This document was written in the course of the ERDF funded project GRETA (2016 – 2018). It is the second deliverable of the Work Package 3 (WP3 or WPT2) “Operational criteria for the utilization of Near-Surface Geothermal Energy in the Alpine environment”. The Geological Survey of Austria (GBA), as responsible partner in this WP, elaborated this catalogue with the contribution from the involved project partners.

The preliminary studies for this deliverable (Del. 3.2.1) were carried out within the Activity 3.2 “Operational criteria and constraints for shallow geothermal systems in the Alpine environment” from 15.05.2016 – 15.06.2017.

The outputs of this study will be taken into account by WP4 (WPT3) (operative constraints and thresholds for the assessment and mapping of Near-Surface Geothermal potential) and WPT4 (elaboration of technical concepts on existing and possible future uses of NSGE for its integration into the energy plans of pilot areas).
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1 Introduction

Within WP3, the aim is to define and analyse criteria relevant for the NSGE use in the Alpine space. The output of this assessment shall be the base for considerations and calculations especially for the potential mapping methods. In order to identify and quantify operational criteria, information is collected by literature research, the monitoring of best practice examples, field measurements in the case study areas and numerical simulations.

To achieve this deliverable, the first step was to identify technical and environmental constraints (see chapter 2) as well as operational criteria in general (see chapter 3). In order to be able to answer the question about how big the influence of these operational criteria are to the NSGE system in a whole, numerical simulations were carried out considering the same load curves for BHE and GWHPs and varying the operational criteria (see chapter 4). This leads to the identification of relevant operational criteria and shows the influence of these to the system.

1.1 Terms and definitions referring to NSGE

**Resource:** the term refers to the source – i.e. thermal energy stored underground, from which benefit can be produced.

**Potential:** these terms define the amount of a known natural resource that may potentially be used in the future, regardless of technical feasibility – i.e. the amount of thermal energy stored underground. This definition refers to the “heat in place” definition by USGS.

**Technical potential:** this term refers to the exploitable thermal energy stored underground, defined according to the “Recoverable Heat in Place” definition by USGS.

**Techno-economical potential:** this term refers to the exploitable thermal energy stored underground that is able to satisfy the thermal demand (partly or totally) in a technically and economically sustainable way.

**Operational criteria:** this term refers to the main criteria that need to be considered in calculating the technical and economic efficiency of a NSGE system. Within this document, they are grouped into the given natural conditions (natural operational criteria), the demand side (design operational criteria) and economic considerations.

**Technical and environmental constraint:** this term refers to limitations or restrictions of NSGE use related to legal, economic and technological requirements. Despite the common definition, technical and environmental constraints have different meanings. **Environmental constraints** are more or less yes/no criteria. They result mostly from given circumstances. Their value range is either fixed due to legal frameworks or the variation of the parameter does not influence any of the operational criteria in a dimension that can be measured.
Aquifer: An aquifer is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt) from which groundwater can be extracted using a water well. (Wikipedia)

Thermal conductivity expressed as $\lambda$: The thermal conductivity is the property of a material to conduct heat and is dependent on the physical properties of the subsurface (geology and hydrology). The unit is [W/(m·K)] and following the simple definition it is defined as the heat flow that transfers in a steady state condition through a homogeneous body exposed to a temperature gradient of 1 K per meter [1] (SIA 384/6, p.9). It is dependent on the composition of the subsurface, and also on its state. In the steady state case, when the system does not change temperature with time, the amount of heat transferred per unit area per unit time is proportional only to the thermal conductivity and the temperature gradient [2]. The Fourier’s law states that, for a certain heat flow, the temperature gradient is inversely proportional to the thermal conductivity of the material through which the heat is being transmitted by heat conduction [3].

Effective thermal conductivity expressed as $\lambda_{eff}$: The effective thermal conductivity in [W/(m·K)] is the mean bulk thermal conductivity of a composite medium which characterizes appropriately heat conduction across the entire sample [3].
2 Description of technical and environmental constraints

**Definition:** The term “technical and environmental constraint” refers to limitations or restrictions of NSGE use related to legal, economic and technological requirements.

Despite the common definition, technical and environmental constraints have different meanings:

- **Environmental constraints** (see Table 1) are more or less yes/no criteria. They result mostly from given circumstances. Their value range is either fixed due to legal frameworks or the variation of the parameter does not influence the NSGE installation in a dimension that can be measured.

  *Example*: the presence of anhydrite layers. A variation of this parameter (e.g. 1 m thickness or 10 meters) will not change any operational criteria. It can be e.g. prohibited to build an NSGE installation or the driller can be aware of the risk and can take precautions.

  Environmental constraint results from the environmental analysis, they are in- or exclusion factors rather than parameters with valid value ranges. Many of these constrains are set up by water regulation administrations (see WP2).

- **Technical constraints** (see Table 2) represent the minimum or maximum value of a parameter that affects the efficiency of a NSGE installation in a dimension that can be measured. The elaborated values can be seen as threshold values for a reasonable (SPF<1?) NSGE installation.

  *Examples*:
  - The transmissivity determines the maximum possible pumping rate. A minimum transmissivity of $X \text{ m}^2/\text{s}$ is necessary to run a GWHP system.
  - The ground temperature may not fall below 3 °C to run a BHE. Hence a certain altitude in combination with exposition/solar irradiation may turn out to be a technical constraint.
  - Geochemistry of groundwater: above a certain water hardness the installation of a GWHP is too elaborate.

The feasible value range (boundary) of technical constraints is derived by analysis of operational criteria (see Table 3). These parameter studies are ongoing, the final results will be available for deliverable 3.3.1 (September 2018).

<table>
<thead>
<tr>
<th>Environmental constraints</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to neighbouring installations</td>
<td>distance to neighbouring installations (water wells, NSGE installations) as indication for conflicting use</td>
<td>[m]</td>
</tr>
<tr>
<td>Reinjection temperature</td>
<td>Minimum / maximum legal reinjection temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>Temperature spreading</td>
<td>maximum legal temperature spreading between groundwater temperature and reinjection temperature; e.g. for Austria: min return temp 5 °C/ max 20 °C/ max spreading + 5 °C</td>
<td>[°C]</td>
</tr>
<tr>
<td>Water protection area</td>
<td>Classification of water protection area (I, II, III, etc.)</td>
<td>text</td>
</tr>
<tr>
<td>Drinking water well protection</td>
<td>protection area or radius around existing drinking water wells</td>
<td>[m] or [m²]</td>
</tr>
<tr>
<td>Available land/ground</td>
<td>size of the available ground</td>
<td>[m²]</td>
</tr>
<tr>
<td>Confined aquifer</td>
<td>A confining layer overlies the aquifer. Thus, the aquifer is under pressure. Penetrating may be forbidden or cause environmental impact.</td>
<td></td>
</tr>
<tr>
<td>NaCl layers</td>
<td>Avoid drilling in NaCl layers due to possible collapse / dilution of the borehole</td>
<td></td>
</tr>
<tr>
<td>Anhydrite layers</td>
<td>Avoid drilling in Anhydrite layers. Causing a contact with water results in swelling and possible damage of infrastructure on the surface.</td>
<td></td>
</tr>
<tr>
<td>Hydrocarbon presence</td>
<td>If HC presence is likely, preventers have to be / should be used while drilling</td>
<td>text</td>
</tr>
</tbody>
</table>
2.1 Environmental constraints

Water Authorities and other competent authorities prescribe many of the environmental constraints. As described in Del. 2.2.1, they vary between countries but also within them, which results in a heterogeneous set of threshold values that have to be taken into account when predicting potentials for NSGE use. In order to prevent existing users from thermal influence induced by new installations and thus, potential performance losses for NSGE systems or reductions of drinking water quality, authorities prescribe minimum distances to neighbouring installations of up to 200 meters (see Annex 10.4 “Required distances” of Del. 2.2.1). Regulations for minimum and maximum reinjection temperatures, for temperature spreading rates as well as whether it is allowed to install NSGE systems within a water or nature protection area, ensure the sustainable exploitation of aquifers – though again, this is dependent on the competent authority and varies from country to country and within them.

Not regulated by authorities are constraints such as the available size of ground, which may influence the decision about the type of NSGE installation. Geogenic factors such as the presence of hydrocarbons or salt-/anhydrite layers in the underground are often exclusion factors for the installation of NSGE systems, but might only be impeding and to be overcome by proper planning, drilling and completion works.

Table 2: Parameters to assess regarding their technical constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar radiation</td>
<td>intensity of solar energy incident on the Earth’s surface</td>
<td>[W/m²]</td>
</tr>
<tr>
<td>Snow levels</td>
<td>amount of annual snow cover</td>
<td>[m] [days]</td>
</tr>
<tr>
<td>Outside air temperature</td>
<td>mean annual outside air temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>Rainfall</td>
<td>amount of annual precipitation</td>
<td>[mm]</td>
</tr>
<tr>
<td>Ground temperature</td>
<td></td>
<td>[°C]</td>
</tr>
<tr>
<td>Morphology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetation</td>
<td>indication whether mainly trees/grass etc. is present at location</td>
<td>text</td>
</tr>
<tr>
<td>Hillslope</td>
<td>gradient</td>
<td>[%]</td>
</tr>
<tr>
<td>Hillside exposure</td>
<td>N-E-S-W orientation of the hillside</td>
<td>text</td>
</tr>
<tr>
<td>Geology / geophysics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock type</td>
<td>lithological classification of rocks</td>
<td>text</td>
</tr>
<tr>
<td>Compactness</td>
<td>compactness of the sediments</td>
<td>[%]</td>
</tr>
<tr>
<td>Grain size</td>
<td>classification of grain size of sedimentary rocks (silt/sand/gravel)</td>
<td>text</td>
</tr>
<tr>
<td>Total porosity</td>
<td>percentage of porosity of sedimentary rocks</td>
<td>[%]</td>
</tr>
<tr>
<td>Effective porosity</td>
<td>the part of total porosity contributing to fluid flow, and thus to advective transport</td>
<td>[%]</td>
</tr>
<tr>
<td>Crevasse formation</td>
<td>degree of crevasse formation of karstic rocks</td>
<td></td>
</tr>
<tr>
<td>Permeability</td>
<td>is a portion of the hydraulic conductivity but is a property of porous media only, not the fluid. 1 Darcy is equal to 10⁻¹²m²</td>
<td>[md]</td>
</tr>
<tr>
<td>Soil type</td>
<td>classification of soil type</td>
<td>text</td>
</tr>
<tr>
<td>Heat-flow density</td>
<td>the heat transferred by conduction from the Earth’s interior to the surface</td>
<td>[W/m²]</td>
</tr>
<tr>
<td>Transmissivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogeology / hydrology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Productive thickness of aquifer</td>
<td>sum of productive layers’ thickness of the aquifer in meters</td>
<td>[m]</td>
</tr>
<tr>
<td>Hydraulic gradient</td>
<td>pressure loss of a flow vs. distance length</td>
<td>[m]</td>
</tr>
<tr>
<td>Depth to groundwater table</td>
<td>depth of groundwater level in meters</td>
<td>[m]</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>flow of water through a porous media / permeability of soil for water</td>
<td>[kf] in [m/s]</td>
</tr>
<tr>
<td>Water saturation</td>
<td>percentage of water content within sedimentary rocks</td>
<td>[%]</td>
</tr>
<tr>
<td>Geochemistry of groundwater</td>
<td>concentration of corroding or clogging minerals</td>
<td>[mg/l]</td>
</tr>
</tbody>
</table>
Aquifer temperature

<table>
<thead>
<tr>
<th>Well design / tube specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole diameter</td>
</tr>
<tr>
<td>Depth of drilling / length of borehole</td>
</tr>
<tr>
<td>Borehole grout</td>
</tr>
<tr>
<td>Type of fluid</td>
</tr>
<tr>
<td>Pipe material</td>
</tr>
<tr>
<td>Tube specifics</td>
</tr>
</tbody>
</table>

2.2 Technical constraints

Climate

| Solar radiation | intensity of solar energy incident on the Earth’s surface | [W/m²] |
| Snow levels | amount of annual snow cover and duration of snow cover | [m] [days] |
| Outside air temperature | mean annual outside air temperature | [°C] |
| Rainfall | amount of annual precipitation | [mm] |
| Ground temperature | | [°C] |

The suitability and efficiency of NSGE systems is strongly linked to the local climate conditions. As described in Del. 3.1.1. “Catalogue of techniques and best practices”, chapter 2.2, six climatic zones (A-F) were identified for the Alpine space region, based on Heating Degree-Days (HDD) and Cooling Degree-Days (CDD) according to Tsikaloudaki et al. (2012, [4]). The evaluation of the suitability of different GSHP typologies for different climate conditions was summarized in Table 5 of Del. 3.1.1, the evaluation of pros and cons of GSHPs in different climate conditions for different usage profiles in Table 4.

As described above, the classification into climate zones is based on HDD/CDDs, which is a reasonable way to estimate the potential for NSGE use of a city or region, though it may not be sufficient to make site-specific statements.

- To assess the heating demand of a building, primarily the thermal insulation, the outside air temperature and the user behaviour need to be taken into account (see chapter 3.2 on thermal demand).
- To assess the amount of energy the underground can provide, primarily ground temperature and the thermal properties of the underground need to be taken into account (see chapter 3.1.1 on ground temperature).

Ground temperature, and to a lesser extent the outside air temperature can change significantly within nearby surroundings – this is especially true for the Alpine space, where valleys surrounded by mountains suffer from strong local temperature variations. Important to note is, that temperature of both, outside air and underground, are dependent on many parameters such as the intensity of solar irradiation or the amount of precipitation (snow- and rainfall).
**Morphology**

| Vegetation | indication whether mainly trees/grass etc. is present at location |
| Hillslope  | gradient |
| Hillside exposure | N-E-S-W orientation of the hillside |

The morphology of an area does play an important role when looking at the suitability of NSGE systems. For obvious reasons, on steep ground only vertical, mostly ground sourced systems apply, whereas on flat ground the whole range of NSGE systems apply.

As many studies have shown, vegetation does have significant influence on the ground temperature and the local climate [5, 6]. For example forested areas do have a large buffer function for both outside air- and ground temperature[7]. The hillside exposure is another significant parameter in this category. Solar irradiation hits a South slope to a much higher degree than a North slope, which influences the temperature regime of a location, and thus, the potential for a NSGE use, to a high degree (see chapter 3.1.1 on ground temperatures). Aquifer characteristics depend mainly on the geological composition of the underground, the amount of infiltrated water but also on the morphology – i.e. the gradient of the ground surface, which strongly influences the velocity of the underground water flow (Darcy velocity). However, as Figure 75 shows, this parameter does not change the efficiency of a GWHP to a significant extent. To read more about these parameters, see chapter 3.1.1 on ground temperature and chapter 3.1.4 on aquifer temperature.

**Geology/geophysics**

| Rock type | lithological classification of rocks |
| Compactness | compactness of the sediments [%] |
| Grain size | classification of grain size of sedimentary rocks (silt/sand/gravel) text |
| Total porosity | percentage of porosity of sedimentary rocks [%] |
| Effective porosity | the part of total porosity contributing to fluid flow, and thus to advective transport [%] |
| Crevasse formation | degree of crevasse formation of karstic rocks |
| Permeability | is a portion of the hydraulic conductivity but is a property of porous media only, not the fluid. SI unit is m², 1 Darcy is equal to 10e-12m² [md] |
| Soil type | classification of soil type text |
| Heat-flow density | the heat transferred by conduction from the Earth's interior to the surface [W/m²] |

The geological properties of the underground should be assessed prior to installing a NSGE system, as it is advisable to consider them when sizing the installation. Thus, they might play a role in decision finding about the type of system to be installed. The effective thermal conductivity (see chapter 3.1.2) of the underground describes how fast heat is transported to the heat exchanger, which in turn determines the efficiency of the system. This parameter depends on the type of underlying rock, it’s compactness, grain size and porosity, and the water saturation as well as the permeability especially for unconsolidated sediments. The type of soil does have an influence on ground temperature, as some types are more insulating than others.
Especially for GWHP systems (and to a minor extent for GCHP systems), the hydrogeological parameters of the underground play a significant role in sizing an installation and determining its efficiency (see chapter 3.1.4 on aquifer temperature, chapter 3.1.4 on groundwater levels and chapter 4.2 on open-loop systems). If the aquifer is well characterized – ideally from monitoring data – proper spatial planning can be carried out in order to ensure sustainable exploitation of the source. Some parameters have little affect for the single user, though are important to consider for larger scale potential mapping [8]. This is, for example, the productive thickness of the aquifer. As Figure 71 shows, increasing values for this parameter causes a reduction of the thermal recycling effect and a consequent increase of the SPF2 value, though with only limited impact on the SPF. As Figure 75 shows, the depth to the groundwater table influences the efficiency of a system to a high degree, as pumping power represents a large portion of the required total electrical power. The temperature of an aquifer is a main efficiency criteria and should be known before planning and sizing the GWHP.

Depending on the concentration of corroding or clogging minerals in the aquifer, such as iron or manganese, groundwater usage may be complicated or even impeded [9-13].

[This topic will probably be studied in more detail in the next months. Literature about critical values, consequences: Bezéluges et al., 2010, Geothermal Potential of Shallow Aquifers: Decision-Aid Tool for Heat-Pump Installation, see page 8-9; or Kevin Rafferty: a study of 1999 on all USA (Rafferty 1999), an article on Ground Water of 2003 (Rafferty 2003) and further recommendations written in 2008 (Rafferty 2008).]

**Well design / tube specifics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit or Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole diameter</td>
<td>diameter of the borehole</td>
<td>cm</td>
</tr>
<tr>
<td>Depth of drilling / length of borehole</td>
<td>the depth of drilling (length of the borehole) results from analysis of technical constraints, energy demand and legal aspects.</td>
<td>m</td>
</tr>
<tr>
<td>Borehole grout</td>
<td>used backfilling material (e.g. bentonite, cement) and related density</td>
<td>Text, g/cm³</td>
</tr>
<tr>
<td>Type of fluid</td>
<td>type of fluid used as the heat transport media, e.g. water, anti-freeze; and related mass of controlled substances in the fluid</td>
<td>Text, kg</td>
</tr>
<tr>
<td>Pipe material</td>
<td></td>
<td>text</td>
</tr>
<tr>
<td>Tube specifics</td>
<td></td>
<td>text</td>
</tr>
</tbody>
</table>

The design of the well depends on parameters from various fields, such as economical (e.g. price category of the heat pump), technical (e.g. tube specifics) or legal (e.g. maximum drilling depth). Chapter 3.2 describes the importance of design parameters and shows, for example the length of the borehole influences the economic efficiency of a BHE. The decision on utilized borehole grouting and their related thermal conductivity should be made in balance with the drilled rocks in order to achieve good exchange between the heat exchanger medium and the surrounding. Choosing environmental friendly heat transport media within the pipes excludes the risk of creating impact in case of leakage. To minimize environmental impact, four regulation criteria are used in EU countries regarding heat carrier fluids and refrigerants – they are recommended to be biodegradable, to have...
low environmental impact, to have low global warming potential and zero ozone depletion potential. For example, CFC (Chlorofluorocarbons) and HCFC (Hydrochloro-fluorocarbons) are being phased out under the Montreal Protocol and EU legislation (see WP2-Deliverable 2.1.1, Annexes 4 and 5).

