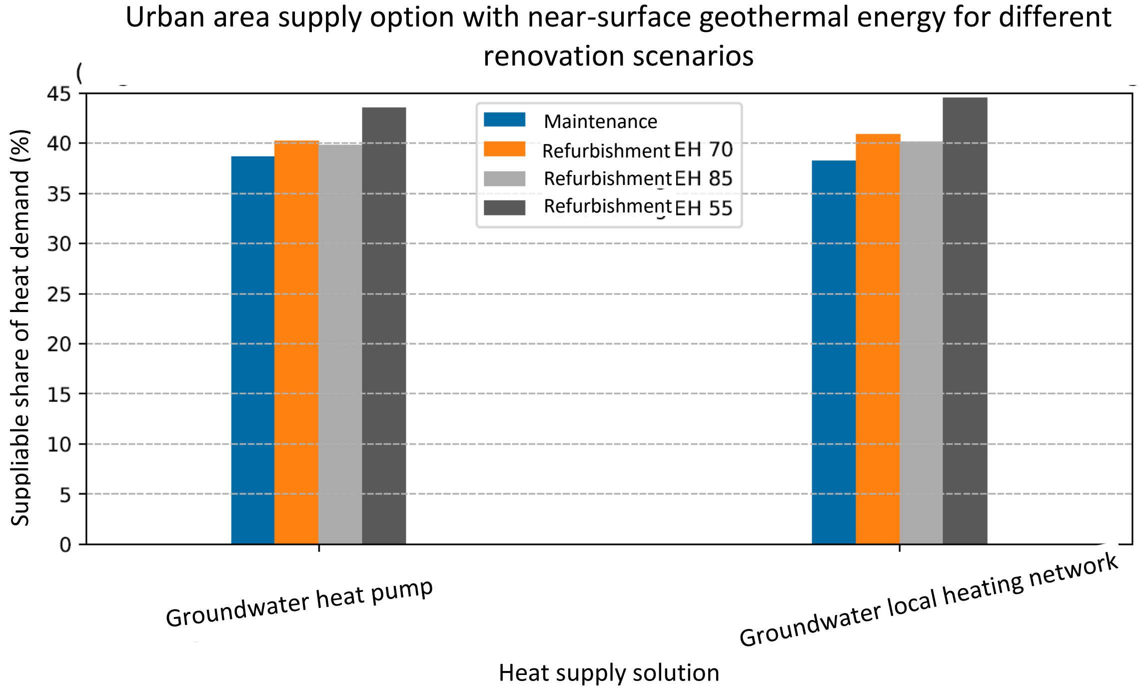


Figure 28: Bar chart on the city-wide share of the technically suppliable heat demand per heat supply solution and refurbishment scenario without optimisation of the spatial expansion (no neighbourhood view).

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6. Appendixes

3.2.2.1 Methods at Regional Level

3.2.2.1.1 Heating Demand Methods

- Energy Balance Method

This method evaluates heating demand by balancing heat gains and heat losses across a region. Heat losses are calculated using building-specific factors, including thermal envelope performance and ventilation losses, as well as environmental characteristics. Heat gains, on the other hand, account for contributions from internal sources such as solar radiation, human occupancy, and the use of electrical equipment. Eurostat (2023) highlights the applicability of this method for regional-level estimations, as it incorporates dynamic factors like seasonal variations in solar gains and temperature fluctuations. By integrating these variables, planners can identify periods of peak demand and assess the overall heating load distribution, enabling targeted policy and infrastructure planning.

- GIS (Geographic Information Systems)-Based Modelling

GIS-based approaches integrate spatial datasets with energy modelling to provide detailed heating demand analyses. These models utilize geospatial data, such as building footprints, land use patterns, and population density, to create demand heatmaps. Schwanebeck et al. (2021) emphasize that GIS-based methods are instrumental in visualising energy hotspots within a region, thereby aiding the prioritization of retrofitting initiatives or new infrastructure development. Furthermore, Gils (2012) demonstrates how GIS tools enable scenario analysis, allowing planners to simulate the impact of urbanization or energy efficiency measures on heating demand across varying spatial scales.

- Statistical Analysis of Consumption Data

This method relies on historical energy consumption data, sourced from utility bills, smart sensors, or targeted measurements, to predict future heating needs. By combining consumption patterns with variables such as temperature, humidity, building characteristics, and socio-economic data, time-series analysis reveals seasonal trends and potential responses to extreme weather events. According to Schüler et al. (2015), such analyses are pivotal for understanding regional energy behaviour, as they uncover underlying drivers of demand variability. Moreover, this approach facilitates the design of adaptive policies by projecting how socio-economic shifts, such as urban expansion or demographic changes, might influence future heating requirements.

3.2.2.1.2 Cooling Demand Methods

- Cooling Degree Days (CDD) Calculation

CDD calculations quantify cooling requirements by measuring the deviation of daily temperatures above a predefined baseline, commonly 18°C. Scoccimarro et al. (2023) underline the simplicity and reliability of this method for estimating regional cooling loads, particularly in scenarios influenced by climate change. By tracking CDD trends, planners can anticipate the evolution of cooling needs and design infrastructure capable of addressing future demands. Additionally, the method aids in evaluating the potential of alternative cooling technologies, such as geothermal systems, by providing baseline data for comparative analyses.

- Building Energy Simulation Models

Simulation models assess cooling demand by replicating the thermal behaviour of buildings or clusters of buildings under varying conditions. Factors such as architectural design, insulation levels, internal heat gains, and localized climate parameters are incorporated to provide a nuanced understanding of cooling requirements. Werner (2016) demonstrates that these models are invaluable for evaluating the efficacy of energy-efficient measures, such as advanced insulation materials or natural ventilation strategies, before their implementation. Furthermore, simulation outcomes support the optimisation of building designs to minimize energy consumption while maintaining thermal comfort.

- GIS (Geographic Information Systems)-Based Modelling

Similar to heating demand assessments, GIS-based methods for cooling demand integrate spatial data with energy demand models to estimate cooling requirements across regions. Lai et al. (2024) highlights the capability of GIS models to capture the influence of urban heat islands, land use patterns, and socio-economic variables on cooling needs. These models facilitate the identification of areas prone to heat stress, enabling targeted interventions such as increasing green spaces or implementing reflective building materials. By integrating such spatial insights, planners can develop localized cooling strategies that address both immediate and long-term urban challenges.

3.2.2.2 Methods at Local Level

3.2.2.2.1 Heating Demand Methods

- Building Energy Simulation Models

These models simulate the heating demand of individual buildings or groups of buildings by considering factors like building design, insulation, occupancy, internal heat gains, and local climate. Building energy simulation models are particularly useful in scenarios requiring precise estimates of energy consumption patterns at the local level. According to Dochev et al. (2020), these models are instrumental in assessing the efficiency of retrofitting strategies and improving the thermal performance of buildings, enabling better-informed decisions for energy planning in local contexts.

- Top-Down Methods

Top-down methods utilize aggregate data, such as total residential sector energy consumption, and macroeconomic indicators like GDP, employment rates, and price indices. They also incorporate climatic conditions, housing construction/demolition rates, and estimates of appliance ownership to attribute energy consumption characteristics to the entire housing sector. As Swan & Ugursal (2009) highlighted, these methods are beneficial in creating a holistic understanding of energy consumption trends, especially for policymakers aiming to address energy efficiency in broader urban planning initiatives. Möller (2015) further emphasized their relevance in identifying sector-wide trends, while Frayssinet et al. (2018) demonstrated their applicability in comparative studies of regional heating systems.

- Bottom-Up Methods

Bottom-up models calculate the energy consumption of individuals or groups of houses and then extrapolate these results to represent the region based on the representative weight of the modeled sample. Swan & Ugursal (2009) identified these methods as essential for capturing detailed consumption patterns, particularly useful for designing localized interventions. Möller (2015) complemented this by discussing their role in integrating diverse building typologies, and Frayssinet et al. (2018) showcased their effectiveness in fine-tuning predictive models based on real-world scenarios.

3.2.2.2.2 Cooling Demand Methods

- Cooling Degree Days (CDD) Calculation

As with heating degree days, the cooling degree day calculation measures the number of degrees where the average daily temperature exceeds a pre-defined threshold, usually 18°C. CDDs are used to estimate the cooling demand during the summer, facilitating the planning of necessary infrastructure. Sivak (2009) underscored the importance of CDDs in understanding the growing cooling demand due to rising global temperatures. By providing a straightforward metric, they allow planners to anticipate the scale of cooling requirements and evaluate the potential impact of adopting geothermal cooling technologies.

- Top-Down Methods

Similar to their application in heating demand analysis, top-down methods for cooling demand rely on macro-level data to attribute energy consumption to the entire residential sector. Swan & Ugursal (2009) and Möller (2015) noted that these methods are particularly effective in understanding overarching trends in cooling demand, such as the influence of urbanization and climate change on the adoption of cooling technologies. Frayssinet et al. (2018) further emphasized their role in assessing the economic feasibility of large-scale cooling interventions.

- Bottom-Up Methods

Bottom-up methods calculate the energy consumption of individuals or groups of houses and extrapolate these results to represent the region. These methods are valuable for identifying specific local needs and tailoring solutions to meet those needs effectively. Swan & Ugursal (2009) provided a comprehensive framework for their implementation, while Möller (2015) highlighted their ability to incorporate diverse building characteristics. Frayssinet et al. (2018) demonstrated their application in urban microclimates, illustrating their importance in designing adaptive cooling systems that respond to localized environmental factors.

7. Appendixes

3.5.2.1 Framework regarding Shallow Geothermal Systems at regional level

- Key Criteria for the Regional Framework
    - Political Priorities

    The regional analysis should be in line with the climate and energy policies of each territory. This includes targets for the reduction of greenhouse gas emissions, such as those defined in national and international climate plans, such as the National Energy and Climate Plans (NECPs) (UNEP, 2019). Region-specific strategies for sustainable development should also be considered, assessing how the integration of geothermal heat pump systems can accelerate the energy transition.

    - Technical Potential:

    Technical analysis focuses on determining the long-term viability of geothermal resources.

        - Identification of geologically favourable zones: Geothermal maps that assess variables such as thermal gradient, soil conductivity and hydrogeological characteristics are used. These zones offer higher energy efficiencies (Baring-Gould et al., 2004).