REFERENCES OF THIS SECTION

3 Description of operational criteria for shallow geothermal systems

**Definition:** The term “operational criteria” refers to the main criteria that need to be considered in calculating the technical and economic efficiency of a NSGE system. Within this document, they are grouped into the given natural conditions (natural operational criteria), the demand side (design operational criteria) and economic considerations.

The identified main operational criteria (see Table 3) are: natural operational criteria (ground and aquifer temperature, effective thermal conductivity, specific heat capacity or volumetric heat capacity, potential production rate of an aquifer), design operational criteria (peak power and yearly thermal demand - both in heating and cooling), economic considerations (drilling costs, installation costs, financing of a NSGE system).

They are dependent on multiple interacting parameters like ground properties, hydrological constraints, climate and technical constraints (see Table 1 and Table 2).

**Table 3: Main operational criteria**

<table>
<thead>
<tr>
<th>Natural operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground temperature</td>
<td>Mean ground temperature</td>
<td>°C</td>
<td>Outside air temp, solar radiation, hillside exposure, hillslope, snow levels, vegetation, heat flow, anthropogenic constructions/ sealing (buildings, roads)</td>
</tr>
<tr>
<td>Effective thermal conductivity</td>
<td>Property of a material to conduct heat. Dependent on the physical properties of the subsurface</td>
<td>W/m K</td>
<td>Anisotropy, compactness, crevasse formation, grain size, permeability, porosity, rock type, soil type, water content</td>
</tr>
<tr>
<td>Specific heat capacity or volumetric heat capacity</td>
<td>Amount of heat that can be absorbed and emitted within one period in relation to a temperature deviation of 1 K and 1 kg / 1 m³.</td>
<td>J/kg K or J/m³ K</td>
<td>Temperature, Density</td>
</tr>
<tr>
<td>Aquifer temperature</td>
<td>Together with the maximum possible temperature spreading indicates the thermal technical potential</td>
<td>°C</td>
<td>Outside air temperature, surface water interaction, rainfall, snow levels, existing groundwater usage,</td>
</tr>
<tr>
<td>Groundwater level</td>
<td>Depth to exploitable aquifer</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Transmissivity</td>
<td></td>
<td>m²/s</td>
<td>Permeability, aquifer thickness</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power</td>
<td>Peak power required by the building in heating and cooling</td>
<td>kW</td>
<td>Thermal insulation</td>
</tr>
<tr>
<td>Thermal demand</td>
<td>Thermal demand required by the building both in heating and cooling</td>
<td>kW</td>
<td>Building characteristics and use</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Economic operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling costs</td>
<td></td>
<td>€</td>
<td>Journey to drilling site, total amount of drilled meters, bedrock properties, GW chemistry</td>
</tr>
<tr>
<td>Installation costs</td>
<td></td>
<td>€</td>
<td>Type of HP, chemical composition of the GW</td>
</tr>
<tr>
<td>Running costs</td>
<td></td>
<td>€</td>
<td>Maintenance, energy price</td>
</tr>
<tr>
<td>Financing</td>
<td></td>
<td>€</td>
<td>Incentive programs, Interest rates</td>
</tr>
</tbody>
</table>
3.1 Given natural conditions (natural operational criteria)

3.1.1 Ground temperature

<table>
<thead>
<tr>
<th>Natural operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground temperature</td>
<td>Mean ground temperature</td>
<td>°C</td>
<td>Outside air temperature, solar radiation, hillside exposure, hillslope, snow levels, vegetation, heat flow from the interior of the earth, anthropogenic constructions/installations/sealing (buildings, roads)</td>
</tr>
</tbody>
</table>

The ground temperature is a key parameter for the calculation of NSGE potentials as it reflects the amount of stored energy and is crucial to the efficiency of NSGE systems [14, 15]. This parameter plays an even more significant role in high-altitude regions where ground temperatures may stay very low the whole year. Therefore, the knowledge about thermal conditions and imbalances induced by NSGE use is important for a sustainable operation of NSGE systems [16]. In general, two major heat sources govern the ground’s heat budget. The Earth’s surface temperature as initial influence from the top and the Earth’s internal heat as constant flux at the bottom [17].

The inner Earth supplies a constant heat flux mainly from the decay of radioactive isotopes and through dissipation of primordial heat from its formation [18]. The geogenic heat flux, however, is difficult to quantify. Differently active heat transport mechanisms and varying thermal properties of the geologic structures generate spatially changing geothermal gradients [19, 20]. The understanding of those deep heat flux processes for the estimation of temperature distributions and negative or positive thermal anomalies is particularly interesting for deep geothermal exploration and subject to recent studies [21].

As upper boundary, the Earth’s surface temperature represents the sum of all sources from outside the solid Earth, ground-atmosphere interactions and terrain effects [17]. Exogenous influences are solar radiation, air temperature, wind speed, relative humidity, precipitation and snow cover [22, 23]. Among ground-atmosphere interactions are effects from different kinds of land cover, like vegetation, anthropogenic structures or water bodies [24]. Terrain effects refer to topography and characteristics of the Earth’s surface such as elevation, hillside exposure and hillslope [25-27].

Especially for urban areas, the influence of subsurface building structures plays an increasingly important role. So-called urban heat islands have been observed under some cities and the evaluation of the connected shallow geothermal potential was subject to several studies [28].

Since there is a large variety of different, possibly significant influences to the surface ground temperature, we focus on air temperature and elevation in the next chapter. The two parameters are known to influence the surface ground temperature globally and offer a long-term and broadly available set of measurement points.
3.1.1.1 Air and soil temperatures of the German Alpine Space region.

The ambient air temperature is the dominant influence on the Earth’s surface temperature [26]. To visualise the air–soil temperature dependence for the German Alpine Space area, we used data from measurement stations maintained by the German weather service DWD “Deutscher Wetterdienst” (c.f. Figure 1). All calculations are based on daily means of 55 air and soil temperature measurement stations within the years 1987 to 2016.

![Measurement stations of air and soil temperature from the DWD in the German ASP area.](image)

In Figure 2 the mean temperatures of air and soil during the whole observation period are plotted against each other. The remaining 20% of unexplained variance shows the additional influences from other external sources, ground-temperature interactions or terrain effects. Early studies already established a functional relation between air temperature and soil temperature and recognised the need of improving soil temperature estimations with additional explanatory influences [29, 30]. However, the air temperature is still the most important influence on the ground temperature in 5 cm depth.

This effect is also visible in Figure 3, where the annual time series of the mean soil and air temperature of all stations from 1987 to 2016 is shown. The regression lines show an increase of 0.3°C per decade for air temperature and 0.4 °C for soil temperature. The mean deviation of air and soil temperatures in 5 cm depth is 1.7 °C. This deviation is commonly referred to the insulating characteristics of snow and the latent heat of the soil moisture buffering the propagation of cool temperatures at the freezing point [31].
In Figure 4, the elevation is introduced as independent variable. The elevation dependence of air and soil temperatures is in particular interesting for spatial mapping. An early approach by Bendel (1948, [32]) used the air temperature with an elevation depended value to estimate the soil temperature. The additions range from 0.8°C at 0 m to 3.0°C at 2500 m and slightly underestimate the measured soil temperatures (cf. Figure 4). The Swiss study by Busslinger and Rybach (1999, [33]) derived a similar linear regression with 43 soil temperature measurements in 0.5 m depth. The determined lapse rate deviates only by 0.1 K km⁻¹, which leads to a good match especially in higher elevations.

Signorelli and Kohl (2004, [34]) reviewed air and soil temperature measurements from 29 Swiss meteorological stations from 1989 to 1999. They derived a refined fit with 3rd-order polynomial regressions for the ground surface temperature and the surface air temperature (cf. Figure 4). Also for...
the DWD temperatures, the functions offer a decent fit with approximately 0.5°C overestimation of air temperatures for medium elevations.

Table 4: Regressions functions from Figure 4.

<table>
<thead>
<tr>
<th>Study:</th>
<th>Regression function:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil T (This study)</td>
<td>( y = 12.82 - 0.0044x )</td>
</tr>
<tr>
<td>Air T (This study)</td>
<td>( y = 11.31 - 0.0048x )</td>
</tr>
<tr>
<td>Soil T: (Busslinger &amp; Rybach, 1999)</td>
<td>( y = 13.50 - 0.0048x )</td>
</tr>
<tr>
<td>Soil T: (Bendel, 1948)</td>
<td>( y = 11.90 - 0.0039x )</td>
</tr>
<tr>
<td>GST: (Signorelli &amp; Kohl, 2004)</td>
<td>( y = 15.23 - 1.08 \times 10^{-2} x + 5.61 \times 10^{-6} x^2 - 1.5 \times 10^{-9} x^3 )</td>
</tr>
<tr>
<td>SAT: (Signorelli &amp; Kohl, 2004)</td>
<td>( y = 13.47 - 1.07 \times 10^{-2} x + 6.88 \times 10^{-6} x^2 - 2.6 \times 10^{-9} x^3 )</td>
</tr>
</tbody>
</table>

In summary, there is still a high remaining variability in the reviewed temperature measurements. These variations are partly originate from the aforementioned influences, which are not taken into account in the simplified regression functions. Therefore, a more comprehensive approach with detailed knowledge of the active influences for the specific working area is needed.

Especially in the Alpine regions – concerning slope and orientation of hillsides, and thus, the solar radiation on the inclined surface is not taken into account. As first results of the measurement campaign by the GBA show, temperature varies strongly dependent on snow cover and the orientation of the hillside.

3.1.1.2 Ground temperature model SoilTempSim

SoilTempSimV3C is a one-dimensional simulation model for calculating soil temperatures on a daily time step basis. It has been written in the GNU Octave language. The model allows inclusion of ground coverage by biomass or a snow layer and accounts for the freezing/thawing effect of soil water in its calculations.

Required inputs for the model are, on the one hand time-dependent data such as:

- daily mean, maximum and minimum air temperatures,
- global solar radiation,
- total aboveground biomass,
- snow (as snow water equivalent),
- actual daily evapotranspiration and
- daily values of the pore volume of the soil (which can vary due to soil cultivation) and volumetric soil water content at all relevant depths,

and on the other hand, configuration and parameterisation data that are regarded as time-independent, such as:

- soil composition (sand, clay and organic fraction),
- annual mean air temperature,
- and some empirical parameters

As output the model will deliver daily mean, maximum and minimum soil temperatures and volumetric ice content (during freezing periods) for all the desired depths. Results have to be validated using real, measured temperatures.
The climatic input data used for underground temperature modelling was delivered by the Austrian Weather Service ZAMG (“Zentralanstalt für Meteorologie und Geodynamik”) as daily grids from 2011 until mid-2016. Data will be delivered on a yearly basis until the end of the GRETA project. Soil temperature simulations will be recalculated with the updated climatic input as soon as available. Up to date, only simplified models are calculated using SoilTempSimV3C as a first step to study the influence of the exposition and hence the solar irradiation on the ground temperature.

Weather data derived from the ZAMG datasets for the four monitoring locations is applied as upper boundary conditions (2015, looped ten times, see Table 4). As material parameters, the same soil conditions are assumed for the four models even though the software is capable of taking different soil compositions in consideration. These simplifications are done to study the influence of the different climatic conditions, and to find proper initial values.

Figure 6 shows the importance of choosing proper initial conditions, in greater depths like shown in the diagram (3 and 10 m) it takes several years for the model to predict the temperature “correctly” or, better, reproducible. Without the simplification of the input data (loop of one year), this effect would not be visible so well – this artefact could be covered by climatic fluctuations. Only the tenth year is used for further evaluation.

Table 5: SoilTempSim data input summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input data</th>
<th>Source</th>
<th>Simplification</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>SPARTACUS</td>
<td>ZAMG</td>
<td>Values from 2015 looped 10 times</td>
<td>Study the influence of initial conditions</td>
</tr>
<tr>
<td>(min, max, mean)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>radiation</td>
<td>SPARTACUS</td>
<td>ZAMG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>snow cover</td>
<td>SNOWGRID</td>
<td>ZAMG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil and foliage</td>
<td>Default values</td>
<td>SoilTempSim</td>
<td>Same standard model for all four stations</td>
<td>Influence of different climatic conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.1.1.3 Measurement campaign in the case study area Leogang – Saalbach-Hinterglemm

In the case study area, no ground-temperature measurement stations from the Austrian Weather Service were present, though these are needed for model validation. Hence, in late October 2016, drillings at four locations have been carried out reaching depths between 1 and 3 m (see Figure 7).

![Image](image-url)

Figure 7: Locations of the accomplished temperature monitoring sites in the municipality of Leogang, Salzburg.

The initial attempt was to drill up to a depth of 3 meters at all locations but this goal was not reached due to underground properties. At all locations, the measurement chains have been installed and drill-holes have been re-filled with excavation material mixed with bentonite pellets in order to achieve good connection to the surrounding soil/sediments. In November, the completion of all prepared measurement stations has been carried out. The temperature measurement chains have been connected to the prepared data-loggers and to the battery. The solar panels were installed on top of the cased data-loggers and connected to the battery in order to ensure power supply. Two stations were realized in the valley at about 800 m, two further up the mountain at 1230 m (south slope) and 1400 m (north slope) (locations see Table 6).

Table 6: Locations of temperature measurement stations with their coordinates and positions.

<table>
<thead>
<tr>
<th>Location</th>
<th>Coordinates (UTM33N)</th>
<th>Elevation</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hirnreit Stadlbauer</td>
<td>332319,909213 / 5256456,26253</td>
<td>760 m</td>
<td>Sedimentary filled valley, about 40 m from the river “Leoganger Ache”</td>
</tr>
<tr>
<td>Sonnberg Neuhäuslsiedlung</td>
<td>329543,974703 / 5256671,43535</td>
<td>810 m</td>
<td>Sedimentary filled valley, about 70 m from the river “Leoganger Ache”</td>
</tr>
<tr>
<td>Sonnberg Riedlalm</td>
<td>328655,512931 / 5258007,46964</td>
<td>1230 m</td>
<td>Northern Calcareous Alps, southern slope</td>
</tr>
<tr>
<td>Asitzbahn Mittelstation</td>
<td>327496,823213 / 5254786,60606</td>
<td>1400 m</td>
<td>Eastern Alps, northern slope</td>
</tr>
</tbody>
</table>

The measurement chains consist of single digital thermometers (Thermistors Ds18b20) measuring the underground temperature. They are attached to a data cable in depths of 10 cm, 20 cm, 50 cm, 1 m.
1.5 m and 3 m below surface. The data loggers are based on an Arduino Micro controller and were, after programming, connected to the measurement chains. Lead accumulators and a solar panel supply power. Data are collected every two hours and stored on an SD card, one sample per day is transmitted via SMS protocol and can be downloaded in *.csv format. The drillings were carried out using an electric hammer. Dependent on underground properties, the drillings reached depths of 1 to 3 m. Samples were taken from the drilling cores in order to perform soil analyses, the remaining material, mixed with bentonite pellets, was used to backfill the drillings.

Table 7: Number and depth of temperature measurement sensors including the lithological description of the soil and sediments in which they are buried. At the location « Hirnreit Stadlbauer », one string of the measurement chain does not function anymore and thus is not able to deliver the temperature values. Only the 10 cm and the 50 cm sensor are still recording temperature values, the others are marked in yellow.

<table>
<thead>
<tr>
<th>No. and depth of sensors</th>
<th>Lithological description of soil/sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hirnreit Stadlbauer</strong></td>
<td></td>
</tr>
<tr>
<td>1 - 10 cm</td>
<td>A-horizon</td>
</tr>
<tr>
<td>2 - 20 cm</td>
<td>Gravel, sandy; material starts to get more coarse – (fine-grained) gravel fraction increases progressively; some components &lt;5 cm are distributed</td>
</tr>
<tr>
<td>3 - 50 cm</td>
<td></td>
</tr>
<tr>
<td>4 - 100 cm</td>
<td></td>
</tr>
<tr>
<td><strong>Sonnberg Neuhäuslsiedlung</strong></td>
<td></td>
</tr>
<tr>
<td>1 - 10 cm</td>
<td>Gravel, sandy, slightly clayey; components ≤ 2 cm, med-brown</td>
</tr>
<tr>
<td>2 - 20 cm</td>
<td>More grey than first section; larger components (≤ 4 cm); gravel, sandy, slightly clayey</td>
</tr>
<tr>
<td>3 - 50 cm</td>
<td></td>
</tr>
<tr>
<td>4 - 100 cm</td>
<td>Light brown sediment; sandy gravels, gravel up to 5 cm, often broken</td>
</tr>
<tr>
<td>5 - 150 cm</td>
<td>Sediment turns more red, gravel components smaller, no large components appear.</td>
</tr>
<tr>
<td>6 - 200 cm</td>
<td></td>
</tr>
<tr>
<td>7 - 300 cm</td>
<td>Like section 150 – 200 cm but with components up to 8 cm, broken (while drilling activities?)</td>
</tr>
<tr>
<td><strong>Sonnberg Riedlalm</strong></td>
<td></td>
</tr>
<tr>
<td>1 - 10 cm</td>
<td>A and B-horizon; rich in organic matter; rooted; dark-brown sediment with gravel (≤ 4cm), clayey</td>
</tr>
<tr>
<td>2 - 20 cm</td>
<td></td>
</tr>
<tr>
<td>3 - 50 cm</td>
<td>Silty, sandy clay; gravel, light-brown sediment, more stones i.t lowest 5 cm; components mainly Werfen Fm.</td>
</tr>
<tr>
<td>4 - 100 cm</td>
<td></td>
</tr>
<tr>
<td>5 - 125 cm</td>
<td>Rocky material; less clay; weathering zone</td>
</tr>
<tr>
<td>6 - 75 cm</td>
<td>Silty, sandy clay; gravel, light-brown sediment, more stones i.t lowest 5 cm; components mainly Werfen Fm.</td>
</tr>
<tr>
<td>7 - few cm</td>
<td>A-horizon</td>
</tr>
<tr>
<td><strong>Asitzbahn Mittelstation</strong></td>
<td></td>
</tr>
<tr>
<td>1 - 10 cm</td>
<td>A-horizon</td>
</tr>
<tr>
<td>2 - 20 cm</td>
<td>Clayey, wet and, rooted; brown sediment (B-horizon?)</td>
</tr>
<tr>
<td>3 - 50 cm</td>
<td></td>
</tr>
<tr>
<td>4 - 100 cm</td>
<td>Clayey, wet; grey sediment with more coarse material</td>
</tr>
<tr>
<td>5 - 75 cm</td>
<td></td>
</tr>
<tr>
<td>6 - few cm</td>
<td>A-horizon</td>
</tr>
<tr>
<td>7 - few cm</td>
<td>A-horizon</td>
</tr>
</tbody>
</table>
Catalogue of operational criteria and constraints

GRETA is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme. See more about GRETA at www.alpine-space.eu/projects/greta.

Figure 8: Photos of drilling activities and the completed temperature measurement stations in the municipality of Leogang, Salzburg.

Figure 9: Geological map 1:200 000 of the Leogang valley

Figure 10: Schematic cross section of the Leogang valley
Interesting is the fact that - almost over the whole measurement period – the two stations located at the mountains show a huge offset in temperature even though they are at about the same altitude. The south-facing station (Sonnberg) behaves pretty much like the stations in the valley. Due to an early snow cover in November, the soil temperature stays above zero at all locations. The earliest, thickest and longest lasting snow cover is at the north facing station 4 (Bergbahn). Here, the temperature drop is the least significant (only about 3 °C). Large temperature differences (7 – 12 °C) were measured in March between the snow covered and snow free stations.

3.1.1.4 Conclusions

Table 8 is a compilation of mean air temperature, the linear regression of the temperature with altitude, and the modelled soil temperature in 50 cm depth. The modelled 50 cm depth temperature values are all higher than the mean air temperature, least significant (+0.2 °C) at the north facing station “Asitz”. The measured annual mean temperature at the Leogang stations in not yet available, since the observation period is too short. Figure 12 shows the time series of measured temperature data.

Since the input data are not yet available for the period of temperature measurement and vice versa no calibration data is available for the available period of model input data the comparison between measured and modelled temperature values can only be carried out quite limited at a qualitative basis. Figure 13 shows the input data for the same time interval but one year before the measured values. The model results (Figure 14) cannot reproduce the big offset between the two elevated stations, but the temperature at the south-facing station is slightly elevated compared to the north flank.

Table 8: Compilation of mean air temperature, linear regression of the temperature with altitude and the modelled soil temperature in 50 cm depth.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Altitude [m]</th>
<th>Exposition</th>
<th>$T_{\text{air}}$ [°C]</th>
<th>$T_{50\text{cm}}$ (calc) [°C]</th>
<th>$T_{50\text{cm}}$ (mod) [°C]</th>
<th>$T_{50\text{cm}}$ (measured) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hirnreith</td>
<td>760 m</td>
<td>Valley, flat</td>
<td>8.8</td>
<td>9.5</td>
<td>10.6</td>
<td>not yet available</td>
</tr>
<tr>
<td>Neuhäusl</td>
<td>810 m</td>
<td>Valley, south</td>
<td>8.6</td>
<td>9.3</td>
<td>10.4</td>
<td>not yet available</td>
</tr>
<tr>
<td>Sonnberg</td>
<td>1230 m</td>
<td>South</td>
<td>7.0</td>
<td>7.4</td>
<td>8.9</td>
<td>not yet available</td>
</tr>
<tr>
<td>Asitz</td>
<td>1400 m</td>
<td>North</td>
<td>6.5</td>
<td>6.7</td>
<td>7.9</td>
<td>not yet available</td>
</tr>
</tbody>
</table>

Sources:

- $T_{\text{air}}$ Average of Spartacus dataset 2006 – 2016
- $T_{50\text{cm}}$ (calc) Calculated after Soil T (this study) [Table 4]
- $T_{50\text{cm}}$ (mod) A-priori SoilTempSim result, average 2015
- $T_{50\text{cm}}$ (measured) Annual mean from measured values – not yet available (measured time too short)
Catalogue of operational criteria and constraints

GRETA is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme.

See more about GRETA at www.alpine-space.eu/projects/greta.

Figure 12: Climatic input data.

Figure 13: Daily mean temperature at 50 cm depth (model result)
REFERENCES OF THIS SECTION


### 3.1.2 Effective thermal conductivity

<table>
<thead>
<tr>
<th>Natural operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective thermal conductivity</td>
<td>Property of a material to conduct heat. Dependent on the physical properties of the subsurface</td>
<td>[W/m K]</td>
<td>Anisotropy, compactness, crevasse formation, grain size, permeability, porosity, rock type, soil type, water content</td>
</tr>
</tbody>
</table>

**Definition:** “thermal conductivity” expressed as $\lambda$:

The thermal conductivity is the property of a material to conduct heat and is dependent on the physical properties of the subsurface (geology and hydrology). The unit is [W/(m·K)] and following the simple definition it is defined as the heat flow that transfers in a steady state condition through a homogeneous body exposed to a temperature gradient of 1 K per meter [1] (SIA 384/6, p.9). It is dependent on the composition of the subsurface, and also on its state. In the steady state case, when the system does not change temperature with time, the amount of heat transferred per unit area per unit time is proportional only to the thermal conductivity and the temperature gradient [2]. The Fourier's law states that, for a certain heat flow, the temperature gradient is inversely proportional to the thermal conductivity of the material through which the heat is being transmitted by heat conduction [3].

**Definition:** “effective thermal conductivity” expressed as $\lambda_{\text{eff}}$:

The effective thermal conductivity in [W/(m·K)] is the mean bulk thermal conductivity of a composite medium which characterizes appropriately heat conduction across the entire sample [1].

In general, heat transfer in the underground is a main factor for the performance of near surface geothermal systems as it describes how fast heat can recover after extraction. The main carrier is (flowing) water, though also solid rock is transporting heat. Values for thermal conductivity of rock types vary in a broad range dependent mainly on mineral composition and texture. As a general statement, it can be said that rocks with higher thermal conductivity values bear higher potential for the usage of geothermal energy via borehole heat exchangers and horizontal collectors. That makes thermal conductivity of the bedrock a very important parameter for designing the necessary number, length and separation of near surface geothermal energy (NSGE) vertical system (NSGE-V).

Thermal conductivity threshold values were compiled after researching among various sources of literature such as ASHRAE [35], UNI 11466 [36], Kappelmeyer and Haenel (1974, [3]), Zoth and Haenel (1988 [37]), VDI 4640 - sheet 1 [38], SIA 384/6 [1] and are displayed in Table 23 in the Annex chapter.

Table 23 and Figure 17 to Figure 20 show graphs of the compiled values for the categories unconsolidated sediments, sedimentary rocks, magmatic and metamorphic rocks. Values indicated as green squares have been measured at the laboratory of the Geological Survey of Slovenia. As these graphs indicate, the variations of thermal conductivity values for the same type of rock are often quite large.
In the category of unconsolidated (loose) sediments, variations are huge mainly due to the degree of water saturation, as rising water content increases the values significantly. “Dry” unconsolidated sediments in general show the lowest thermal conductivity values of all rock types, the highest values are typical for dolomite and sandstone, for sandstone especially if it is rich with quartz.

### 3.1.2.1 Thermal conductivity measurements in Cerkno (Slovenia)

In 2016 – 2017, a rock sampling campaign in the region of Cerkno was carried out aiming at performing thermal conductivity measurements of the most characteristic geological units. The campaign was planned based on existing geological maps and new findings in order to collect samples from the region’s most representative rock types, with special focus on very heterogeneous varieties of rocks.

Sixteen samples (30 single rock pieces) from the area of the Cerkno town and 16 samples (23 single rock pieces) from the wider Cerkno municipality were analysed. Altogether 53 single rock pieces have been collected and measured, representing 32 different rock types (samples).

The high precision noncontact thermal conductivity measurements were carried out using an optical thermal conductivity scanner (TCS) [2, 3]. The samples were prepared to meet the requirements of the TCS measurements. Big effort was put to keep the samples as intact as possible and to keep their moisture in original condition until the measurement campaign, as they were not additionally saturated. When applying the TCS method, it is necessary to draw a black line with acrylic paint along the scanned flat surface of each sample (see Figure 14a). For the TCS method, a low tolerance is prescribed for the flatness of the sample (+/- 0.5 mm), and hence a great majority of samples were cut with a circular saw to cope with this requirement. A precision of ±3 % can be achieved in the measurement range of 0.2 to 25 Wm⁻¹K⁻¹.
Catalogue of operational criteria and constraints

For the region of Cerkno, measurement results demonstrate that rocks with high thermal conductivity values, and thus, higher potential for NSGE use, are (with value ranges of the measured rock pieces in \([\text{W}/(\text{m} \cdot \text{K})]\)):

- Dolomites, massive and layered, [3.33 to 5.94]
- Quartz sandstones, [3.47 to 5.73], and quartz conglomerates [3.85 to 5.37]
- Dolomitic limestones, [2.78 to 3.29]
- Different varieties of tuffs (keratophyre, porphyre), [2.76 to 4.31]

In addition, some other rock types (with value ranges in \([\text{W}/(\text{m} \cdot \text{K})]\)) should not be neglected, such as:

- Limestones [1.86 to 3.07]
- Carbonate sandstones [2.19 to 3.42]
- Siltstones [1.60 to 3.86]
- Diabase [2.49 to 3.25]

The results of this measurement campaign were compared to the values from standards [4, 5, 6, 7], as well as to literature values [8]. The comparison is visualized in Figure 17 and Figure 19, showing that standard/literature as well as measured values are in good agreement. The red dots in these figures are the recommended values for calculations - suggested from the standards themselves. Some of these values are at the low end of the range. However, one can observe a very wide range of values for certain types of rocks from the Cerkno municipality. This is due to the heterogeneity of individual rock pieces (samples), which depends also on their state. Heterogeneity is generally more typical and
highlighted for clastic rocks (Figure 16a, for example), while the carbonate rocks usually do not show large variations of thermal parameters along the scanning line (Figure 16b, for example).

Figure 15a: TC profile of a sandstone sample
Figure 15b: TC profile of a dolomite sample
Figure 15: Comparison of two thermal conductivity profiles for a) sample of clastic rock (sandstone), showing the wider range of values and b) carbonate rock (dolomite), showing the narrower range of values.

Due to well-known difficulties inherent within some older measurement methods, especially:

- a transient hot wire method [39, 40],
- and probably to a minor extent a transient heat impulse method [41]
- as well as a needle probe method [42],

we are convinced that more accurate values can be achieved nowadays by using the TCS method. This method can be compared in a scientific way with the accurate results to the heat impulse method and the well-known divided bar method [2].

Figure 16: Thermal conductivity values for magmatic rocks. Red dots indicate recommended values for calculations from the standards themselves. Green dots are the arithmetic means of measured values on rock samples (usually few rock pieces for every sample) at GeoZS (using the TCS method) and yellow dots are measured values on saturated rock samples from Austrian Central Alpine units (as recommended values) at Leoben Univ. (using the transient needle probe method with TK04 meter).
Figure 17: Thermal conductivity values for metamorphic rocks. Red dots indicate recommended values for calculations from the standards themselves, and yellow dots are measured values on saturated rock samples from Austrian Central Alpine units (as recommended values) at Leoben Univ. (using the transient needle probe method with TK04 meter). For the latter a grouping of values was done for sake of simplification.

Figure 18: Thermal conductivity values for sedimentary rocks. Recommended values for calculation: red dots indicate recommended values for calculations from the standards themselves. Green dots are the arithmetic means of measured values on rock samples (usually few rock pieces for every sample) at GeoZS (using the TCS method) and yellow dots are measured values on saturated rock samples from Austrian Central Alpine units (as recommended values) at Leoben Univ. (using the transient needle probe method with TK04 meter).
Figure 19: Thermal conductivity values for unconsolidated sediments. Red dots indicate recommended values for calculations from the standards themselves and a yellow dot is a measured value on saturated sample (as recommended value) at Leoben Univ. (using the transient needle probe method with TK04 meter).

REFERENCES OF THIS SECTION

[38] VDI, VDI 4640 - Thermal use of underground, 2010.
3.1.3 Effective heat storage capacity

<table>
<thead>
<tr>
<th>Natural operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat capacity or volumetric heat capacity</td>
<td>Amount of heat that can be absorbed and emitted within one period in relation to a temperature deviation of 1 K and 1 kg / 1 m³. Has a low variance and is therefore usually estimated.</td>
<td>[J/kg K] or [J/m³K]</td>
<td>Temperature, Density</td>
</tr>
</tbody>
</table>

The specific heat capacity is defined by the amount of heat that is absorbed or emitted by one kilogram of material leading to a temperature change of 1 K. The volumetric heat capacity is the product of the specific heat capacity at constant pressure and the density \( \rho \) of the material, therefore, the amount of heat that is absorbed or emitted by one cubic meter of material leading to a temperature change of 1 K. It is preferable to accept the volumetric rather than the specific heat capacity as a thermal property, since it has a lower variance. For a great majority of minerals and impervious rocks it lies within 20 % of \( 2.3 \times 10^{-6} \text{ J m}^{-3} \text{ K}^{-1} \) (Beck, 1988, p.88, Ref. [43]). It has a low variance and is therefore usually estimated.

3.1.4 Aquifer temperature

<table>
<thead>
<tr>
<th>Natural operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer temperature</td>
<td>Together with the maximum possible temperature spread, the aquifer temperature indicates the thermal potential</td>
<td>°C</td>
<td>Thickness of the unsaturated zone, aquifer thickness, hydraulic gradient (groundwater velocity), permeability/ hydr. conductivity, surface water interaction, groundwater recharge (rate and temperature), existing groundwater usage, hydraulic anisotropy, dispersivity</td>
</tr>
</tbody>
</table>

The aquifer temperature, similarly to the ground temperature, is a key parameter for the calculation of NSGE potentials as well. In open loop systems, the temperature of the pumped groundwater is directly used, e.g. in a heat pump, and therefore the key parameter for the efficiency of the system. The aquifer temperature will also influence closed loop systems reaching into aquifers. In addition, the advective heat transport by groundwater flow will constantly dissipate heat from the ground heat exchanger.

In contrast to the mainly conductive heat transport in the unsaturated ground, advective heat transfer generally governs the heat transport in the groundwater. Groundwater flow in aquifers of different depth will therefore result in a disturbance of the subsurface thermal regime (Powell et al. 1988). The capability of an aquifer to create thermal disturbances with advection depends initially on the permeability. For permeabilities less than \( 1.0 \times 10^{-17} \text{ m}^2 \) the thermal regime is described as entirely conductive and only aquifers with greater permeabilities will be increasingly affected by advective heat transport through groundwater flow [44].

The transition from conduction-dominated to advection-dominated thermal regimes is sharp and depends primarily on the topographic configuration of the water table, the magnitude and spatial distribution of permeability, hydraulic anisotropy, and the depth of active flow [44]. In addition, the aquifer temperature is dependent on the drainage area, the retention time of the water in the aquifer and the amount and temperature of the groundwater recharge. Due to the formation history of the
aquifer, permeabilities may also vary significantly in horizontal or vertical direction. Therefore, lateral and vertical thermal disturbances can be differently present. On sites with high hydraulic anisotropy, the changed heat flow can have significant influence on the planning of thermal groundwater uses, like ATEs [45]. In summary, complex interactions of multiple parameters govern the development of aquifer temperatures and the hydraulic conditions can have significant influence on the regional subsurface heat flux.

Considerable thermal disturbances can also occur in areas where hydraulically connected surface water reservoirs infiltrate into aquifers. Because of its direct exposure to the atmosphere, the temperature fluctuation of surface water is extreme, compared to groundwater. Thermal anomalies in aquifers adjacent to surface waters are commonly observed and the tracing of surface water infiltration is a well-established research topic in hydrogeology [46]. In areas where the hydrogeological setting is poorly known, however, this phenomenon will increase the difficulty of correct thermal regime interpretations.

In urban areas, the heat island effect will also influence the shallow aquifers below cities. This effect is observed in many cities of the Alpine Space and studies reviewed the possible advantage for the geothermal potential [47, 48]. Also in the urban area of Munich this phenomenon was observed. Near the city centre, aquifer temperatures near 20°C can be measured. In this areas, the thermal use of the aquifer for cooling purposes is very limited, due to the legal restriction that the aquifer temperature must not be artificially elevated above 20 °C. It was observed that low depths to water table and a low aquifer thickness supports the temperature rise in the quaternary aquifer. In channel structures of quaternary gravel with higher aquifer thickness, the heat dissipation is enhanced and temperatures stay on a level where the thermal use of groundwater for cooling is still possible.

To get a spatially reasonable picture of the temporally dynamic groundwater head and the aquifer temperature, a cut-off date measurement of groundwater wells and hydraulically connected surface water bodies and springs is necessary. Within the GRETA project, the area of the German study case area, the Upper Iller valley will be examined by such a measurement campaign, to get comprehensive information on the geothermal key parameters aquifer temperature and aquifer thickness.

The depth to the exploitable aquifer determines the pumping energy demand of the system and is therefore an important parameter that has to be considered for efficiency calculations.

3.1.5 Transmissivity

The transmissivity determines the size of the drawdown cone for a given pumping rate. The pumping head is the sum of groundwater depth plus drawdown cone.
REFERENCES OF THIS SECTION

3.2 Demand side (design operational criteria)

Key issues for the design of geothermal heat pump systems are the thermal load and the annual energy demand of the building. Particular attention should be paid to the correct sizing of the system, in order to maximize the efficiency and keep it economically competitive compared to conventional combustibles. For this reason, a correct analysis of the technical and economic efficiency of a NSGE system requires a detailed and precise evaluation of the thermal loads of the building. The energy demand of the construction, to be met by the geothermal heat pump, depends on a large number of variables, of which the most relevant are:

- **Climatic condition** (external air temperature and solar irradiance)
- **Building type** (related to the final use, occupancy and internal heat gains)
- **Envelope thermal insulation** (thermal resistance of windows, walls, ceilings and floors)

In this chapter, a study about the identification of thermal load curves for different types of buildings in the Alpine space is described. The results of this analysis will further be the starting point for the study on operational criteria for GSHP/GWHP systems performed in chapter 4 of this deliverable.

A total number of 36 different cases were identified according to climate, building type and insulation, in order to cover a wide range of real applications in the Alpine space. Afterwards, thermal loads were assessed by means of transient simulation software TRNSYS, which allows to create a detailed model of a building and calculate the hourly energy balance between occupancy, walls and external ambience over a period of 1 year, using the TRNBuild module. The model is shown in Figure 20.

![Figure 20: Scheme of the transient model for thermal load evaluation (TRNSYS)](image)

The building (type 56) interacts with weather data from Meteonorm database and with a distribution system in order to keep the internal temperature at the specified set point (20 °C during winter, 26 °C during summer), by means of a thermostat component (type 108). Fan coils are supposed to work with an inlet/outlet water temperature of 50/40 °C, and they are controlled with variable air flow rate strategy in order to provide the required thermal power. Fan coils can be installed also in existing buildings as energy retrofit measure. For each model, an operating schedule of the building is set according to occupancy and use. Simulations were run for 1 year of operation of the heating/cooling.
system, and thermal load curves for heating and cooling as well as for annual energy consumption were analysed. The energy demand for Domestic Hot Water (DHW) was also evaluated, considering a storage temperature of 60 °C and a consumption of 50 l/day per person for residential housing, 60 l/day for hotel occupants and 0.2 l/m² for the office building, as prescribed from Italian norm [49].