- Compatibility with existing infrastructure: Assessment of the ability to integrate geothermal heat pumps (GHPs) in regions with district heating networks, to increase efficiency and reduce fossil fuel use is assessed (Bayer et al., 2019)

- Sustainability of the resource: Analysis of the thermal recovery rate from the subsurface to ensure that heat extraction does not compromise the natural regeneration capacity (García-Gil et al., 2015).

○ Energy Demand

Assessment of how geothermal systems can complement other renewable sources, ensuring a balanced and resilient energy supply. Regional energy demand analysis helps to identify priority areas where geothermal systems can meet significant energy deficits. This is particularly relevant in densely populated urban regions or rural areas with limited energy infrastructure (REN21, 2021).

○ Economic Feasibility

The economic feasibility of geothermal projects is analysed by considering initial development costs, long-term economic benefits and access to financial incentives. At this stage, it is recommended to collect data on government subsidies, low-interest loans and local energy prices. This data helps to design business models that are sustainable and attractive to investors, strengthening the economic case for the adoption of these technologies (Robins et al., 2021).

○ Development of the Regulatory Framework

- Coherent and Standardized Regulations: establish common regulations that provide a clear and consistent approach to the deployment of GHPs across the region. These regulations must ensure that GHP systems meet high standards of safety, performance, and environmental compatibility (European Commission, 2020).
- Consistency with National and European Legislation: The regulatory framework for GHPs must align with both national and European legislative frameworks to ensure consistency and legal compliance. Specifically, it should be consistent with the Renewable Energy Directive (RED II) and the European Green Deal, which set out the EU's ambitious energy and climate goals (European Commission, 2019).
- Simplification and Digitization of Licensing Processes: Prioritize the simplification and digitization of the licensing processes for shallow

geothermal systems installations, remove administrative hurdles and speed up approval times (Euroheat & Power, 2021).

3.5.2.2 Framework regarding Shallow Geothermal Systems at local level

- Key Criteria for the Local Framework
  - Urban Constraints

    The integration of geothermal systems in urban areas should be aligned with urban planning and existing infrastructure, such as residential, commercial and industrial buildings. This analysis should include land use restrictions, compatibility with urban renewal projects and the capacity of heating or cooling networks to incorporate new technologies (Geothermal Energy Association, 2021).

  - Economic Feasibility

    Initial development costs and opportunities for expansion of district heating networks need to be weighed against the long-term economic benefits. This includes

    - Cost-benefit comparison: assessing the economic impact of geothermal projects compared to alternatives such as natural gas.
    - Community financing initiatives: projects can be financed through crowdfunding schemes, which encourages citizen participation.
    - Return on investment: Geothermal systems, although initially high cost, offer significant savings on energy bills and lower maintenance in the long term.

The implementation of financial incentive schemes tailored to local needs can be a decisive factor in the success of projects.

  - Local Regulations and Licensing

    Local regulations are determinant in the implementation of geothermal systems, as local policies ensure the incentive to use renewable technologies. The review of licensing processes, land use permits, and environmental impact assessments allows identifying possible barriers and proposing administrative simplification measures (European Commission, 2019).

  - Community Participation

Public consultations, surveys and educational workshops should be carried out to involve local communities from the early stages of the project, as well as creating communication channels for communities to express concerns or suggestions. These activities help to build trust and ensure that the benefits of geothermal systems are understood and valued by all stakeholders (Hildebrand, et al., 2022).

- Joint Planning with Local Stakeholders

Active collaboration with local governments, landowners, universities, research centres, developers and communities enable the design of projects tailored to the specific needs and characteristics of the area. This approach ensures that solutions are sustainable and aligned with local priorities, fostering cooperation and reducing potential conflicts (Haf & Robison, 2020).

8. Appendixes

3.6.2.1 Framework and procedure regarding shallow geothermal systems at regional level

- Financial Incentives and Support Policies:
    - Subsidies and regional financing: Develop subsidy or tax incentive programmes that promote the installation of renewable energy systems, GHPs, especially in areas where upfront cost is a barrier (Dumas & Angelino, 2015).
    - Public-private financing schemes: Encourage private investment through public-private partnerships, offering innovative financing mechanisms that facilitate access to geothermal technologies (Polzin et al., 2019).
- Integrated Regional Planning and Design
    - Interaction with existing infrastructure: Ensure that Shallow geothermal energy systems, GHP systems, are properly integrated with other energy and water resources infrastructure, especially in urban and suburban areas, by providing guidelines on the design and planning of shallow geothermal energy systems, GHP systems (Akhmetzyanov et al., 2021).

- Coordination between regional departments: Facilitate cooperation between different government agencies and regional authorities responsible for urban development, environment and energy to ensure coordinated project implementation (Dumas & Angelino, 2015).

- Education and Training
    - Technical training programmes: Provide specialised training to installers, engineers and technicians at regional level to ensure the correct installation and maintenance of geothermal heat pump systems (European Geothermal Energy Council, 2023).
    - Public awareness campaigns: Inform citizens about the benefits of geothermal heat pump systems, promoting their adoption in local residences, businesses and industries (Global Geothermal Alliance, 2023).

- Supportive Policies:

Implementation of new regulations detailed technical guidelines and simplified administrative processes that reduce barriers for developers, as well as fiscal incentives for developers and end-users to adopt geothermal technologies. It is also important to promote awareness campaigns to increase social acceptance and minimise potential conflicts related to land use or environmental concerns (European Commission, 2020).