Climatic condition
The Alpine space is a wide region characterized by very different climatic areas, ranging from cold mountain climate to the Mediterranean climate at the seaside. The main climatic parameters that influence the energy demand profile of a building are the external air temperature and the solar irradiance; the latter especially is a key driver for cooling demand during summer. According to the climatic zones identified in the Chapter 2.2 of the previous project deliverable (D.3.1.1.), six different cities were selected as representative of the Alpine space, one for each climatic area:

Table 9: Selected cities for the study covering all climatic zones, average annual temperature and heating/cooling degree days

<table>
<thead>
<tr>
<th>City</th>
<th>Climate zone</th>
<th>Average annual temperature [°C]</th>
<th>Heating Degree Days</th>
<th>Cooling Degree Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genoa (IT)</td>
<td>A</td>
<td>15.8</td>
<td>1375</td>
<td>558</td>
</tr>
<tr>
<td>Koper (SLO)</td>
<td>B</td>
<td>14.6</td>
<td>1995</td>
<td>504</td>
</tr>
<tr>
<td>Laigueglia (IT)</td>
<td>C</td>
<td>15.2</td>
<td>1459</td>
<td>419</td>
</tr>
<tr>
<td>Turin (IT)</td>
<td>D</td>
<td>12.2</td>
<td>2453</td>
<td>322</td>
</tr>
<tr>
<td>Graz (AU)</td>
<td>E</td>
<td>8.4</td>
<td>3528</td>
<td>27</td>
</tr>
<tr>
<td>Davos (CH)</td>
<td>F</td>
<td>3.3</td>
<td>5356</td>
<td>0</td>
</tr>
</tbody>
</table>

Building type
Geothermal heat pumps can be used to meet the energy demand for heating, cooling and domestic hot water (DHW) for different final uses, such as residential houses and offices. The final use of the building determines different occupancy schedules, internal gains generated by people and appliances and architectural elements of the building itself (i.e.: large windowed area in office buildings). Three different types of building were considered in the analysis, and modelled starting from existing buildings:

- Residential house (unoccupied during the day, low internal gains)
- Office (occupied 10 hours/day during the working week, high internal gains)
- Hotel (occupancy distributed throughout the year, seasonal schedules)

Buildings were modelled using the SketchUp plugin (see Figure 21) and implemented in TRNSYS with occupancy schedules defined according to the building use, as reported in Table 10.

Figure 21 : Building models for residential house (A), office (B) and hotel (C)

---

1 data obtained from Meteonorm weather database
2 calculated according to ASHRAE method, with a base temperature of 18 °C
Table 10: Building schedules for heating and cooling

<table>
<thead>
<tr>
<th>Building</th>
<th>Heating</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monday</td>
<td>Week day</td>
</tr>
<tr>
<td>House</td>
<td>6–8 am</td>
<td>6–8 am</td>
</tr>
<tr>
<td>Office</td>
<td>4 am – 6 pm</td>
<td>6 am – 6 pm</td>
</tr>
<tr>
<td>Hotel</td>
<td>Always on</td>
<td>Always on</td>
</tr>
</tbody>
</table>

Envelope thermal insulation

NSGE technology can be applied both to new and existing buildings. New constructions are particularly well suited for heat pumps because of the lower peaks required for heating and cooling, however also old and historical buildings can be retrofitted and high temperature radiators can be replaced with low temperature radiators and fan coils, which can be coupled with geothermal heat pump systems. Therefore, two typologies of thermal insulation of the building where considered for the analysis:

- **Poor insulation**: typical for old buildings (period: 1930 - 1975), low quality or no insulation of walls, ceilings and floors, single-glazed windows and highly conductive frames
- **Good insulation**: new building envelope (period: 2000 - today), low-conductivity walls, ceilings and floors, double-glazed windows and low-conductivity frames

Data for thermal transmittance of walls and windows were taken from TABULA database [50], and summarized in Table 11.

Table 11: Thermal transmittance values of architectural components defined in the building models

<table>
<thead>
<tr>
<th>Component</th>
<th>U-value [W/m²K]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good insulation</td>
</tr>
<tr>
<td>External wall</td>
<td>0.28</td>
</tr>
<tr>
<td>Floor slab</td>
<td>0.51</td>
</tr>
<tr>
<td>Roof</td>
<td>0.24</td>
</tr>
<tr>
<td>Floor</td>
<td>0.15</td>
</tr>
<tr>
<td>Internal wall</td>
<td>2.36</td>
</tr>
<tr>
<td>Interfloor</td>
<td>1.78</td>
</tr>
<tr>
<td>Window</td>
<td>1.43</td>
</tr>
</tbody>
</table>
3.2.1 Peak power

<table>
<thead>
<tr>
<th>Design operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power</td>
<td>Peak power required by the building in heating and cooling</td>
<td>[kW] – [W/m²]</td>
<td>Thermal insulation, ambient temperature, solar irradiance</td>
</tr>
</tbody>
</table>

The peak power is defined by the energy power required by the building in heating and cooling mode. It is the design value for the sizing of the heat pump and it is dependent mainly on external ambient conditions and the thermal insulation of the building.

Results of the simulations are reported in Figure 22. The unit peak load for heating and cooling, calculated as peak load in kW over the total floor area of the building, is far more dependent on insulation quality than on building usage. The poorly insulated residential house and hotel are characterized by similar values of unit peak power, except for a slightly higher cooling demand of the hotel. High internal gains related to the appliances (computer and electrical devices) within the office building leads to high thermal peak load requirements for cooling, even in colder regions. Buildings with high quality insulation have thermal loads sensibly lower than poorly insulated buildings, as heating loads are reduced by 50 - 70 %. A good insulation envelope reduces the cooling load in hot climates, however it introduces a cooling energy need also in colder climates, as internal gains become important, especially for the office building. Peak loads for heating and cooling are generally more balanced in well-insulated buildings, especially for the climate zones B, C and D. This condition is particularly favourable for the installation of a single reversible heat pump, which is able to operate both in heating and cooling mode.

The amount of energy exchanged with the ground during the year affects the soil temperature and therefore the future performance of the system. For this reason, an overall annual balance between heat extracted from and injected into the ground is the most desirable condition in order to maintain a high efficiency of the NSGE system during the years. In particular, the office building has very balanced peak loads in each climatic condition, therefore the thermal impact on the ground is minimized and the efficiency of the NSGE system is maximized. It is interesting to note that in most of the analysed cases the heat pump should be sized for the heating peak load, since its value is often higher than the cooling load.
Heat pumps are usually installed to cover only a fraction of the thermal demand, and a backup system is used to cover the peaks during the year. Another common technique is the application of storage tanks to buffer peak load. The use of a backup system is usually limited to heating, as gas boilers are easy to install and the installation cost is very low, compared to water chillers for cooling purposes, while storage tanks can be used as heat and cold storage. The results of the simulations show that the percentage of heating demand that a heat pump can cover if sized for a thermal power lower than the required peak load is mainly dependent on characteristics of the building, as usage and insulation, than on climatic condition. As depicted in Figure 23, a heat pump sized for almost 50% of the peak heating load is able to meet more than 90% of the total yearly energy demand. Similar results were found in previous studies [51]. Generally, high insulation envelopes cut the peaks of thermal energy required.
during the year, especially for buildings with high requirements for air change and comfort, such as hotel and office buildings; hence, the fraction of heating demand that can be covered with a heat pump designed for a capacity lower than the maximum peak value increases. For this reason, cumulate load curves of well-insulated buildings are shifted up compared to the poor insulation case (Figure 23; Figure 24). This means that combined heating systems with a heat pump for baseload covering and a backup system for peak loads are even more suitable for new buildings. Hence, the installation cost of the NSGE system can be lowered significantly. Detailed research on installation costs of NSGE systems is carried out as part of WP5 (Integration of the Near Surface Geothermal Energy into Energy Plans). Additionally, using the heat pump for covering peak load results in frequent on/off switching, which negatively affects the lifespan of the heat pump. Peak load for DHW production is much lower than the heating and cooling loads (Table 12). The thermal peak load for DHW in office and hotel buildings is almost negligible, while it has a certain weight in residential detached house, especially for the good insulation case.

Since the cumulative heating load curve could have an important influence on the installation cost, and therefore on the economic feasibility of the system, we compared the cumulative curve obtained from the TRNSYS simulations with real monitored data of a recent residential building in Bolzano. The climatic zone of Bolzano is D with 2605 heating degree days. The monitored buildings are part of a new residential area in Bolzano (941 apartments for about 3500 people) that is called: “Casanova”. Casanova was constructed from 2008 to 2012, implementing and using innovative and efficient technologies for the heating and cooling system, with a monitored total heating averaged consumption for the year 2014 of 50 kWh/m² [52].

The comparison (Figure 24) shows that the curves of well-insulated residential house and Casanova complex are quite similar, with some differences due to the different shape of the building and occupants usage.

![Figure 23: Cumulate heating load curves of the heat pump, for buildings with poor insulation and different typologies](image)
3.2.2 Thermal demand

<table>
<thead>
<tr>
<th>Design operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal demand</td>
<td>Thermal demand required by the building both in heating and cooling</td>
<td>[kWh/y] – [kWh/m²/y]</td>
<td>Building use, ambient temperature, thermal insulation</td>
</tr>
</tbody>
</table>

Thermal demand is defined as the thermal energy required by the building both in heating and cooling mode during the year by a single building. It is dependent on the type of thermal energy use for heating (or cooling), i.e. the types of thermal heating and cooling installations (HVAC distribution system installed), the season length for heating and cooling and the external ambient temperature evolution throughout the year. Energy required for heating/cooling is usually expressed in kWh/m²y of occupied floor area of the building and has a sinusoidal trend over the year, as it is strongly influenced by the external air temperature. The annual energy demand for heating and cooling for each studied case is reported in Figure 26.
Figure 25: Monthly energy demand of a new office building, for different climatic zones (positive for heating, negative for cooling).

Figure 26: Annual energy demand for heating and cooling for different climatic zones, building typologies and insulations.
As Figure 26 shows, the poorly insulated buildings have quite similar energy demand for heating, which confirms that the heating need is mainly determined by external ambient conditions. With a low thermal insulation, the transmittance of walls and windows is very high and therefore, thermal inertia is very low. This means that the effect of internal gains and occupancy are negligible when compared to the external ambient temperature. Heating energy consumption is similar for buildings in climatic zones A, B and C. The amount of energy required to heat a building located in region “F” is almost four times higher than the heating need of a building in zone “A”. Modern buildings are built with low thermal transmittance walls and windows, which reduce drastically the energy consumption for heating (up to 80 % reduction), however usually they require energy for cooling even in climatic areas where such need is equal to zero for poorly-insulated buildings. Consequently, the cooling season is usually longer for well insulated buildings, because of the higher relative influence of the internal gains during the warmer months of the year [53]. The cooling demand of the office building is quite high in almost every of the climatic zones, due to the high internal gains of computers and appliances and the large windowed area which increases the solar gains. The office with good insulation envelope resulted to be the building with the most balanced energy demand for heating and cooling for most of the climate zones taken in consideration in the analysis. The energy demand for DHW is relatively high for the modern residential house with good insulation, as the energy consumption for heating is very low, while for the other typologies its value is always lower than 15 % of the total heating demand, as shown in Table 13.

### Table 13: Fraction of energy demand for DHW production over heating demand for different building typologies and insulations

<table>
<thead>
<tr>
<th>Building type</th>
<th>Poor insulation</th>
<th>Good insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>4-10 %</td>
<td>17-50 %</td>
</tr>
<tr>
<td>Office</td>
<td>0.5-2 %</td>
<td>3-15 %</td>
</tr>
<tr>
<td>Hotel</td>
<td>0.5-1 %</td>
<td>2-4 %</td>
</tr>
</tbody>
</table>

Comparison of simulation results of energy demand for heating for residential building and the monitored data from different apartments of Casanova complex in Bolzano are summarized in Table 6. The energy consumption obtained from TRNSYS simulation is slightly underestimated compared to the monitored data from the real case. However, the same occurs for the results of the simulations that were performed to design the heating system of Casanova complex. This highlights that the real energy consumption of the buildings is usually higher than expected. The assumptions made for the utilization of the building by the occupants are usually optimistic from the point of view of the energy saving, and the real energy demand for heating increases due to utilization of natural ventilation instead of mechanical ventilation, higher adopted set-point temperatures as well as energy losses in the distribution network.
Catalogue of operational criteria and constraints

GRETA is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme.

See more about GRETA at www.alpine-space.eu/projects/greta.

Table 14: Annual energy demand for heating of simulated residential building and for Casanova complex, in Bolzano (IT)

<table>
<thead>
<tr>
<th>Building</th>
<th>Annual energy demand for heating [kWh/m²/y]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential house (simulated)</td>
<td>36</td>
</tr>
<tr>
<td>Casanova apartments (simulated)</td>
<td>25-50</td>
</tr>
<tr>
<td>Casanova apartments (monitored)</td>
<td>40-65</td>
</tr>
</tbody>
</table>

3.2.3 Conclusions

The analyses conducted in the previous paragraphs allow some conclusions to be drawn on the suitability of GSHPs for different climate conditions and usage profiles, which are reported in the previous paragraphs. The following aspects have been addressed:

- **Climate zone**
  For the residential building and the hotel, the most suitable demand profile for GS/GWHPs was identified for well-insulated buildings in hot and temperate climates. Offices are characterized by a cooling-dominated or well-balanced demand in most of the climatic zones, especially in the plains and cities (zones B, D). The residential house energy demand is balanced in zone A and C.

- **Building type**
  Office buildings are characterized by large cooling demands due to the high internal gains generated by people and appliances. Therefore, the energy demand is usually more balanced than for residential and hotel buildings. Hotels and residential buildings are characterized by a heating-dominated energy demand; therefore, the economic convenience of the heat pump compared to conventional technologies is reduced and should be carefully assessed. The highest heating peak loads are concentrated in few hours per year, thus allowing designing the heat pump system at only 50% of the maximum load in order to cover more than 90% of the demand.

- **Envelope thermal insulation**
  Residential and office buildings with good insulation have shown similar monthly energy demand profiles for heating and cooling independent of their use. Hotel energy demand is slightly higher due to the strict requirements for comfort. A low-conductive envelope cuts down the heating demand and increases the cooling demand of the building, compared to the poor insulation case. Moreover, there is a peak shaving effect which cuts off the thermal load peaks during the year. In particular, new hotels and offices are well suitable for NSGE systems due to the favourable load curve, characterized by very few peak load hours during the year.

- **Cooling demand**
  The higher the cooling demand, the higher the economic convenience of GSHPs, for the following reasons:
  - For cooling, electricity is the dominant energy vector (absorption heat pumps are rarely used for cooling), and GSHPs allow a significant reduction of the energy expense. It is straightforward that, the larger the cooling demand, the larger the margin for savings.
If cooling of a building is needed, the additional cost for a GSHP compared to conventional cooling techniques is lower than the additional cost compared to conventional heating techniques. Of course, this holds true if the cooling peak load is not much lower than the heating peak load.

The temperature of the shallow geothermal reservoir is normally below the room and the outer air temperature in the cooling season. The resulting low temperature spread the GSHP has to accommodate makes it economically superior to conventional chillers and even to GSHP heating, where the needed spread is higher.

If the ground is sufficiently cold (e.g., at the beginning of the cooling season), the heat exchange can be performed between the building and the ground directly, without the heat pump. This cooling mode is called “free cooling” and it allows significant energy and economic savings.

- **Balance between heating and cooling demand**
  The ideal thermal load is perfectly balanced between heating and cooling, thus avoiding long-term temperature drift of the ground. Office buildings are particularly suited for NSGE applications because of their balanced thermal needs.

- **Domestic Hot Water**
  DHW requires a higher temperature compared to heating terminals (e.g. 60 °C against 50 °C of fan coils). For this reason, a lower heat pump COP is achieved. On the other hand, when the demands for cooling and DHW are combined, the use of heat pumps result in noticeable energy saving, as part of the excess heat from cooling can be used for water heating. The energy demand for DHW is usually only a small fraction on the total energy required for heating and cooling of the building.

**REFERENCES OF THIS SECTION**

3.3 Economic considerations/factors

<table>
<thead>
<tr>
<th>Economic operational criteria</th>
<th>Description</th>
<th>Unit</th>
<th>Dependent on parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment costs</td>
<td>Drilling costs incl. probe realization, heat pump costs incl. installation</td>
<td>€</td>
<td>Consumer behaviour, location of drilling site, total amount of drilled meters, subsurface characteristics, type and size of HP, chemical composition of the GW, drilling diameter</td>
</tr>
<tr>
<td>Running costs</td>
<td>Mainly electrical energy used by the pumps and to a small extent maintenance of the system</td>
<td>€</td>
<td>Electrical energy price, type of system</td>
</tr>
<tr>
<td>Financing</td>
<td>Funding schemes offered by public/private initiatives, interest rates for loans</td>
<td>€</td>
<td>Investment grants, tax reductions, low or zero interest loans, CO2 tax</td>
</tr>
</tbody>
</table>

The assessment of factors that influence the economic efficiency of a NSGE system is still in process and will be a main topic for WP5 (WPT4) “Integration of the NSGE into energy plans” within the three selected pilot areas. As a basic principle, it can be determined that these factors are broadly diversified. Studies on economics of NSGE systems, and in particular of combined systems such as e.g. NSGE – solar panels, have shown the price competitiveness compared to conventional heating systems [54]. The economic efficiency is dependent on multiple parameters of which many are heavily fluctuating due to market dynamics and funding programs, but also more stable parameters of the site suitability (e.g. depth to water table, see Figure 71) are significant.

Generally, one can distinguish between initial investment costs, running costs and the financing. Apart from expectable and relatively stable costs for electrical energy or for heat pumps, large variations of the total investment costs for the NSGE installation result from factors like local market dynamics, national funding programs but also from the consumer’s behaviour to invite offers. The ability to formulate an accurate call for bids, which includes basic knowledge about the system as well as the negotiation skills of the costumer, will influence the investment costs of the installation [55].

In Germany, analyses of 1100 private household’s GSHP installations showed the large variation in capital cost, which is in the range of 23.500 +/- 6.800 € [56]. Blum et al. further stated that capital costs are significantly higher in Germany than in other countries in- and outside the EU, the assumption is that this is mainly due to the economies of scale, but also country-specific legal requirements – which are particularly strict for Germany – might contribute.

3.3.1 Investment costs

**Consumer behaviour**
The behaviour of the consumer in the whole process – from the planning stage through the call for bids until the completion and the negotiation about the maintenance contract – can influence the costs of the NSGE installation substantially [55]. Factors that might influence the installation costs:

- Timely and proper planning
- Formulation of call for bids (the accuracy of the call for bids) – dependent on the state of knowledge about the system by the customer
- Willingness to pay - How obvious the customer signals to be willing to pay & negotiation skills of the customer
Drilling incl. completion of BHE - exemplary from France

From 2009 to 2014 BRGM managed QUALIFORAGE, a quality commitment dedicated to borehole heat exchanger drillers (Qualiforage is now managed by Qualit’EnR) [57]. Prices of BHE realization (i.e. invoiced to the final customer) were collected from 2009 to 2012 per administrative region (see Table 15). The prices integrate the drilling, the loop and the borehole grouting, but neither the trenches nor the connection to the heat pump. The drilling prices in 2017 were estimated assuming a 5.8 % inflation rate from 2011 to 2017 (INSEE data). For most regions (Alsace, Franche-Comté, Rhône-Alpes), the average drilling price estimated in 2017 is between 58 €/m and 60 €/m. The prices depend upon the drilling technology related to geological features. The average price in Franche-Comté is a bit higher (69 €/m), which may be due to a more complex geological environment (karst).

Table 15: Estimation of minimum, average and maximum prices of BHE in the 4 French regions of the Alpine space, expressed in VAT-excluded prices per meter (€/m). Source: BRGM, 2013 [57].

<table>
<thead>
<tr>
<th>Region</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2009 - 2012</th>
<th>2017 (estimation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Avg</td>
<td>Min</td>
<td>Max</td>
<td>Avg</td>
</tr>
<tr>
<td>Alsace</td>
<td>47</td>
<td>70</td>
<td>56</td>
<td>7</td>
<td>47</td>
<td>70</td>
</tr>
<tr>
<td>Franche Comté</td>
<td>45</td>
<td>66</td>
<td>57</td>
<td>3</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>PACA</td>
<td>35</td>
<td>75</td>
<td>53</td>
<td>8</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>Rhône Alpes</td>
<td>46</td>
<td>70</td>
<td>54</td>
<td>8</td>
<td>50</td>
<td>70</td>
</tr>
</tbody>
</table>

Borehole diameter of open loop systems - exemplary from France

Prices for open loop systems have been collected in France through the AQUAPAC insurance. AQUAPAC covers the geological risk of near surface open-loop installations (unexpected low and/or unsustainable flow-rates). Every applicant to the insurance gives the information about the price of the drilling operation (€/m), the well diameter and equipment, the drilling technology and the expected flow-rate, on which the warranty is based. Relations between the drilling price and the diameter have been established for the three most common drilling technologies (odex, down-the-hole drill and rotary) based on 107 applications [58] (cf. Figure 28). The drilling price grows exponentially with the diameter. ODEX leads to the higher drilling prices, followed by down-the-hole drill and rotary.
Heat pump size – exemplary from Austria

Within the project DEGENT-NET (climate- and energy funds, Austria), assessment for heat pump prices in Austria was carried out. Figure 28 illustrates the prices for heat pumps without accessories, planning- and installation services, dependent on their rated power. This evaluation shows how prices per kW of installed power drop significantly when rated power is increased. This effect is not subject of infinite extrapolation - when exceeding the common sizes for heat pumps, prices increase again. Consequently, a common approach is to merge heat pumps for large utilizations [55]. Roughly said, heat pumps with nominal thermal capacities of 20 – 40 kW show the best price/performance ratio of around 400 €/kW.
**Subsurface characteristics – exemplary from Germany**

Blum et al. (2011, [56]) have tried to find economical and technical correlations from the analysis of data from 1100 GSHP installations in the German federal state of Baden-Württemberg. Those were mainly individual households with a typical heating demand of 11 kW and a typical length of 95 m double-U BHE. They concluded that from this dataset, no significant correlations between design-related or subsurface characteristics and financial parameters were observed.

Although maybe not significant, but still present trends were observed – for example in “zone 5”, the so-called molasses zone to the southeast of the study area (brown colour in Figure 29, left), made up of unconsolidated sands and gravels. Figure 29, right, shows the distribution of mean capital cost per kW, indicating that the geological “zone 5” profits from the lowest capital costs per heating demand with 1.935 €/kW. In comparison, “zone 4” with early Triassic clay- and limestones suffers from the highest costs of 2.298 €/kW. The authors link this difference to the market situation rather than the subsurface properties. “Zone 5” can be considered as a pioneer area for NSGE in Baden-Württemberg, thus the local market economy in this zone is well developed and in comparison to other areas already more consolidated.

![Geological Zones in Baden-Württemberg](image1)

![Distribution of mean capital cost per unit heating demand (kW) in Baden-Württemberg](image2)

**Figure 29a:** Geological zones in Baden-Württemberg

**Figure 29b:** Distribution of mean capital cost per kW in Baden-Württemberg

Figure 29: Study by Blum et al. (2011, [56]), left: map of the five defined geological zones in Baden-Württemberg including the locations of all studied GSHP systems; right: spatial distribution of the mean capital cost per unit heating demand (1kW) in Baden-Württemberg using the neighbourhood statistics function.
3.3.2 Operating costs

The collection of best practice examples (see Annex to the Del. 3.1.1.) offers a very rough overview of operating costs. It is important to keep in mind that these examples are displaying an overview of the diversity of NSGE installations rather than a comparable set of data. Thus, values for operating costs cannot be directly compared. The amount of electrical energy used in combination with the costs per kWh represents the largest part of the annual operating costs; costs for maintenance are generally low and are reported to be a maximum of 10 % of the total operating costs.

Electrical energy price

As illustrated in Figure 32 by Büttner et al. (2016, [59]), electrical energy prices are strongly differing for private households and industrial customers. The price difference is most significant for Denmark, where costs for industrial consumers is about 0,08 € vs. for private households it is about 0,30 €. Generally, medium sized households in Germany suffer from the highest electricity prices among the GRETA partner countries and are ranked second in the list of highest electricity prices in Europe after Denmark (see also Figure 31). For all GRETA partner countries, electricity prices almost halves for industrial customers (>500 MWh), which includes most supermarket and hotel operators. This demonstrates that upscaling from single household NSGE installations towards housing estate uses can result in significant cost reductions.

Figure 30: Electricity prices by type of user - for medium size households within the GRETA partner countries: Germany, France, Italy, Austria, Slovenia and Switzerland (no information) per kWh from 2010 – 2016. Source: Eurostat May 2017 [60]. This indicator presents electricity prices charged to final consumers; average national price in €/kWh incl. taxes and levies; medium size household consumer: consumption band Dc with annual consumption between 2500 and 5.000 kWh.
Maintenance

The costs for maintenance of NSGE systems can generally be considered to be very low, especially in comparison to other heating systems, as no costs arise for e.g. exhaust measurements or annual chimney cleaning. Independent of their type, NSGE systems are practically maintenance-free, because no combustion is taking place and components are in a closed system protected from external influences. From many sources one can read that the annual maintenance costs are zero (e.g. Ref.[61]). However, to ensure efficient, long-term performance, professionals suggest an installation audit every 1 to 3 years, as closed-loop collectors should have periodic heat carrier fluid concentration checks and open-loop collector boreholes may need periodic cleaning. Reported costs for servicing of individual household’s NSGE systems are in the range of 50 – 250 €/a (e.g. Ref. [62]).

From the collection of best practice examples (see Annex to the Del. 3.1.1.), only few statements about the costs for maintenance can be made, because only few operators have provided this information. Operators of three medium sized GWHP installations (two industrial sites and one pool heating application), as well as of one BHE field (7 x 120 m wells) report their costs for maintenance are in the range of 500 €/a. One large BHE field using 66 wells, each 120 m deep, is reported to cause annual...
maintenance costs of about 2000 €, though combined with maintenance for their solar panel installation.

3.3.3 Financing

The third part of the economic criteria is the financing of the NSGE installation, which decisively influences the economic efficiency of the system for investors. As the installation usually represents the largest part of the costs, public support schemes for this initial investment are crucial in persuading consumers to choose this type of energy supply.

The project REGEOCITIES (www.regeocities.eu) has addressed this topic and produced a factsheet on support schemes for financing shallow geothermal projects. This factsheet encompasses a map indicating the types of support schemes provided by various European countries. The list of possible schemes are investment grants, feed-in tariffs, tax rebates/VAT reduction, low or zero interest loans and CO2 tax. Two of the GRETA partner countries are displayed, indicated that Italy provides investment grants and VAT reduction and Slovenia provides investment grants and low or zero interest loans.

An excerpt from the compiled information from the “National action plan 2010 for renewable energy for Austria (NREAP-AT)” according to the directive 2009/28/EG of the EU parliament and the council, shows, how different investment grants are offered for different regions in Austria (see Table 16). Apart from the national environmental support act, all federal states offer incentives, though with varying support of 850 – max. 7.000 €.

<table>
<thead>
<tr>
<th>Table 16: Investment grants in Austria</th>
</tr>
</thead>
<tbody>
<tr>
<td>National environmental support act (processed by the Kommunalkredit Public Consulting GmbH)</td>
</tr>
<tr>
<td>&lt; 400 kW: 85 €/kW for 0 – 80 kW, 45 €/kW for every additional kW; max. 30 % of the environmental related investment costs</td>
</tr>
<tr>
<td>&gt; 400 kW: max. 15 % of the environmental related investment costs</td>
</tr>
<tr>
<td>Federal states incentives</td>
</tr>
<tr>
<td>Burgenland</td>
</tr>
<tr>
<td>Lower Austria</td>
</tr>
<tr>
<td>Styria</td>
</tr>
<tr>
<td>Salzburg</td>
</tr>
<tr>
<td>Tyrol</td>
</tr>
<tr>
<td>Vorarlberg</td>
</tr>
<tr>
<td>Vienna</td>
</tr>
<tr>
<td>Carinthia</td>
</tr>
<tr>
<td>Upper Austria</td>
</tr>
</tbody>
</table>

3.3.4 Conclusions

Factors influencing the economic efficiency of a NSGE system can be categorized into three topics: investment costs, running costs and the financing. As the initial investment costs are relatively high compared to many conventional heating systems like oil burning systems, investment grants are important to persuade consumers to choose this type of energy supply.
The investment costs described in this chapter relate to the drillings incl. the probe realization and to the costs for heat pumps including their installation. Predicting the total influence of one parameter (e.g. underground characteristics or HP size) on the price for an installation is virtually impossible – for example:

- As Figure 27 shows, prices in France do vary depending on the drilled diameter, though for a diameter of 250 mm, prices range from 50 – 200 € per drilled meter.
- As Figure 28 shows, prices for HPs in Austria do vary depending on their size, though for the size of 30 kW rated power, prices range from 300 – 700 €.
- As described in chapter 3.3.1, the geological “zone 5” profits from the lowest mean capital cost per kW heating demand with 1.935 €/kW compared to 2.298 €/kW for “zone 4”. Though, as the legend of Figure 29 (right) indicates, prices of the full range can be found, from around 800 – 3.000 €/kW.

At this point, we can conclude that the cost for a NSGE system depends to a greater extent on the market dynamics rather than on characteristics of the installation, though there are definitive trends for the single parameters which cannot be neglected. To display and analyse these trends is important as they give threshold values for cost estimation. Another big factor relating the investment costs is the consumer’s level of knowledge about NSGE systems, as this influences the whole process from the planning stage through the call for bids until the completion.

The main factor for running costs is the energy consumption of the system, and thus, the price for electrical energy. The price per kWh ranges from about 0.16 – 0.3 € for medium size households within the GRETA partner countries (see Figure 31). As Figure 32 shows, energy prices are usually about twice as high for private households than for industrial customers. This demonstrates that upscaling from single household NSGE installations towards housing estate uses can result in significant cost reductions.

REFERENCES OF THIS SECTION
4 Influence of the single operational criterion to the NSGE system

To identify relevant operational criteria and to demonstrate their importance, simulations are being carried out.

4.1 Borehole heat exchanger (BHE) fields

The objective of this section is to estimate how some key parameters affect the seasonal performance factor (SPF) of a heat pump (HP) connected to a field of borehole heat exchangers. As for open loop systems, the well-insulated Davos and Genoa hotels have been considered, as they represent for extreme climates in the AS, respectively cold and Mediterranean. The mathematical background and sizing of the ground-sourced heat pumps (GSHP) are briefly exposed in section 4.1.1 and 4.1.2 respectively. The influence of the following parameters on SPF and extreme fluid temperatures is discussed in section 4.1.3:

- Ground thermal conductivity \( \lambda_m \) (W.K\(^{-1}\).m\(^{-1}\))
- Ground volume-specific heat capacity \((\varrho C_p)_m\) (J.K\(^{-1}\).m\(^{-3}\))
- Initial ground temperature \( T_0 \) (°C)
- Underground water flow \( v_D \) (Darcy velocity) (m.s\(^{-1}\))
- Number of borehole \( N \)

4.1.1 Mathematical model

4.1.1.1 Heat transfer in the ground

A thermal dynamic simulation with small time step (one hour or less) is necessary to estimate the SPF of heat pump on borehole heat exchangers. The computation of the ground temperature in the vicinity of the borehole with numerical techniques such as the finite element (FE) often leads to long computation times. Analytical solutions are an alternative. Besides, the sizing process of BHE fields often considers conduction and neglects the influence of advection (the transfer of heat through underground water movement), such as in EED sizing software or ASHRAE method. The influence of unexpected underground water flows on GSHP performances remains an open topic. The analytical solution known as the Moving Finite Line Source (MFLS) [63] have been used in this work to compute the evolution of the heat-carrier fluid temperature (Figure 32). The MFLS model accounts for both conduction and advection in the ground. The MFLS relies on the following assumptions:

- Physical properties of the materials (ground matrix, ground water, grout, pipes, heat-carrier fluid) do not depend upon the temperature.
- The ground is a homogenous, isotropic media where Darcy’s law applies. The underground water flow is assumed to be stationary along the (Ox) axis, with Darcy velocity \( v_D \) (m.s\(^{-1}\)).
- The Initial temperature \( T_0 \) (°C) is homogenous in the ground and remains constant at the surface, and in the ground far away from the boreholes.
- The borehole is a finite line source emitting a power by unit length \( p \) (W.m\(^{-1}\)) homogenously distributed along the borehole.
The functions produced by analytical models are often referred to as “step-responses” or G-functions. G-functions describe the evolution of the normalized temperature on the borehole perimeter under a constant value of \( p \). The evolution of the temperature change in the ground \( \Delta T \) is then given by:

\[
\Delta T = \frac{p}{\lambda_m} G(t^*)
\]

Equation 1

Where \( G(t^*) \) is the response function, \( t^* \) a dimensionless time factor, \( \lambda_m \) the ground thermal conductivity (W.K\(^{-1}\).m\(^{-1}\)). G-functions are usually configured so that the temperature computed is that at the borehole wall. A large number of G-functions have been developed so far, see for instance the discussion of the validity range of some solutions in the case there is no underground water flow [64].

The MFLS G-function allows computing the temperature change defined in eq. 1 at distance \( r \) from a BHE, depth \( z \), angle \( \theta \) with the underground water flow direction and time \( t \) [63]:

\[
G_{MFLS}(r^*, z^*, \theta, Pe, t^*) = 2 \exp \left( \frac{Pe}{2} r^* \cos(\theta) \right) \left( \int_{-H^*}^{H^*} f(r^{**}, z^*, z'^*, Pe, t^*) dz'^* \right)
\]

\[
f(r^{**}, z^*, z'^*, Pe, t^*) = \frac{1}{4r'^*} \left( \exp \left( - \frac{Pe}{2} r'^* \right) \text{erfc} \left( \frac{r'^* - Pe t^*}{2\sqrt{t^*}} \right) + \exp \left( \frac{Pe}{2} r'^* \right) \text{erfc} \left( \frac{r'^* + Pe t^*}{2\sqrt{t^*}} \right) \right)
\]

Equation 2

The normalized variables \( r^*, z^*, Pe, t^* \) are defined as follows:

\[
r^* = \frac{r}{r_b} ; H^* = \frac{H}{r_b} ; z^* = \frac{z}{r_b} ; t^* = \frac{\lambda_m}{(\rho C_p)_m r_b^2} t ; Pe = \frac{(\rho C_p)_w v_D r_b}{\lambda_m}
\]

Equation 3

\((\rho C_p)_m\) and \((\rho C_p)_w\) for the volume-specific heat capacity of the ground and the underground water respectively (J.K\(^{-1}\).m\(^{-3}\)).
The step response of a single BHE \( g_{BHE}(t) \) is obtained by averaging \( G_{MFLS} \) along the borehole depth and perimeter, and taking into account thermal transfer inside the borehole grout through a thermal resistance \( R_b \) (K.m.W\(^{-1}\)):

\[
g_{BHE}(t) = \frac{1}{2\pi H^*} \int_0^{H^*} \int_0^{2\pi} G_{MFLS}(1, z^*, \theta, Pe, t^*) \, d\theta \, dz^* + \lambda_m R_b
\]

Equation 4

By applying the spatial superimposition principle \[65\] one gets the step response of the whole BHE field \( G \):

\[
G(t) = g_{BHE}(t) + \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} g_{i\rightarrow j}(t)
\]

Equation 5

The step response from BHE \( i \) to BHE \( j \) (see Figure 33) \( g_{i\rightarrow j}(t) \) is obtained by averaging \( G_{MFLS} \) along the depth of borehole \( j \):

\[
g_{i\rightarrow j}(t) = \frac{1}{H^*} \int_0^{H^*} G_{MFLS}(d_{ij}^*, z^*, \theta_{i\rightarrow j}, Pe, t^*) \, dz^*
\]

Equation 6

The mean fluid temperature in the BHE field \( T_{fl}^n \) at discrete time step \( n \Delta t \) in the BHE field is computed with the superposition principle \[65\]:

\[
T_{fl,u}^n = T_0 + \frac{1}{\lambda m N H} \left( P_u^1 G^n + \sum_{i=1}^{n-1} (P_u^{i+1} - P_u^i) G^{n-i} \right)
\]

Equation 7

\( P_u \) being the power exchanged between the heat-carrier fluid and the surrounding ground.

4.1.1.2 Ground-sourced heat pump (GSHP) model

The GSHP covers the whole cooling and heating loads to the building, and no complementary sources such as gas boiler is necessary. The simulation time step is \( \Delta t = 1h \) in the whole report. At every time \( t_n = n\Delta t \), the building requires a thermal energy \( P_b^n \). \( P_b^n \) is algebraic: \( P_b^n > 0 \) means the building requires heating, reversely \( P_b^n < 0 \) is for building cooling. The same convention applies for \( P_u \): \( P_u > 0 \) means that the BHE field is being warmed up (i.e. the building is cooled down).
The GSHP system is described by seven variables:

- $P_{HP}$ (W): the power delivered by the HP to the building (calorific power if heating is required, frigorific power if cooling is required).
- $P_u$ (W): the power exchanged between the heat-carrier fluid and the surrounding ground:

$$
\begin{align*}
& \begin{cases}
    P_b^n (COP^n - 1) + P_u^n COP^n & \text{if } P_b^n > 0 \\
    P_u^n (COP^n - 1) + P_b^n COP^n & \text{if } P_b^n < 0 \\
    0 & \text{if } P_b^n = 0
\end{cases} \\
\end{align*}
$$

Equation 8

Where $COP^n$ is the coefficient of performance of the heat pump in heating mode, estimated at time step $n$.

- $T_{in,u}, T_{out,u}, T_{fl,u}$ (°C): Inlet, outlet and mean BHE field temperature, defined as:

$$
\begin{align*}
T_{fl,u}^n &= \frac{T_{in,u}^n + T_{out,u}^n}{2} \\
T_{in,u}^n - T_{out,u}^n &= -\Delta T_{HP} \text{sgn}(P_b^n)
\end{align*}
$$

Equation 9

Where $\Delta T_{HP} = 3$ °C is the temperature difference at the HP.