- Evaluation Framework

Evaluation framework will focus on key performance indicators that offer comprehensive insights into the effectiveness and impact of GHP systems over time. The following example parameters should be assessed regularly:

- Installed Capacity: Track the total capacity of GHPs installed across the region, considering the growth in both residential and commercial installations. This data will help gauge the scale of adoption and identify regions or sectors with significant potential for further deployment (Lund and Boyd, 2015).
- Emission Reductions: Measure the reduction in greenhouse gas emissions resulting from the shift to GHPs compared to conventional heating and cooling systems. This includes direct carbon savings as well as broader environmental benefits, such as reduced air pollution and contributions to climate change mitigation goals (Lund & Toth, 2019).

- Energy Savings: Quantify the energy savings realized through the use of GHPs. This involves comparing the energy consumption of GHP systems with that of traditional heating and cooling systems, with particular attention to the reduction in fossil fuel usage (Bojic et al., 2017).

- Energy Supplied: Assess the amount of energy supplied by GHP systems to end-users, including both heating and cooling energy. This metric helps evaluate the operational effectiveness of GHPs in fulfilling regional energy demands, particularly in areas with varying climate conditions and energy needs (Reynders et al., 2013).

- Systems Replaced: Analyse the number of older, less efficient heating and cooling systems that have been replaced by GHPs. This is essential for understanding the degree of modernization in energy infrastructure and the potential for further market penetration (Giordano & Nardo, 2020).

- Systems Installed: Track the total number of new GHP systems installed, broken down by type, size, and application. This will provide insights into the trends in GHP adoption, the sectors that are leading the way, and the level of interest across different market segments. (He et al, (2018).

- Socio-Economic Impacts: Evaluate the broader socio-economic effects of GHP adoption, including job creation, local economic development, energy cost savings for consumers, and improved energy security. This component of the evaluation will also examine how the increased use of GHPs supports regional economic policies and contributes to social equity by making clean energy more accessible (Bertoldi et al., 2016).

3.6.2.1 Framework and procedure regarding shallow geothermal systems at regional level

- Simplified Licensing Procedures (Kłonowski et al., 2020)
    - Quality and Safety Standards: Establish local guidelines that ensure the quality and safety of geothermal installations, as minimum technical requirements for installation and maintenance of systems. Additionally, implementing a database of installed systems, capturing key parameters such as energy use and system characteristics, could aid in monitoring, ensuring compliance, and streamlining the licensing process.

    - Regulatory Flexibility: Adapt existing regulations to suit local conditions, allowing municipalities the ability to adjust installation and maintenance standards according to their needs.

- Planning and Design of Projects at the Local Level (Trier et al., 2018)

    - Community pilot projects: Implement pilot projects in key urban or rural areas to demonstrate the feasibility of GHPs and generate valuable data for future expansion.

    - Integration with existing infrastructure: Ensure that GHP systems fit into the local energy infrastructure, maximising their efficiency and avoiding problems with other utilities.

- Citizen Participation and Community Management (Teladia & van der Windt, 2024).

    - Community involvement in planning: Conduct public consultations and community participation workshops to integrate residents' views and needs into project planning.

    - Local management of systems: Encourage the creation of local cooperatives or associations responsible for the management, operation and maintenance of GHPs.

- Incentives and Local Financing (Borge-Diez et al., 2015)

    - Financial incentives for small installations: Implement financial incentive schemes at municipal or local level for homeowners and businesses wishing to install GHP systems, such as tax rebates or access to preferential financing.

    - Community support programmes: Provide funding for community projects that promote the use of GHPs in public buildings, schools or community centres.

- Monitoring and Evaluation at Local Level (IDAE, 2008)

    - Local Monitoring and Evaluation: Conduct periodic assessments to measure the environmental, social and economic impacts of shallow geothermal installations. Assess the contribution of these systems to broader sustainability goals, such as greenhouse gas reduction and energy security.

    - Regulatory Compliance: Control the adaptive regulatory frameworks to ensure continued compliance with local and national regulations.

- Flexible Adaptation Strategies: Carryout assessing protocols for adjustments in the design, financing and operation of geothermal systems. Incorporate feedback loops that involve stakeholders, such as municipalities, energy providers and the community, to refine and improve system performance.

- Fostering Collaboration: Evaluate partnerships between municipalities to share monitoring data, lessons learned and best practices. Also encourage joint training and capacity building initiatives, enabling local governments to address challenges more effectively.

- Stakeholder Engagement: Actively involve stakeholders, including local governments, developers and community members, in the M&E process. Use participatory approaches to ensure transparency, inclusiveness and shared ownership of results.

- Integration with Financial Mechanisms: Link monitoring results with financial incentives to encourage compliance and performance improvements. Use insights from evaluations to design funding programmes that reward innovation and efficiency.