- $\dot{m}_u$ (kg.s$^{-1}$): Total mass flow-rate in the BHE field:

$$
\dot{m}_u^n = \dot{m}_u^n C_{p,fl} \Delta T_{HP}
$$

Equation 10

Equations 7 to 10 are rearranged into a system of equations solved with $fsolve$ function of MATLAB® software at every time step $n$:

$$
\begin{align*}
F \left( \begin{array}{c}
    P_u \\
    T_{in,u} \\
    T_{out,u} \\
    T_{fl,u} \\
    \dot{m}_u
\end{array} \right) &= \begin{cases}
    T_{fl,u}^n - T_0 - \frac{1}{\lambda_m NH} \left( P_u^1 G^n + \sum_{i=1}^{n-1} (P_u^{i+1} - P_u^i) G^{n-1} \right) \\
    2T_{fl,u}^n - T_{in,u}^n - T_{out,u}^n \\
    \begin{cases}
        P_b^n (COP^n - 1) + P_u^n COP^n & \text{if } P_b^n > 0 \\
        P_u^n (COP^n - 1) + P_b^n COP^n & \text{if } P_b^n < 0 \\
        0 & \text{if } P_b^n = 0
    \end{cases} \\
    \Delta T_{HP} \text{sgn}(P_b^n) + T_{in,u}^n - T_{out,u}^n \\
    P_u^n - \dot{m}_u^n C_{p,fl} \Delta T_{HP}
\end{cases} \\
= \begin{bmatrix}
    0 \\
    0 \\
    0
\end{bmatrix}
\end{align*}
$$

Equation 11
4.1.2 Modelling of BHE fields (reference cases)

The thermal need of Davos hotel is almost exclusively heating, while the Genoa hotel requires winter heating and summer cooling in the same order of magnitude (see Figure 33 and Table 17).

![Figure 33: Hourly thermal needs of Davos (left) and Genoa (right)](image)

The locations and number of boreholes must take into account the mismatch between building heat supply (leading to underground cooling) and building cooling supply (leading to underground warming) to ensure operation sustainability. In the case of an unbalanced operation, boreholes located far from each other limit interferences and long-term temperature drift. Contrarily if the heat supplies and withdrawal on BHE side are well balanced, a compact structure is more adequate.

An “unbalance ratio” is introduced to estimate the balance on BHE field side:

\[
\eta_u = \frac{E_{c,u} - |E_{h,u}|}{E_{c,u} + |E_{h,u}|}
\]

Equation 12

With \(E_{h,u}\) the thermal energy extracted from the ground for heating supply \((E_{h,u} < 0)\) and \(E_{c,u}\) the heat supplied to the ground when the building id cooled down \((E_{c,u} > 0)\). They are roughly estimated assuming SPF for heating and cooling and reported in Table 17. The operation of Genoa BHE field will be almost balanced \((\eta_u=4.3\%)\), while in Davos operation is largely unbalanced.

<table>
<thead>
<tr>
<th></th>
<th>Building side</th>
<th>Underground side (sizing estimation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating supply (E_{h,b}) (MWh/(y))</td>
<td>Cooling supply (E_{c,b}) (MWh/(y))</td>
</tr>
<tr>
<td>Davos</td>
<td>507.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Genoa</td>
<td>146.8</td>
<td>93.9</td>
</tr>
</tbody>
</table>
The parameters shared by both cases (Davos and Genoa) are given in Table 17. Typical values of ground properties were assumed. Radiant panels are assumed as heat terminals in the building. These low temperature emitters enable higher SPF than fan coils.

Table 18: Parameters shared by both cases (Davos and Genoa)

<table>
<thead>
<tr>
<th>Ground characteristics</th>
<th>Borehole characteristics</th>
<th>Outlet temperature from HP (to radiant panels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity $\lambda_m$</td>
<td>Volume-specific heat capacity $(\rho C_p)_m$</td>
<td>Geothermal gradient</td>
</tr>
<tr>
<td>1.8 W.K$^{-1}$.m$^{-1}$</td>
<td>2.2 MJ.K$^{-1}$.m$^{-3}$</td>
<td>0.30 K.m$^{-1}$</td>
</tr>
</tbody>
</table>

For both cases the surface temperature was taken equal to the yearly averaged air temperature (3.33 °C in Davos and 15.76 °C in Genoa). The initial ground temperature $T_0$ was estimated at BHE mid-depth (i.e. 50 m). The equipment of the boreholes match technical practices in France: Boreholes are equipped with double-U heat exchangers and sealed with adequate grout ($\lambda = 1.8$ W.K$^{-1}$.m$^{-1}$). Polyethylene pipes (outer diameter = 32 mm, thickness = 2.9 mm) with a distance between opposite pipes equal to 81 mm. Heat-carrier fluid was a mixture of water and monopropylene glycol (MP), an antifreezing. The MP concentration was estimated so that to ensure a solidification temperature 20 °C lower than the initial ground temperature. The effective BHE resistance $R_b$ was computed with EED software (cf. Table 19). Note that $R_b$ was higher for Davos than for Genoa, since the MP concentration and fluid viscosity is higher in Davos case than in Genoa case, leading to laminar flow in pipes for Davos and turbulent flow for Genoa.

Table 19: BHE characteristics

<table>
<thead>
<tr>
<th>Initial ground temperature (°C)</th>
<th>Heat-carrier fluid concentration of antifreezing</th>
<th>Heat-carrier fluid temperature of solidification (°C)</th>
<th>BHE resistance $R_b$ (K.m.W$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davos 4.83 (=3.33+0.03×100/2)</td>
<td>30.8%</td>
<td>-15.17</td>
<td>0.123</td>
</tr>
<tr>
<td>Genoa 17.26 (=15.76+0.03×100/2)</td>
<td>9.6%</td>
<td>-2.74</td>
<td>0.077</td>
</tr>
</tbody>
</table>

For Genoa case the BHE field was designed to be compact since the unbalance ratio is small. The boreholes are located on a hexagonal grid within a cylinder, with spacing $a = 6$ m, as shown in Figure 35. Alternatively for the Davos case the BHE are located in a hollow rectangular configuration (with the hotel being within the rectangle for instance), with spacing $a = 10$ m, so that to minimize the interferences between the BHE.
To assess the relative performances of the different scenarios, SPF₁ and SPF₂ were assessed. SPF₁ only takes into account the electric consumption of the HP compressor, while SPF₂ integrates an estimation of the electric consumption of the pumps located on BHE side as well [66]. Consumption of the pumps was estimated with a circulation pump efficiency $\eta_{\text{circul}} = 60\%$.

For each building location (Genoa or Davos), 2 sizings were considered with an upper and a lower value of the number of boreholes $N$: 29 or 22 BHE for Genoa, 64 or 48 BHE for Davos. Upper value of $N$ results in higher performances at the expense of higher investment costs. For the sensitivity analysis described in this report, only 2 sizings per building were considered. Finding reasonable trade-offs between investment, operation costs and performances will be an output of next GRETA WP3 deliverable.

All simulations were carried out over 10 years. A preliminary analysis of the influence of the number of boreholes on SPF and extreme BHE fluid temperatures was carried out for Genoa from $N = 17$ to 36 (cf. Figure 35) and Davos for $N = 48$ to 72 (cf. Figure 36). $N$ has a limited influence on SPF₂, from 5.93 for $N = 17$ to 6.72 for $N = 36$. With 29 BHE, SPF₂ is 6.42, while SPF₂ = 6.15 with 22 BHE: a decrease of 24% of the BHE length leads to a SPF₂ decrease by only 3.7%. The minimum and maximum temperatures at BHE inlet are respectively 2.3 °C lower and 2.9 °C higher for 22 BHE than for 29 BHE: the limiting factor of the sizing will be the acceptable temperature for the HP.

Figure 34: BHE locations for Genoa (cases A and B) for 29 BHE (left) and Davos (cases C and D) for 72 BHE (right).
Catalogue of operational criteria and constraints

GRETA is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme. See more about GRETA at www.alpine-space.eu/projects/greta.

Key output data are reported in Table 20. For both Genoa cases, the fluid temperature slightly decreases from one year to the next one (cf. Figure 37), which is reflected in SPF2 evolutions: SPF2 goes from 6.53 at year 1 to 6.42 at year 10 for case A, and from 6.18 to 6.13 for case B (cf. Figure 39). BHE field sustainability is ensured since heat withdrawals and supplies are well balanced.

The performances of both Davos cases are much lower, with estimated SPF2 being 3.66 for case C and 3.51 for case D. Further, the fluid temperature decreases from one year to the next one, leading to a SPF2 decrease over the 10 years, from 3.76 at year 1 to 3.51 at year 10 for case C, by about 7 % (cf. Figure 38 and Figure 40).

Figure 35: Genoa: Influence of the number of boreholes N on SPF2, maximum and minimum BHE inlet BHE fluid temperatures.

Figure 36: Davos: Influence of the number of boreholes N on SPF2, maximum and minimum BHE inlet BHE fluid temperatures.
Table 20: Modelled cases with key output data. SPF$_1$ and SPF$_2$ are given on the 10th year of operation

<table>
<thead>
<tr>
<th>Case</th>
<th>Building location</th>
<th>Number of boreholes</th>
<th>SPF$_1$</th>
<th>SPF$<em>2$ ($\eta</em>{\text{circ}} = 60%$)</th>
<th>Minimum fluid temp. at BHE inlet (°C)</th>
<th>Maximum fluid temp. at BHE inlet (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Genoa</td>
<td>29</td>
<td>6.66</td>
<td>6.42</td>
<td>7.55</td>
<td>27.34</td>
</tr>
<tr>
<td>B</td>
<td>Genoa</td>
<td>22</td>
<td>6.43</td>
<td>6.13</td>
<td>5.30</td>
<td>30.29</td>
</tr>
<tr>
<td>C</td>
<td>Davos</td>
<td>64</td>
<td>3.87</td>
<td>3.66</td>
<td>-8.58</td>
<td>5.88</td>
</tr>
<tr>
<td>D</td>
<td>Davos</td>
<td>48</td>
<td>3.74</td>
<td>3.51</td>
<td>-11.37</td>
<td>5.77</td>
</tr>
</tbody>
</table>

Figure 37: Cases A (Genoa, 29 BHE) and B (Genoa, 22 BHE): Evolution of inlet and outlet BHE fluid temperatures

Figure 38: Cases C (Davos, 64 BHE) and D (Davos, 48 BHE): Evolution of inlet and outlet BHE fluid temperatures
Figure 39: Cases A (Genoa, 29 BHE) (top) and B (Genoa, 22 BHE) (down): Evolution of HP electric consumption (upper figure), SPF$_1$ and SPF$_2$ (lower figure) over the 10 years of simulation. In the report $\eta_{circul} = 60\%$ is used when computing SPF$_2$.

Figure 40: Cases C (Davos, 64 BHE) (top) and D (Davos, 48 BHE) (down): Evolution of HP electric consumption (upper figure), SPF$_1$ and SPF$_2$ (lower figure) over the 10 years of simulation. In the report $\eta_{circul} = 60\%$ is used when computing SPF$_2$.

The temperature evolution of the BHE field heat-carrier fluid, as represented in Figure 38, is highly dynamic, changing from one hour to the next one by several °C. Figure 42 aims at showing the range of outlet temperature from BHE field $T_{out,BHE}$ for heating and cooling productions, as this will impact HP efficiency. For instance, 50% of the heating (73.3 MWh.y$^{-1}$) is produced at $T_{out,BHE}$ lower (or greater)
than 14.0 °C for case A and 12.7 °C for case B, while 50% of the cooling (46.97 MWh.y⁻¹) is produced at $T_{\text{out,BHE}}$ lower (or greater) than 21.0 °C for case A and 23.0 °C for case B. An interesting result is that, though the ground is cooled down during the winter by the heat withdrawal, only a small part of the cooling (9.6% and 7.5% for cases A and B respectively) is produced at $T_{\text{out,BHE}}$ lower than the initial temperature $T_0$. The amount of heating produced at $T_{\text{out,BHE}} > T_0$ is even lower (3.1% and 2.4% for cases A and B respectively). The heat stored in the BHE field in summer is quickly depleted in winter, and the BHE field can barely be considered as a seasonal thermal energy storage.

For Davos hotel, 50% of the heating is produced at $T_{\text{out,BHE}}$ greater than -0.5°C for case C (64 BHE) and -2.1 °C for case D (48 BHE) (cf. Figure 42).

4.1.3 Influence of parameters on SPF: Ranges, results and discussion

The upper and lower bounds of the parameter ranges were chosen as follows, with 5 values per parameter (cf. Table 21):

- Ground thermal conductivity and heat capacity: values 25% lower to 25% higher than the values used for the reference case (section 4.1.2)
- Initial ground temperature: value used for the reference cases ± 4 °C
- Underground water flow: from $v_D = 0$ m.a⁻¹ (ref. case) to $v_D = 60$ m.a⁻¹
- Number of boreholes: values 25% lower to 25% higher than the values used for the reference case (rounded)

For case D (N=48), the influence of N was not investigated, as the minimum fluid temperature is -11.37 °C at the 10th year, only 3.80 °C above the heat-carrier fluid freezing point. Higher values of N (N>48) are covered by case C, while lower values (N<48) will lead to even lower temperature, which may jeopardize the installation.
Table 21: Considered values of key parameters for the sensitivity analysis. Parameters used for reference cases (presented in section 4.1.2) are underlined.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A (Genoa, 29 BHE)</th>
<th>B (Genoa, 22 BHE)</th>
<th>C (Davos, 64 BHE)</th>
<th>D (Davos, 48 BHE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground thermal conductivity ( \lambda_m ) (W.K(^{-1}).m(^{-1}))</td>
<td>1.35, 1.53, 1.80</td>
<td>1.35, 1.53, 1.80</td>
<td>1.35, 1.53, 1.80</td>
<td>1.35, 1.53, 1.80</td>
</tr>
<tr>
<td>Ground volume-specific heat capacity ((\rho C_p)_m) (MJ.K(^{-1}).m(^{-3}))</td>
<td>1.65, 1.87, 2.20, 2.53, 2.75</td>
<td>1.65, 1.87, 2.20, 2.53, 2.75</td>
<td>1.65, 1.87, 2.20, 2.53, 2.75</td>
<td>1.65, 1.87, 2.20, 2.53, 2.75</td>
</tr>
<tr>
<td>Underground water flow ( v_D ) (Darcy velocity) (m.y(^{-1}))</td>
<td>0, 15, 30, 45, 60</td>
<td>0, 15, 30, 45, 60</td>
<td>0, 15, 30, 45, 60</td>
<td>0, 15, 30, 45, 60</td>
</tr>
<tr>
<td>Number of borehole ( N )</td>
<td>22, 25, 29, 33, 36</td>
<td>17, 19, 22, 25, 28</td>
<td>48, 54, 64, 70</td>
<td>X</td>
</tr>
</tbody>
</table>

The main trends are summarized below:

- **The thermal conductivity \( \lambda_m \) in the investigated range has a moderate impact on performances**, SPF\( _2 \) increasing with increasing values of \( \lambda_m \). A change of 0.45 W.K\(^{-1}\).m\(^{-1}\) (larger change investigated) leads to a change of SPF\( _2 \) by c.a. 1 to 2\% for Genoa case A, and c.a. 2 to 4\% for Genoa case B. Similar trends are observed for Davos case B: The change of 0.45 W.K\(^{-1}\).m\(^{-1}\) leads to a SPF\( _2 \) change by c.a. 2\%.

- **The initial temperature \( T_0 \) has a large impact on performances.** The fluid temperatures increases by c.a. 1°C per additional °C of \( T_0 \). An increase of 4 °C increases the SPF\( _2 \) by c.a. 4 to 6\%, while a decrease of 4°C decreases SPF\( _2 \) by c.a. 7 to 8\%.

- **The ground volume-specific heat capacity \((\rho C_p)_m\) has a small impact on performances,** SPF\( _2 \) increasing with increasing values of \((\rho C_p)_m\). A change of 0.55 MJ.K\(^{-1}\).m\(^{-3}\) (larger change investigated) leads to a change of SPF\( _2 \) below 1\% for Genoa case A, and c.a. 1\% for Davos case C. The influence of \((\rho C_p)_m\) on the extreme fluid outlet temperatures is limited: A decrease of \( \lambda_m \) by 0.45 W.K\(^{-1}\).m\(^{-1}\) leads to a change of \( T_{in,BHE,min} \) by -1.48 °C and and \( T_{in,BHE,max} \) by +1.83 °C for Case A, and a change of \( T_{in,BHE,min} \) by -1.76 °C foe Case C.

- **For both climates, underground water flow is beneficial to GSHP performances,** SPF\( _2 \) increasing when \( v_D \) increases. For Genoa cases, SPF\( _2 \) increases by 3 to 4\% at the highest investigated value of \( v_D \) (60 m.a\(^{-1}\)), the increase being c.a. 9\% for Davos cases. An interesting result is that the underground water flow is beneficial to performances even for balanced operation of the BHE field. Though some cooling stored in the BHE field in winter is dissipated by advection, the underground water flow decreases the variations of mid-term to long-term BHE fluid temperature, leading to higher HP performances. For instance, for case A, the minimum and maximum temperature respectively increase by 1.7 °C and decrease by 1.3 °C at the highest investigated value of \( v_D \) (60 m.a\(^{-1}\)). **One practical consequence is that neglecting underground water flow when sizing a BHE field for GSHP is a conservative approach.** Unexpected underground water flow will lead to an increase of HP performances, the increase being higher for unbalanced field operation.
Figure 60 to Figure 71 (see Annex) show the sensitivity of SPF$_2$ at the 10$^{th}$ year of operation along with the maximal and minimum BHE field inlet temperatures over the 10 years of operation. Parameters of the reference case is figured with red dots (○) and changing parameters with blue crosses (+).

### 4.1.4 Conclusions

For both Genoa and Davos, the main results are reported on concluding Figure 59. The normalized value of every parameter ranges between 0 % and 100 %, where 0% corresponds to the lowest investigated value of the parameter, and 100 % to the highest one.

References of this section

4.2 Open-loop

4.2.1 Factors affecting the energy efficiency of open-loop geothermal systems

Groundwater heat pumps, also known as open-loop ground source heat pumps, are widely acknowledged as the most efficient utilisation of shallow geothermal resources. Indeed, while closed-loop GSHPs are based on a mainly conductive heat exchange between the heat carrier fluid and the ground, open-loop GSHPs directly use groundwater as a heat exchange medium. If we consider heating mode, the temperature of the heat carrier fluid circulated into BHEs should be sufficiently lower than the surrounding ground to ensure conductive transfer from the borehole wall and the fluid; for cooling mode, the heat carrier fluid temperature should be raised in order to ensure conductive transfer from the fluid to the ground (see Figure 44 on the left). On the other hand, the temperature of abstracted groundwater could remain unaltered through time, and the thermal exchange will influence the reinjecting temperature, which will be lower in heating mode and higher in cooling mode, compared to the abstraction well (see Figure 44 on the right).

Figure 44: Comparison between heat carrier fluid temperatures in a 30 probes Borehole Heat Exchanger field (left) and in a Groundwater Heat Pump (right).

The temperature of the heat source for the evaporator (in heating mode) or of the heat sink for the condenser (cooling mode) influences the COP of the heat pump: the lower the difference between evaporation and condensation in a heat pump, the higher the COP and hence the lower the electrical power needed by the heat pump to deliver a certain thermal power. If we consider subsurface water and the surrounding ground in thermal equilibrium, i.e. at the same temperature, we can say that thermally unaltered groundwater is warmer than the heat carrier fluid of a BHE, when working in heating mode, and cooler than the BHE’s fluid in cooling mode: both these conditions lead to a higher COP.

However, the assumption of no thermal alteration of the abstracted groundwater should be verified. Since reinjection into the same aquifer is usually foreseen to avoid its depletion (see outputs of WP 2 on legal requirements), part of the reinjected flow rate can return to the abstraction well. This phenomenon is known as thermal short-circuit and it has been studied for a long time for well doublets in high enthalpy geothermal systems and in industrial cooling systems, e.g. in thermo-electrical power plants [67-70]. Thermal short-circuit has been studied by Milnes and Perrochet, who distinguished two phenomena: thermal feedback, which occurs when reinjection is performed at a prescribed temperature, and thermal recycling, when a temperature drop between abstraction and injection is...
set [71] (see Figure 45). For both cases, the abstracted water temperature starts to change at some point, when injected water reaches the abstraction well. This phenomenon is defined as thermal breakthrough, both for thermal feedback and recycling. Further information is reported in Chapter 4.2.1.1.

Figure 45: Distinction between thermal feedback (on the left) and thermal recycling (on the right) in an open-loop well doublet. From: Casasso and Sethi, 2015 [72].

The energy consumption for pumping is another factor which can strongly affect the energy efficiency of GWHPs. While the head to be provided by the circulation pump of a closed-loop GSHP is equal to friction losses into the pipe loops of BHEs, pumps in open-loop geothermal systems should also lift groundwater from the underground. For closed-loop systems, the use of low viscosity fluids and a sensible choice of pipe diameters and flow rates can limit the consumption of the circulation pump to about 12 ± 15 % of the electric power required by the heat pump [35]. The friction losses in open-loop systems can be reduced too with a wise choice of pumps and pipes, but the depth to water table is the most influential parameter for the determination of pumping costs. Further information is reported in Chapter 4.2.1.2.

4.2.1.1 Mathematical modelling of thermal short-circuit

Thermal short-circuit in open-loop geothermal systems depends on the following parameters:
- aquifer properties: hydraulic conductivity $k$ (m s$^{-1}$), saturated thickness $b$ (m), hydraulic gradient $J$ (non-dimensional), and flow direction $\theta$;
- plant properties: flow rate $Q_w$ (m$^3$s$^{-1}$), well distance $L$ (m) and temperature difference $\Delta T$ (°C) for thermal recycling, or the reinjection temperature $T_i$ (°C) if we consider thermal feedback.

All the aforementioned parameters are homogeneous and/or constant. If these conditions are met, and groundwater flow is aligned with the well doublet with the reinjection well downstream, the non-dimensional parameter $X$ is identified [71], which describes the strength of possible hydraulic and thermal short-circuit into the well doublet:

$$X = \frac{2Q_w}{\pi bk J L}$$

Equation 13
Hydraulic (and hence thermal) short-circuit in a well doublet occurs if $X > 1$, while the abstracted water temperature remains unaltered if $X \leq 1$. Hydraulic and thermal short-circuit occur if the capture front of the abstraction well and the release front of the injection well overlap.

Figure 46: Capture zone of the abstraction well and injection zone of the reinjection well in the absence (left) and in the presence (right) of hydraulic short-circuit. In the second case, the flow rate has been increased by 5 times compared to the first one.

In this case, the time at which thermal breakthrough occurs is given by the following formula [68]:

$$t_{tb} = \frac{R_{th} n_e L}{kj} \left[ \frac{X}{\sqrt{X - 1}} \tan^{-1} \left( \frac{1}{\sqrt{X - 1}} \right) - 1 \right]$$

Equation 14

where $R_{th}$ (non-dimensional) is the thermal retardation factor [73], i.e. the ratio between groundwater effective velocity ($v_e$) and heat transport velocity ($v_{e-th}$):

$$R_{th} = \frac{v_e}{v_{e-th}} = 1 + \frac{(1 - n_e) \rho_s c_s}{n_e \rho_f c_f} \geq 1$$

Equation 15

where $n_e$ (non-dimensional) is the effective velocity of the porous medium, and $\rho_s c_s$, $\rho_f c_f$ are the thermal capacities ($J m^{-3} K^{-1}$) respectively of the solid and the fluid phase. The thermal retardation factor $R_{th}$ expresses how the propagation of heat in porous media is retarded by the thermal exchange between water and the solid matrix. Using input values typical of aquifers, e.g., $n_e = 0.2$, $\rho_s c_s = 2.4 MJ m^{-3} K^{-1}$ and $\rho_f c_f = 4.2 MJ m^{-3} K^{-1}$ [74, 75], the thermal retardation factor is $R_{th} = 3.29$.

When hydraulic/thermal recycling occurs, a fraction $RR(t)$ of the reinjected flow rate returns to the abstraction well, which increases with time and reaches an asymptotical value:

$$RR_{max} = \frac{2}{\pi} \left[ \tan^{-1}(\sqrt{X - 1}) - \frac{\sqrt{X - 1}}{X} \right]$$

Equation 16

Equation 16 allows the maximum variation of $T_E$ to be calculated for thermal feedback (Equation 17) and recycling (Equation 18) [71]:

$$T_E(\infty) - T_0 = RR_{max} \cdot (T_i - T_0)$$

Equation 17

$$T_E(\infty) - T_0 = \frac{RR_{max}}{1 - RR_{max}} \cdot \Delta T$$

Equation 18
where $T_i$ is the imposed injection temperature, $\Delta T$ is the imposed difference between the injection ($T_i(t)$) and the abstraction ($T_E(t)$) temperatures, and $T_0$ is the undisturbed aquifer temperature.

Equation 17 - Equation 18 provide the value of the maximum thermal alteration at the abstraction well, but no information on the time evolution of the abstraction well temperature. Lippmann and Tsang [68] developed a formula for the calculation of $T_E(t)$ in case of thermal feedback (i.e., with imposed injection temperature $T_i$) and no regional groundwater flow ($v_e = 0$):

$$\frac{T_E(t > t_{tb}) - T_0}{T_i - T_0} = 0.338 \exp \left( -0.0023 \frac{t}{t_{tb}} \right) + 0.337 \exp \left( -1.093 \frac{t}{t_{tb}} \right) + 1.368 \exp \left( -1.3343 \frac{t}{t_{tb}} \right)$$

Equation 19

Casasso and Sethi (2015, [72]) recently developed a numerical MATLAB code to calculate thermal alterations at the abstraction well in the case of thermal recycling and calibrated an empirical formula

$$\frac{T_E(t > t_{tb}) - T_0}{T_E(\infty) - T_0} = 1 - \exp \left( 1 - \frac{2.3}{0.0372 X^2 + 1.7136 X - 1.7508} \frac{t}{t_{tb}} \right)$$

Equation 20

where $T_E(\infty) - T_0$ is calculated according to Equation 18.

For both Equation 19 and Equation 20, the thermal breakthrough time $t_{tb}$ is calculated according to Equation 14.

### 4.2.1.2 Calculation of pumping costs

Pumping from water wells is usually performed with submersed electrical pumps. The pump power is proportional to the flow rate $Q$ (m$^3$s$^{-1}$) and the head $\Delta H$ (m):

$$P_{pump} = Q_w \cdot \Delta H \cdot \gamma \eta$$

Equation 21

where $\gamma = 9800$ N/m$^3$ is the specific weight of water and $\eta$ is the energy yield of the pump (non-dimensional).

The head required to the pump is composed of three main contributions [74], as shown in Figure 47:

- the level drawdown occurring in the well due to pumping ($\Delta H_1$);
- the friction losses ($\Delta H_2$), which are further divided into distributed losses along the pipes and concentrated losses in valves, pipe curves, pipe inlets and outlets, etc.;
- the elevation difference between the undisturbed water table and the geothermal system ($\Delta H_3$).
Figure 47: Example of a flow rate-head curve for a pumping system.

While $\Delta H_1$ and $\Delta H_2$ depend on the flow rate, in particular on $Q^2$, the geodetic term $\Delta H_3$ is obviously independent of the flow rate. If the pumping system is properly designed, $\Delta H_2$ is in the order of a few meters. On the other hand, the elevation difference between the well level during pumping and the geothermal system (i.e., $\Delta H_2 + \Delta H_3$) can be in the order of tens of meters. For the sake of simplicity, the value of $\Delta H$ is considered as constant in the analyses reported in next paragraphs.

Regarding the energy yield of submersed pumps, it depends on the pump type and on the flow rate range, as reported in the example of Figure 48 with a quite flat behaviour ($70 \div 80\%$) in the optimal range.

Figure 48: Energy yield ($\eta$) of a submersed electrical pump, depending on the flow rate. Source: Caprari water pump catalogue.

4.2.2 Numerical simulation of GWHPs

In order to investigate the influence of the thermal recycling on the efficiency of a GWHP, a set of numerical simulations were run considering different hydrogeological parameters (groundwater velocity $v$, saturated thickness of the aquifer $b$), different well distances ($L$), and different thermal loads. In particular, we considered the thermal load of a well thermally insulated hotel located in two very different climates of the Alpine Space: Davos (5356 HDD) and Genoa (1435 HDD). The hotel in Davos needs 516 MWh yr$^{-1}$ for heating and DHW (with a negligible cooling load), while it needs 153 MWh yr$^{-1}$ for heating and DHW and 93 MWh yr$^{-1}$ for cooling in Genoa hotel.
4.2.2.1 Numerical model setup

For each of the two climate zones, 45 different conditions have been simulated, combing 4 variables, namely the Darcy velocity of the water in a porous medium \((v)\), the thickness of the aquifer \((b)\), the distance between the two wells \((L)\). The adopted values are shown in Table 22. \(X_{max}\) represents the maximum value of the short-circuit parameter \(X\) (Equation 13):

\[
X_{max} = \frac{2Q_{max}}{\pi vbL}
\]

Every simulation was set to a simulation period of 3650 days, since 10 years proved to be a sufficient time for the stabilization of the thermal plume in the nearby environment of the well doublet.
The simulations were performed with the software Feflow 7.0 with the following hydrogeological and geometrical parameters:

- Hydraulic gradient ($i$): 0.2 % along the conjunction between wells, with the same slope applied to each layer;
- Depth to water table: 10m (Figure 49);
- $K_{yy} = K_{xx}$ and $K_{zz} = 0.1 K_{xx}$;
- Thermal conductivities: solid phase $\lambda_s = 3 \, W\,m^{-1}\,K^{-1}$; fluid phase $\lambda_w = 0.65 \, W\,m^{-1}\,K^{-1}$;
- Volumetric heat capacity: solid phase $\rho_s c_s = 2.52 \, MJ\,m^{-3}\,K^{-1}$; fluid phase $\rho_w c_w = 4.2 \, MJ\,m^{-3}\,K^{-1}$;
- Effective porosity: $n_e = 0.2$

![Figure 49: Initial hydraulic head distribution.](image)

A temperature difference $\Delta T = \pm 3 \, ^\circ C$ was applied between the injection and the abstraction well.

### 4.2.2.2 Calculation of the COP and EER

The efficiency of the HP is described by the COP (Coefficient Of Performance) in heating mode and by the EER (Energy Efficiency Ratio) in cooling mode. COP and EER depend by temperature values and are calculated through the eq. 11 and 12 (values are supposed in °C):

\[
COP = \eta_{HP} \cdot \frac{273.15 + T_{T,H}}{(T_{T,H} - T_G + \Delta T_{HP,H})}
\]

Equation 23

where $T_{T,H}$ is the temperature of heating terminals, $T_G$ is the groundwater temperature (resulting from the simulations), and $\Delta T_{HP,H}$ is sum of the temperature drops between evaporator and groundwater and between condenser and heating terminal circuit.

\[
EER = \eta_{HP} \cdot \frac{273.15 + T_{T,C}}{(T_G - T_{T,C} + \Delta T_{HP,C})}
\]

Equation 24

where $T_{T,C}$ is the temperature of cooling terminals and $\Delta T_{HP,C}$ is sum of the temperature drops between condenser and groundwater and between evaporator and cooling terminal circuit.

Values adopted in the COP and EER calculation are shown in Table 23. The chosen temperatures of the terminal circuit are the typical temperatures of the radial panels.
The groundwater undisturbed temperature ($T_0$) was set to $6^\circ C$ for Davos [76] and $15^\circ C$ for Genoa [77]. The values of $\Delta T_{HP,H}$, $\Delta T_{HP,C}$ and $\eta_{HP}$ have been calibrated fitting the values reported in the Multistack water-to-water heat pumps catalogue, that reports COP and EER values compared with different working temperatures of the HP [78].

COP and EER were calculated with a daily frequency, respectively with Equation 23 and Equation 24, and the electric energy consumption of the HP at the i-th day ($E_{HP,i}$, expressed in kWh) is, respectively in heating and cooling mode:

\[
E_{HP,i} = \frac{P_{HVAC,h,i}}{COP} \cdot 24
\]

Equation 25

\[
E_{HP,i} = \frac{P_{HVAC,c,i}}{EER} \cdot 24
\]

Equation 26

where $P_{HVAC,h/c,i}$ (kW) is the thermal load in heating (h) or cooling (c) mode at the i-th day.

Summing the daily values of the energy consumed by the HP ($E_{HP,i}$), it is possible to calculate the Seasonal Performance Factor:

\[
SPF = \frac{\sum E_{HVAC,h,i}}{\sum E_{HP,i}} + \frac{\sum E_{HVAC,c,i}}{\sum E_{HP,i}}
\]

Equation 27

### 4.2.2.3 Results and discussion

In order to compare the influence of the hydrogeological parameters and the distance between the wells, the value of the SPF at the 10th year (worst case) was calculated. In Figure 50 and Figure 51, the SPF values are shown related to the $X_{max}$ value of each simulation, for Davos and Geona respectively. In the same charts is even shown the calculated minimum temperature of the reinjected water. Concerning the Davos case, this value is sometimes below zero. This limit cannot obviously be passed, and we have supposed that under the precautionary limit of $2^\circ C$ the installation of a GWHP is not recommended.
In Genoa we can observe a range of $T_{\text{min}}$ of less than 4 °C (between 12 °C and 8.3 °C) when in Davos this range is 6 °C (between 3 °C and -3 °C) because the thermal demand is higher in Davos, and there is not alternation between heating and cooling period.

In a half of the simulated conditions in Davos (23 on 45) the calculated temperature of the water in reinjection well is below 2 °C, affected by the risk of freezing. This may prevent the possibility to install this kind of installations. This risk does not exist for the Genoa case, because the minimum registered temperature of the water is 8.3 °C, due to two factors: the higher groundwater temperature and the different thermal load.

In Figure 52 the calculated minimum temperatures of reinjected water in Davos are shown, related with the hydrogeological and the setup plant data ($v, b, L$). In Figure 53 the Genoa case study is presented: in this case, due to the cooling period, even the maximum groundwater temperature values ($T_{\text{max}}$) are shown, the thickness of the aquifer in this chart is fixed to $b = 5m$. 

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**Figure 50:** SPF and minimum calculated temperature of reinjected water in Davos.

**Figure 51:** SPF and minimum calculated temperature of reinjected water in Genoa.

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**Figure 52:** Minimum calculated temperature values of the reinjected water in Davos with different aquifer characteristics.

**Figure 53:** Minimum and maximum temperature values of the reinjected water in Genoa.
In Figure 54 (Genoa case only) it is possible to evaluate how the $T_0$ value has a great impact on the $T_{\text{min}}$ and $T_{\text{max}}$ values.

![Figure 54: $T_{\text{max}}$ and $T_{\text{min}}$ of reinjected water in Genoa with different $T_0$ values (b=10m; L= 20m)](image)

Usually the increase of $b$, $v$ and $L$ causes an increase of the reinjected water minimum temperatures (and a reduction of the $T_{\text{max}}$ in conditioning mode). The influence of $L$ and $b$ on the efficiency of the system is investigated if Figure 55 and Figure 56 (Genoa case only), where the $v$ value is set at $7e-6$ m/s.

![Figure 55: SPF2(20m) values related to different saturated thickness and wells distance in Genoa](image)

![Figure 56: influence of wells distance on the SPF2(20m) in Genoa](image)

The increase of the wells distance and of the saturated thickness causes a reduction of the thermal recycling effect and a consequent increase of the SPF2 value. This increase has anyway a limited impact on the SPF and consequently on the HP electrical consumption (maximum calculated augmentation of electrical power consumption: +12.9 % in Davos and +7.6 % in Genoa) and generally has a negligible impact ($<+5\%$) if the $X_{\text{max}}<10$. 
Concluding our analysis, we have to study the influence of the energetic consumption of the pumps in an open loop system. In order to quantify the influence of this energetic cost, we introduce the $SPF_2$, i.e. the Seasonal Perform Factor calculated including the energy consumption of the circulation pumps. A similar approach was adopted by Montagud et al. [66] for closed-loop GSHPs.

We calculated the $SPF_2$ adopting three different values of the depth to water table of the aquifer, i.e. 10 m, 20m, 50m, which are reported in the charts below (Figure 57 for Davos and Figure 58 for Genoa) as SPF2(10m), SPF2(20m) and SPF2(50m). In order to estimate the energetic consumption of the pumps, the annual water volume exchanged with the aquifer was calculated, obtaining about 148000 m$^3$ for Davos and 69000 m$^3$ for Genoa. The results are reported in Figure 57 and Figure 58, and show that, for very high depth to water table (e.g. from 20 to 50 m) the $SPF_2$ can fall to much lower values, which are typical of closed-loop systems. BHE can therefore be considered in such cases, at least for small systems in which it is not possible to achieve the economies of scale of drilling a few water wells instead that thousands of meters of boreholes.

In Davos we can observe a difference between SPF1 and SPF2(10m) of more than 0.2; between SPF1 and SPF2(50m) of almost 1. This result shows that considering a depth to the water table of more than 20m, the influence of the energetic consumption of the pumps is more relevant than the thermal recycling effect.

In Genoa we can observe that the influence of the pumps consumption on the SPF2 is even more relevant: the annual energy consumption of the pumps for a 20 m depth to water table represents, in fact, around one sixth of the energy consumption of the heat pump annual consumption (5 MWh vs 29-32 MWh). This causes a difference between SPF1 and SPF2(20m) of almost 1.1 more than 2 times if compared to the maximum loss of efficiency due to thermal recycling.

4.2.2.4 Conclusions

The thermal recycling effect affects the performance of GWHP less than factors such as the groundwater temperatures and the depth to water table, especially if $X_{max}$<10. The electric energy consumption of the pumps is not negligible, especially for high depth to water table. In Figure 59 it is
possible to compare the relevant impact of the depth to water table and the soil temperature on an open loop system efficiency, compared to the other analysed values.

A problem that can seriously prevent the installation of open loop systems in low temperatures areas is the reinjected water temperature. If this temperature is near to 0 °C (typical of installation characterized by low Darcy velocities and low aquifer thickness), the installation of open loop systems should be avoided, and if it is installed, the distance between abstraction and reinjection wells have to be as large as possible.

Figure 59: Influence of the analysed parameters on the SPF2 value in the Genoa case study
REFERENCES OF THIS SECTION


5 Innovative Systems

In this section two innovative geothermal system groups are being described, which have proven successful and provide significant energy saving potentials especially in the alpine region. The first group is the utilization of tunnels as a geothermal heat source and heat sink. There are some examples, but the potential has by far not being exhausted yet. The second group is the utilization of shallow geothermal energy for heating and cooling of traffic areas like roads, bridges and pedestrian areas including train station platforms.