9. Appendixes

3.7.2.1 Framework and Procedure regarding Shallow Geothermal Systems at regional level

Procedure

- Definition of Monitoring Objectives and Scope

The establishment of monitoring objectives for renewable systems should not only ensure that the systems operate efficiently but also consider their effective integration into regional energy plans. This involves ensuring that shallow geothermal systems (GHPs) meet regional sustainability requirements, energy regulations, and environmental expectations, while evaluating the effectiveness of the regional regulatory framework and financial incentives that support their adoption (Tsagarakis et al., 2020; Bloemendal et al., 2018). The monitoring should address how these systems contribute to meeting the energy transition goals at the regional level, considering incentive policies and adaptation to energy transition plans.

- Monitoring System Implementation

The implementation of an effective monitoring system should allow for the evaluation of both the technical performance of shallow geothermal systems and the effectiveness of regional regulatory policies and strategies. This includes data collection and management through centralized databases, the use of predictive analytics, and IoT technologies to optimize performance and ensure rapid responses to potential operational issues. Additionally, it should include the monitoring of the implementation of financial incentives at the regional level, such as subsidies or tax incentives, to facilitate the adoption of GHPs (Julli et al., 2023; Cheddadi et al., 2020). The monitoring should also assess how these systems are being integrated into regional energy development plans and sustainable infrastructure planning.

- Continuous Assessment Process

The continuous assessment process should include not only monitoring the technical performance of GHP systems but also evaluating their alignment with regional regulations and energy policies, ensuring that the systems contribute to regional energy transition goals. This involves the periodic review of key performance indicators (KPIs), such as energy efficiency, grid impact, and CO2 emission reductions, comparing them to the limits established by energy plans. Moreover, it should include the evaluation of the effectiveness of financial incentives and regulatory policies to ensure GHPs are adopted efficiently and effectively. The monitoring results should be communicated through regular reports, deviation alerts, and recommendations for corrective actions, with a focus on ensuring that financial and regulatory support policies are optimised to promote the adoption of GHPs (Bateman et al., 2017). Additionally, environmental, socio-economic impact, and regulatory compliance assessments should be included (Saner et al., 2010; Bateman et al., 2017).

- Adaptation Process

The adaptation process must ensure that shallow geothermal systems adjust to changing conditions, energy efficiency requirements, and current regulations, while considering regional policy and regulatory frameworks. This process should include three key steps: i) Identification of adaptation needs (Rybach and Eugster, 2010), both operational and regulatory; ii) Implementation of adaptation measures, ensuring the systems remain viable under new environmental and regulatory conditions; and iii) Evaluation of the effectiveness of the adopted measures (Omer, 2008)., ensuring GHP systems continue to meet sustainability and energy transition goals. This adaptation process should be part of a long-term strategy to ensure compliance with local regulations and energy transition goals, supporting the development of sustainable solutions through financial incentives and a flexible regulatory framework.

- Stakeholder Engagement

Stakeholder engagement should be continuously assessed to ensure the effectiveness of strategies for integrating GHPs into regional energy plans. This includes collaboration between governments, businesses, communities, and universities to make informed decisions that foster social acceptance and the success of GHP projects. Additionally, monitoring should evaluate how financial incentives, regulatory policies, and education and training strategies are promoting GHP integration and improving collaboration among all relevant stakeholders. Ensuring the effectiveness of these engagements guarantees the sustainability of systems and their effective integration into regional energy plans (Wüstenhagen et al., 2007).

3.7.2.2 Framework and Procedure regarding Shallow Geothermal Systems at regional level

Procedure

- Local Monitoring System Design

Designing an effective monitoring system for shallow geothermal systems at the local level requires a deep understanding of the community's specific energy and environmental needs (Halilovic et al., 2023). The monitoring system should be tailored to optimize the use of local geothermal resources, improve energy efficiency, and reduce energy costs while ensuring adaptability to climate change and variable demand. The system should also support the integration of renewable energy sources like solar or wind to optimize the area’s energy mix (Karunathilake et al., 2018). In addition to the technical considerations, simplified licensing procedures should be integrated into the design process (Batini et al, 2020). By streamlining the licensing process at the local level, authorities can remove barriers and expedite the implementation of geothermal systems. This will help communities adopt renewable energy solutions more efficiently, ensuring that the monitoring infrastructure is in place as quickly as possible to assess system performance and environmental impacts (Rivera et al., 2022).

- Monitoring and Data Collection Procedure

Robust monitoring and data collection procedure allow to ensure the effective operation of geothermal systems. Continuous, real-time monitoring enables operators to assess performance and adjust the systems according to local conditions (Park et al., 2022). Key monitoring parameters include subsurface temperature, groundwater quality, energy efficiency, and local energy demand. Data should be collected automatically, ensuring that it is readily available for analysis, with remote access for decision-makers to facilitate timely adjustments. The local planning and design process should ensure that monitoring systems are integrated into the infrastructure from the outset, with data collection aligned with the energy needs and environmental goals of the community. Furthermore, incentives and local funding should be considered as part of the monitoring strategy (Chen et al, 2019). Local governments or regional bodies could offer financial incentives to support the initial setup of the monitoring systems, ensuring that the necessary infrastructure is in place to effectively track system performance and energy savings.

- Local Adaptation of Strategies and Measures

Monitoring results should guide the adaptation of strategies and measures to optimize geothermal system integration at the local level (Karunathilake et al., 2018). As monitoring data is collected, adjustments may be required in installation density, energy distribution systems, or local regulations. Local project planning and design should take these factors into account to ensure that geothermal systems are well-integrated into the local infrastructure and meet the community's energy needs. Additionally, citizen participation and community management are central at this stage. Engaging local communities in the decision-making process will help ensure that the adaptation strategies reflect local priorities and concerns. Community input can also help to identify any potential barriers to system adoption or areas where local knowledge can improve the overall design of the geothermal network (Walsh et al., 2020). Local authorities should work closely with communities to address these issues and encourage wider adoption of geothermal heat pumps (GHPs), especially in areas with high energy demand or where traditional energy sources are less sustainable.

- Local Authorities and Community Involvement

Local authorities are responsible for the implementation, monitoring, and adaptation of shallow geothermal systems (Somogyi et al., 2017). These authorities should oversee the proper execution of the system, verify collected data and issuing necessary permits. Their role also includes ensuring that systems meet local regulations and facilitating simplified licensing procedures to remove administrative barriers. Furthermore, citizen participation and community management allow to ensure the success of geothermal projects (van der Schoor & Scholtens, 2015). Engaging communities, particularly in areas where geothermal systems may impact water use or local infrastructure, foster social acceptance and ensures that the systems meet the needs of the population. Active community participation in decision-making ensures that the projects are perceived as beneficial, which can help improve public trust and support for future renewable energy projects.

- Regular Reporting to Local Authorities

Regular reporting to local authorities helps maintain transparency and ensures that geothermal systems are operating as expected. Reports should include detailed monitoring results, adjustments made to improve system performance, and assessments of environmental impacts. These reports should also highlight long-term projections regarding the sustainability and future performance of the geothermal systems (Meng et al., 2019). By providing local authorities with this information, governments can make more informed decisions about energy and land use planning (Puig & Morgen, 2013). Additionally, these reports should include an assessment of the effectiveness of incentives and local funding schemes. By regularly reviewing the financial support provided to geothermal projects, local governments can adjust their strategies to ensure that funding mechanisms remain effective in encouraging the adoption of renewable energy technologies (Bölük & Kaplan, 2022). This report also helps in evaluating the success of monitoring and evaluation at the local level, ensuring that systems are continually assessed for improvements in efficiency and impact.

10. Appendixes

Geodata of the Geothermal Atlas

The Geothermal Atlas provides spatial datasets to support planning for BHEs and GWHPs. Currently, the available data cover only Vienna, with collection ongoing for other federal states.

This section presents the geothermal-relevant datasets and outlines the methodology developed to produce them. This summary description is based on Steiner (2023a, 2023b). Further details are available in these references as well as in the project's final report (Steiner et al., 2021). The data collection and processing were conducted under the GEL-SEP project, with GeoSphere Austria carrying out the work in Vienna on behalf of MA 20 (city of Vienna's Municipal Department for Energy Planning).

Aside from spatial geodata related to or indicating geothermal potential, the Atlas features a traffic light map (Steiner, 2023c) indicating possible restrictions on shallow geothermal energy use. Users can query all this data at specific locations by clicking on the map. This will also give a text-based summary of all values available for the selected location.

General framework

A wide range of parameters is available for assessing the potential and limitations of shallow geothermal energy. These parameters were categorised into resources and limitations/indications as part of the developed methodology:

- ***Resource***: The technical potential is quantified by resource parameters without considering external restrictions. A standardised methodology has been established for consistent application across different regions and can be applied both in data-rich areas (typically urban) and data-scarce regions (usually rural). This methodology builds upon previous projects (IIOG-S, WC-33, GeoPLASMA-CE) and emphasises broad coverage using all available data, while inherent uncertainties are acknowledged.

- ***Restrictions*** are identified as parameters that might limit the practical use of geothermal resources, such as competing land uses, or potential risks for or indicated by geothermal installations. These restrictions do not affect the technical subsurface potential and were therefore determined independently from the resource data, but they can affect the feasibility of utilisation and may change over time.

- ***Indications*** are highlighted as areas where additional considerations are needed for geothermal use. They do not represent actual restrictions but indicate special conditions, recommended to be addressed, in order to ensure a sustainable and efficient use.

The data foundation for this Geothermal Atlas was largely built upon prior works, mostly the WC-33 (Fuchsluger & Götzl, 2017) and GeoPLASMA-CE (Görz et al., 2019) projects for Vienna. To address gaps in data availability for specific parameters, additional data was collected as needed. For BHE resource assessments, new data was obtained from Thermal Response Tests (TRTs) conducted by drilling companies and engineering firms. Additionally, updated hydraulic conductivity values for thermal groundwater utilisation were sourced from water registries ("*Wasserbuch*").

Thermal use of groundwater (Steiner, 2023a)

Quantifying the resources in terms of energy and power units requires spatially mapping key aquifer parameters. The process begins with delineating near-surface groundwater bodies. For sites within these delineated zones, well performance hinges on aquifer properties such as thickness, permeability, depth to water table, and groundwater temperature. These hydrogeological characteristics are then used to derive energy yields and power capacities. The approaches used for the development of resource parameters for the thermal use of groundwater are outlined below.

- ***Delineation of suitable groundwater bodies***

Suitable near-surface aquifer boundaries have been revised and categorised based on hydrogeological research conducted by the Wiener Gewässer Management (WGM) for the Alluvial boundary Liesingbach and Donautalsohle areas. Two main categories were distinguished:

  - High-yield aquifers (e.g., along the Danube), for which quantitative resource estimations (thermal capacity and potential) are provided.

  - Smaller or less productive aquifers in the western parts of the city, where only groundwater temperature is provided because yields may be too low or uncertain for standard open-loop systems.

- ***Aquifer thickness and depth to water table***

The determination of aquifer thickness and depth to water table was done using groundwater table heights and, additionally for aquifer thickness, the ground surface elevation. For Vienna, groundwater table heights had been provided as isolines for the connected quaternary Danube floodplain (recent Danube gravel). For resource estimation, data representing low groundwater level is employed. Spatial dataset indicating the bottom of the aquifer was provided as well. Based on this input data, parameters were calculated as follows:

  - Aquifer thickness: Derived from the difference between the aquifer base and groundwater isolines. This is the vertical extent of the groundwater-bearing zone.

  - Depth to water table: Calculated from the difference between the ground surface and groundwater isolines.

- ***Hydraulic conductivity (kf)***

Where available, pumping tests were uniformly analysed (following Hölting & Coldewey, 2013) to estimate kf values. For parts of Vienna with comprehensive numerical modelling (e.g., left bank of the Danube), results from previous modelling (GeoPLASMA-CE) were used. Elsewhere, new test data from municipal water rights records were incorporated and remaining data gaps were filled with literature data.

- ***Groundwater temperature***

Multiple data analysis steps were performed on heterogeneous groundwater temperature data from 255 measurement sites (1982–2021) before interpolation. First, daily average temperatures were calculated for each observation well. Sinusoidal curves with linear trends were then fitted to the time series, allowing the determination of minimum, maximum, and mean groundwater temperatures for a reference year (2020). These point measurements and groundwater boundaries were used to create comprehensive temperature maps based on interpolation.

- ***Resource parameters***

Using the above input layers, the maximum feasible pumping rate (l/s), thermal load (kW), and annual energy yield (kWh) for a standard well doublet (50 m spacing) were calculated. The formula used is based on the Dupuit-Thiem approach, adapted from the ÖWAV Rule Sheet 207 (ÖWAV, 2009).

The annual energy yield if given for "balanced operation" (where heat extracted in winter is fully replaced in summer) and "norm operation" (typical heating/cooling schedules in Austrian climate), along with constraints related to legal return temperature limits (5°C minimum return in winter, 18°C maximum return in summer). The two temperature limits correspond to the limit values specified in ÖWAV regulation sheet 207 (ÖWAV, 2009) and standard practices in Vienna.

Table X lists the final GIS layers and raster datasets (25 m cell size in ETRS 1989 LAEA, EPSG: 3035) that collectively form the groundwater component data of the Geothermal Atlas. Accordingly, the generated datasets cover both hydrogeological aspects (aquifer boundaries, aquifer thickness, hydraulic conductivity, and groundwater temperatures), in addition to energy and performance potential, distinguishing between balanced and typical operational modes.

Table 25. Spatial datasets available to support planning for GWHPs in the Geothermal Atlas.

Parameter name	**Unit/Category**	**Description**
Shallow groundwater bodies suitable for thermal utilisation	-	Definition of near-surface groundwater aquifers suitable for thermal utilization. Distinguishes between two categories: ▪ Highly productive aquifers: Comprehensive initial assessments for power and energy resources are available. ▪ Locally/restrictedly productive aquifers: Groundwater is either only locally present or exists at greater depths not generally suitable for thermal utilization. Detailed investigations are required for the installation of GWHPs in these areas.
Depth to water table	m	Depth of the groundwater table below the ground surface.
Aquifer thickness	m	Thickness of the groundwater-bearing zone.
Hydraulic conductivity (kf value)	m/s	Estimated hydraulic conductivity of the aquifer.
Mean groundwater temperature	°C	Mean groundwater temperature for the year 2020.
Minimum groundwater temperature	°C	Minimum groundwater temperature for the year 2020.
Maximum groundwater temperature	°C	Maximum groundwater temperature for the year 2020.
Area-specific annual energy - A well pair for heating and cooling with balanced operation	kWh/m²/a	Area-specific annual energy for thermal groundwater utilisation with a balanced annual balance, where the heat extracted for heating in the winter is fully returned in the summer. This depends on the existing groundwater temperature and a minimum return temperature of 5°C and a maximum return temperature of 18°C.

Area-specific annual energy - A well pair for heating and cooling with standard operating hours	kWh/m²/a	Area-specific annual energy for thermal groundwater utilization in heating and cooling operations under standard operating hours. This depends on the existing groundwater temperature and a minimum return temperature of 5°C and a maximum return temperature of 18°C.
Well performance	l/s	Maximum pumping capacity of a well pair with a 50 m distance between the extraction and return wells.
Full load capacity	kW	Maximum full load capacity of a well pair with a 50 m distance between the extraction and return wells.

Borehole heat exchangers (Steiner, 2023b)

The performance of BHEs hinges on three key factors: (i) subsurface conditions (usable temperature gradient and thermal conductivity), (ii) system design (borehole thermal resistance, radius, depth, field size, and spacing between probes), and (iii) operational parameters (full-load heating/cooling hours and energy balance). Geometry and operational variables are integrated into a single function (g-function), while site-specific subsurface parameters are mapped to support performance and energy calculations. A target depth of 100 m was established for resource assessments, based on an analysis of registered systems in Vienna and Salzburg (as of April 2021), where the average depth of installed systems was 100 m. All geological datasets and energy/performance outputs are standardised to this depth reference. The approaches used for the development of resource parameters for BHE are outlined below.

- ***Thermal conductivity of the subsurface***

Vienna's subsurface thermal conductivity was derived from WC-33 project data (Fuchsluger & Götzl, 2017), calculating conductive-only values (excluding groundwater flow) using borehole lithology across 0–30 m, 0–100 m, and 0–200 m depths. Validation by means of 39 TRTs revealed that the WC-33 values are locally underestimated due to convective heat transfer (e.g., groundwater flow). These convective effects can be accounted for in future development.

- ***Surface temperature***

Land surface temperatures are derived from satellite data corrected via a continental model (Metz et al., 2014), providing 250 m resolution averages for 2000–2013. This dataset was validated against ground measurements (in the range of 10–100 cm depth, 2006–2013) from two stations (Donaufeld and Groß-Enzersdorf). Good alignment with 10 cm depth temperatures confirmed its reliability, leading to its adoption for Vienna.

- ***Subsurface temperature***

Temperature profiles, while spatially limited for direct interpolation, were used for determining geothermal gradients. For Vienna, 15 temperature profiles, measured during TRTs in existing installations, were analysed. They were grouped into five clusters based on hydrogeological homogeneity. For each cluster, an average geothermal gradient was calculated, and a historical surface temperature was derived by extrapolating the gradient to the surface. The historical surface temperature differs from the current annual average due to climate change and the urban heat island effect.

To enhance accuracy, the actual annual surface temperature, derived from satellite data was incorporated. This integration allowed the creation of specific temperature profiles for each raster cell, starting from the actual surface temperature and extending to depths influenced by geothermal processes. Groundwater temperature from shallow aquifers was also included in the transition zone. These combined inputs enabled the calculation of average temperatures for the 0–100 m depth interval across Vienna.

- ***Standard operating hours***

Estimating the performance and energy resources of BHEs requires assumptions about operational modes and annual heating and cooling needs, which depend on building type, size, and climate. Climate effects are typically linked to heating and cooling degree days. The Swiss standard SIA 384/6 (2010) ties this climatic factor to ground temperature or elevation through standard operating hours, an approach also adopted here. Elevation-dependent operating hours were recalculated to depend on the land surface temperature. An additional 200 hours was added to account for hot water needs as a general approximation. For cooling, no demand was assumed for land surface temperatures below 8°C. Above this, cooling demand increases linearly, reaching about 1000 full load hours at 13.5°C. This cooling calculation is provisional and subject to improvement in future updates.

- ***Performance calculations***

The Python program "BHEseppy" was created to calculate BHE performance using the Finite Line Source theory and g-functions (Eskilson, 1987) via the "pygfunction" plugin (Cimmino, 2018). It models heating, cooling, and natural regeneration based on standard operating hours over 20 years, including balanced operation scenarios with equal heating and cooling use. The program calculates borehole performance and annual energy yield using subsurface properties, operational hours, and borehole field geometry. Heat extraction rate is given as W/m for a 100 m borehole, and annual energy yield is expressed in kWh/m²/a for two field sizes (1156 m²): a 4x4 field (16 boreholes, 10 m spacing) and a 7x7 field (49 boreholes, 5 m spacing). Results include internal field interactions but exclude neighbouring systems, providing a reliable preliminary estimate for standard or balanced operation.

Table 25. Spatial datasets available to support planning for BHEs in the Geothermal Atlas.

Parameter Name	Unit/Category	Resolution (m)	Description
Operating hours - heating	h/a	50	Annual standard full load hours for heating, depending on ground temperature.
Operating hours - cooling	h/a	50	Annual standard full load hours for cooling, depending on ground temperature.
Thermal conductivity	W/m·K	25	Average conductive thermal conductivity of the subsurface for depths between 0 and 100 m.
Subsurface temperature	°C	100	Average subsurface temperature for depths between 0 and 100 m.
Land surface temperature	°C	250	Average annual ground temperature at the surface, based on satellite data (MODIS).
Specific annual energy yield - borehole field (4x4)	kWh/m²/a	50	Annual energy yield of a 4x4 borehole field (16 boreholes, 10 m spacing, 100 m depth), primarily used as a heat source with partial regeneration via cooling in summer. Heating and cooling demand depends on the annual mean temperature.
Specific annual energy yield - borehole field (7x7)	kWh/m²/a	50	Annual energy yield of a 7x7 borehole field (49 boreholes, 5 m spacing, 100 m depth), used as a thermal storage system. Assumes balanced operation where winter heating demand is fully offset by summer cooling regeneration.
Specific borehole heat extraction rate - single borehole (standard operating hours)	W/m	50	Heat extraction rate of a 100 m deep single borehole, primarily used as a heat source with partial regeneration via cooling in summer. Above mentioned, operation hours Heating and cooling
Specific borehole heat extraction rate - single borehole (balanced operation)	W/m	50	Heat extraction rate of a 100 m deep single borehole, used as a thermal storage system. Assumes balanced operation where winter heating demand is fully offset by summer cooling regeneration.