Last but not least, the application of Heat Pipes as Borehole heat exchangers is to be mentioned in the context of surface or infrastructure heating as it is a completely passive system with high resilience.

5.1 Thermal Tunnel Activation

When discussing thermal tunnel activation, these technologies have to be distinguished:

Open systems: utilization of the drainage water from the tunnel as heat source:
In the alpine region various installations of this type have been carried out. A comprehensive description is provided with the documents [1] and [2]. Open systems have the huge advantage that in most cases they can easily be installed at existing tunnels by feeding the drainage water (which is collected anyway) to heat pumps.

Closed Systems: closed loops installed within the tunnel as a heat source or heat sink:
With Closed Systems, traditional construction methods and the construction with pre-fabricated load bearing lining segments ("tubbings") have to be distinguished.

Figure 60: Schematic tunnel section and drainage [1]
In tunnels being constructed traditionally, the heat transport pipes are clamped onto the tunnel wall and are being covered with sprayed concrete afterwards.
When tunnels are constructed with pre-fabricated lining elements, the pipes are being installed at the manufacturing plant of the tubing supplier onto the metal reinforcement. After installation of the tubbings, only the ends of the heat transport pipes have to be connected.

5.1.1 Open Systems / Drainage Water Utilisation

The majority of tunnels need a drainage system to dispose off the water seeping to and into the tunnel. Subject to the rock coverage, the drainage water can reach temperatures of up to 20-40°C and is therefore an ideal geothermal heat source. The following chart shows the geothermal potential of some Swiss tunnels if the drainage water would be cooled down to 6°C. The data in the right column show the annual heating / cooling energy of tunnels where drainage water heat utilization has already been installed.

As the warm water collected within the tunnels is available “free of charge”, the economics of its utilization typically is very favourable – even, if the heat has to be transported over a distance. In many cases, the drainage water even has to be cooled before discharging into rivers or becks anyway, increasing the temperature level of the excess waste heat. This technique can be applied for already existing tunnels, while Closed Loop Systems have to be installed during the construction of a tunnel.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Furka Railway</td>
<td>5400</td>
<td>15</td>
<td>3756</td>
<td>1700/-</td>
</tr>
<tr>
<td>Gotthard Road</td>
<td>7200</td>
<td>15</td>
<td>4510</td>
<td>660/1440</td>
</tr>
<tr>
<td>Hauenstein Base Tunnel Railway</td>
<td>2500</td>
<td>19</td>
<td>2262</td>
<td>2100/-</td>
</tr>
<tr>
<td>Mappo-Morettina Highway</td>
<td>983</td>
<td>16</td>
<td>684</td>
<td>120/200</td>
</tr>
<tr>
<td>Ricken Railway</td>
<td>1200</td>
<td>12</td>
<td>501</td>
<td>250/-</td>
</tr>
</tbody>
</table>
5.1.2 Closed Systems: traditionally constructed Tunnels

In this case the installation pattern of absorber pipes can be adjusted easily to site constraints, but all installation work has to be done within the tunnel requiring the respective coordination with other works. Even without the potential conflict with other works, the installation of the absorber pipes at the sides and especially on the top of the tunnel is challenging. Finally, there is always the risk that absorber pipes which have been installed properly can suffer damages between pressure testing and covering with concrete.

5.1.3 Tunnels constructed with tubbings

If a tunnel is planned to be constructed with tubbings (pre-fabricated tunnel elements), the majority of the installation work can be done outside of the tunnel, allowing for a controlled working environment and limiting the risk of damages to the pipework. As the absorber pipes can be pressure tested before and after filling the tubbing casing with concrete, tight absorber pipes are guaranteed even after the transport and installation.

The pictures below show the attaching of the absorber pipes to the outer reinforcement, the pipes attached to the casings, one tubbing equipped with the absorber pipes and a tunnel section with 6 tubbing rings.
Inside the tunnel, only the connections between the tubbings and from each tubbing ring to the manifold pipe have to be made, see pictures below. Afterwards, the cut-out has to be filled with insulation material in order to avoid heat transfer to or from the tunnel air. PE-Xa is the most suitable pipe material, as it provides ultimate resistance against crack propagation and allows easy connection in these cut-outs with axial compression sleeves.
Good practice example: Brenner base tunnel at Jenbach, Tyrol

A 54m long section of the feeding tunnel made from tubbings to the Brenner Base Tunnel underneath Jenbach has been equipped with 4700m of absorber pipes with an outer diameter of 25mm in order to provide heat to a building of the municipal building yard, see pictures below.

The thermally activated tunnel section has a contact area of 2000m² to the bedrock.

The extracted heat is being used to feed a 41,5kW gas driven heat pump with a gas demand of 15 kW, resulting in a COP of 2.53.

The installation proved to be significantly oversized, the capacity of the absorber area could not be exhausted by the heat pump. Therefore, trials have been carried out with a cooling unit, resulting in a heat flux capacity of appr. 16 W/m²:

Figure 66: Operation data of the geothermal tunnel activation at Jenbach. Source: [4]
5.1.4 Design Guidelines

At open systems, the amount and temperature of warm drainage water cannot be altered or engineered and determines the potential heat extraction. At closed systems, the difference between metro and railway tunnels is significant; the construction method – conventional or tunnel segments – has no systematic influence onto the heat extraction.

Metro tunnels (like the “Fasanenhof” tunnel described in section 5.1.2) are typically characterized by
• high train frequency
• many braking events
• constructed in cities / underneath buildings
• small diameters

All these factors result in relatively high temperatures, therefore these tunnels are referred to as “warm tunnels” while railway tunnels lack all these factors, resulting in low tunnel temperatures and the designation as “cold tunnels”. Another factor of the heat capacity is the speed of the heat transfer fluid: at warm tunnels, the absorber capacity can be increased by 150 % when changing from a laminar to a turbulent flow mode, at cold tunnels the increase is still 80%.

Turbulent flow mode requires high flow speeds and thus a high pressure drop, resulting in a high pump power demand.

Therefore, an efficient installation imperatively requires an automation which adjusts the pump power to the current heat demand.

The distance between the absorber pipes should be approximately 40 cm. A smaller distance leads to (nearly proportionally) higher investment and operation cost, but the additional gains are significantly smaller.

The distribution pipes and manifolds connected to the absorber pipes usually have to be installed in the lower section of the tunnel, therefore the installing turning points of the absorber pipes may be up to 10 m above the connection to the manifold. If it is not possible to install venting devices there and to guarantee access to these venting valves, it is essential to equip the manifolds with valves, enabling to concentrate the total flow into one pipe to force any air out of the pipe.
5.1.5 Economics

At open systems the warm drainage water collected within the tunnels anyway is available “free of charge”. In many cases, the drainage water even has to be cooled before discharging into rivers or becks anyway, increasing the temperature level of the excess waste heat. Therefore, the economics of the utilisation of the drainage water of tunnels typically is very favourable – even, if the heat has to be transported over a distance.

For closed systems, the additional cost to equip a tunnel with installations for thermal activation are approximately 1 % of the total cost.

Based on an annual full load operation of 2196 hours and (constant) heat cost of 0,06 EUR/kWh, the estimation of the installation cost, the pay-back and the amortisation are shown in Figure 68:

- for train tunnels, the amortisation time is approximately 12 years
- for metro tunnels there is a variation between 8 years and 13.5 years.

Valuating these amortisation times, the life expectancy of tunnels and installations within and future energy cost price increases have to be taken into account.

![Figure 68: The curve “Metro min” is based on a heat flux of 25 W/m², the curve “Metro max” on 38 W/m² [4]](image)
5.2 Geothermal Reservoirs coupled with traffic infrastructure

There are numerous opportunities for both economic and ecological utilizations of road heating and cooling combined with geothermal installations.

In winter, the advantages for these applications are the prevention or at least reduction of:

- accident risks as a result of ice and snow on traffic areas
- the cost associated with ice and snow removal
- other processes damaging the environment and structures (e.g. salting)
- pollution of adjoining areas by salt, grit and dirty snow

If such geothermal installations are operated in summer as well, the advantages are:

- reducing the wear, especially the creation of lane grooves, in tarmac and the associated maintenance cost
- reducing the stresses in concrete structures, increasing the design life
- regeneration of the geothermal reservoir.

For preventing ice and snow building on traffic areas, (surface) temperatures above 3-5°C are sufficient. This temperature level can be provided both with pure circulation and with the support of heat pumps, probably with additional heat sources and/or buffer tanks. For systems relying on geothermal sources only (be it with or without heat pumps), it is practically impossible to design economically viable systems which prevent the ice and snow building under all conditions, e.g. extremely long and cold winters and/or extreme snowfall. This is similar to the engineering of dikes: they can be designed for a high water probably occurring every 100 or every 500 years – but this event may happen next year.

5.2.2 Traffic Surfaces coupled directly with geothermal Sources

The obvious advantage of the direct coupling of traffic surface to be activated thermally by geothermal resources are that the operation cost (and the associated CO₂ production) of heat pumps can be avoided. The investment cost are not necessarily lower, as the geothermal installation has to be designed larger and hence more expensive. The disadvantage of such systems however is, that they are especially vulnerable in the case of extreme weather conditions. Such systems are sometimes referred to as “passive” systems – this however is misleading, as both circulation pumps and automation systems are required. Only systems based on the heat pipe principle (see chapter 5.4) can really be regarded as passive systems. A well documented example are two train station platforms at Bad Lauterberg at the Harz region in Germany. The climate conditions there are similar to those in southern Bavaria, i.e. the Alpine Space.

The platforms have a total surface of 620m² and are directly connected to 9 borehole heat exchangers with a length of 200m each. With a calculated performance of 50 W/m based on the bedrock profile, the design capacity of 90kW of the BHE results in a heating performance of 145 W/m². [7, 8]
The circulation pumps are switched on if the surface temperature is between 3° and -10°C, as at lower temperatures, no snow fall occurs anymore. At high temperatures in summer, the circulation pump is switched on as well, transporting heat into the ground source. The amount of heat extracted in winter (appr. 155,000 kWh) is very similar to that returned in summer (130,000 kWh), nearly eliminating any long time temperature drift of the geothermal reservoir.

The platform is constructed with pre-fabricated modules 2,5 x 2,5m. The heating / absorber pipes are attached to the steel reinforcement at a relatively large distance of 28cm.

During the monitoring of the first three years after the installation this performance had been documented:
- 56 x snow without accumulation
- 32 x snow with accumulation
- 2x manual snow removal had been required

In all cases, the surface temperature of the platform remained above 0°C, i.e. there has been no ice-building and hence no danger of slippery snow on top of an icy underground.
Figure 70: Example from the Bad Lauterberg train platform with temporary snow accumulation after 10cm snowfall within 1.5 hours which melted within 6 hours. [8]
5.2.1 Traffic Surfaces coupled with geothermal Sources via Heat Pumps

With the installation of heat pumps the performance of surface heating installations can be improved, but the operation cost and the CO₂ production associated with heat pump operation has to be taken into account. One example is a truck test site of MAN at Karlsfeld, a suburb of Munich, where noise measurements of trucks are carried out for approval purposes. These tests have to be carried out under strictly specified conditions, dry road surfaces are one of them. In order to avoid lengthy time periods during which no testing can be carried out, the test area of 340 m² has been equipped with heating pipes.

![Noise test site and installation of the surface heating system](image)

The test conditions require a tarmac surface. In order to ensure a proper installation of the heating pipes, they have to be laid in or covered by mastic asphalt. This requires the utilization of pipes made of PE-Xα with an aluminium layer, which withstands both the temperatures of 240 °C of the mastic asphalt and reduces the otherwise high coefficient of heat expansion of pure PE-Xα [9]. The heat is provided by a 75 kW Alpha Innotec SWP 820-86/W53, which is coupled with two wells 12m deep at a flow rate of 50 m³/h. The annual operation time is appr. 2500 hours, resulting in a consumption of 140.000 kWhel/a. The additional cost compared to a gas boiler including the connection to the gas mains have been appr. 35.000 EUR, the operation cost savings are 7.800 EUR/a and the reduction of CO₂ production is about 22t/a or 41% and the reduction of primary energy consumption is 33 %.
Another example is the geothermal heating of a road section underneath a railway bridge in Munich. Ground water tends to penetrate the road surface, and rain water trickles through joints of the bridge, resulting in the creation of massive ice layers in winter which can only be removed mechanically. Again, a tarmac surface was specified, requiring the installation of PE-Xa pipes with an aluminium layer. The heated section has 450 m², the pipe distance is 0.1 m, resulting in a total pipe length of 4500 m. The heat is extracted from ground water at a flow rate of with two wells with a depth of 10 m each. The ground water can be used directly or can be heated by a 100 kW Weidner heat pump. The content of a 560 l buffer tank held at 35°C can provide another 50 kW of peak heat, resulting in 330 W/m² heat flux.

With these parameters, the road can be kept free of ice with less than 150 annual heat pump operation hours. Compared to a surface heating with natural gas, 63 t/a or 93% of CO₂ production can be avoided. A scenario without a surface heating installation does not mean that no CO₂ is being produced: the transport of service personnel and the operation of ice removing machinery does produce CO₂, and traffic congestions as a result of slippery or blocked roads as well.

Finally, the surface heating of a new built steel bridge near Berkenthin, northern Germany is to be mentioned. This is not within the Alpine Space, but with 69-135 frost days/a and 6-49 ice days/a it has a demanding climate as well. Details can be extracted from [10].

5.2.2 Design Guidelines

Traffic area heating to prevent the creation of ice and the accumulation of snow always has to cope with weather and especially weather extremes, which are especially difficult to predict: even a weather condition which statistically will occur every 500 years only may occur in the next season. When engineering a traffic area heating system based on geothermal resources, the designers and the customer therefore have to agree on the objectives and the resulting consequences.

The following topics have to be considered during the engineering process:

The utilization of advanced simulation modelling software like TRNSYS and real weather data of the last years provided by met offices can give valuable information. Additionally they allow to simulate stipulated weather extremes (e.g. 5cm of snow per hour for 48 hours) – but theoretically even more snow may fall during the operation period of the system.

For preventing ice building as a result of rain or air humidity, a heat flux of 150 W/m² will be sufficient in most cases. Higher values are required at bridges, especially steel bridges, as their thermal buffer capacities are very limited. Regions with high humidity, e.g. at lakes or large rivers, will require higher heat fluxes as well to prevent ice building with a high probability.

Preventing the accumulation of snow is more demanding. As snowfall may last for many days, with a geothermal source alone the accumulation of snow practically cannot be prevented. However, in most cases a heat flux of 300 W/m² will be sufficient to limit the accumulation of snow to a small number of hours per year. As the heating prevents the creation of an ice layer between the road and the snow, the surface will not be excessively slippery even with accumulated snow.
Surface heating systems without heat pumps, i.e. with a circulation only between the geothermal reservoir and the surface to be heated are possible, but need careful engineering. The obvious advantages are negligible operation cost and energy demand. If ground water can be utilized, the investment is likely to be lower as well. If borehole heat exchangers are to be used, investment savings however cannot be expected, as the necessary increase of the size of the BHE length might compensate the savings when omitting the heat pump.

Surface heating systems with heat pumps provide a better performance and more operation options. The associated downside are the much higher energy demand and operation cost, and potentially higher investment.

Hybrid systems, which have a heat pump that can be bypassed, will be the optimum in most cases. They allow a highly efficient operation without the heat pump, i.e. a circulation pump only, for the majority of the time. Only if the circulation alone does not provide sufficient heat, the heat pump is being switched on.

In theory, a system based on BHE can work with one fluid and a simple bypass of the heat pump only. However, the fluid in the heating pipes in the traffic area needs a frost prevention of up to -20°C or even lower (in case the installation fails), resulting in a high viscosity and associated pressure loss. Subject to the project specific conditions to be considered, it might be advantageous to have two circles with different viscosities coupled by a heat exchanger.

If high peak loads are expected, the heat pump can be complemented by other heat sources and/or a water buffer tank to provide additional peak heating. If the additional peak heat demand is high, but the annual operation time very low, even the utilisation of gas/oil boilers or electrical heating as “other heat sources” may be economically efficient and ecologically acceptable.

For all closed-loop systems, the thermal regeneration of the geothermal reservoir improves the long-time performance of the installation significantly by avoiding or at least reducing the temperature drift of the bedrock. Ideally, the same amount of heat extracted in the winter should be returned in summer.

Extracting heat from the surface has additional positive effects: the design life of concrete structures is increased, the creation of lane grooves in tarmac surfaces is reduced, and last but not least the reduction of the surface temperature in summer positively influences the urban climate.

Finally, the control strategy has a decisive impact on the performance of the system. A simple strategy is to simply control the heating system by surface and air temperature: The heating is switched on, if the surface and air temperature falls below e.g. 3°C. More sophisticated systems also take snowfall and air humidity into account. Different control strategies are discussed in [9].

The University of Applied Science at Ingolstadt is working on intelligent control strategies including weather forecast data from meteorological offices. Contrary to other shallow geothermal utilizations, such installations are not designed for maximum efficiency but for maximum safety. This has to be taken into account for the choice of the proper control strategy.
5.2.3 Economics

When calculating the economics, two scenarios have to be distinguished:

a) surface heating is specified, the question only is which heat source shall be selected
b) surface heating is optional

ad a): If the heating of traffic surfaces is specified anyway, the geothermal system has to be compared to a conventional solution:

Table 25: Economic factors that need to be considered comparing geothermal to conventional surface heating

<table>
<thead>
<tr>
<th></th>
<th>Geothermal</th>
<th>Conventional</th>
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<tbody>
<tr>
<td>Investment</td>
<td>Borehole heat exchangers or ground water wells</td>
<td>Boiler for natural gas or oil</td>
</tr>
<tr>
<td></td>
<td>Heat pumps and/or circulation pumps</td>
<td>Connection to the gas mains or oil tank</td>
</tr>
<tr>
<td></td>
<td>Probably booster heating equipment</td>
<td>Chimney</td>
</tr>
<tr>
<td>Operation Cost</td>
<td>Power for heat pump or circulation pump</td>
<td>Cost for natural gas or oil</td>
</tr>
<tr>
<td></td>
<td>Maintenance (Heat pump, neglectable for circulation</td>
<td>Maintenance (Boiler and chimney)</td>
</tr>
<tr>
<td></td>
<td>pumps)</td>
<td>Financing Cost</td>
</tr>
<tr>
<td></td>
<td>Financing Cost</td>
<td></td>
</tr>
<tr>
<td>CO2 production</td>
<td>With heat pumps: power demand is approx. 25% of that</td>
<td>That associated with burning</td>
</tr>
<tr>
<td></td>
<td>of gas or oil. The CO2 production depends on the</td>
<td>natural gas or oil</td>
</tr>
<tr>
<td></td>
<td>local share of renewable/nuclear/fossil contribution to the power production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>With circulation pumps only: CO2 production is</td>
<td></td>
</tr>
<tr>
<td></td>
<td>neglectable</td>
<td></td>
</tr>
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</table>

This comparison shows that the economics depend both on regional factors (power tariffs, oil and gas prices) and local conditions (availability and costs of natural gas and availability / accessibility of geothermal resources).

ad b): If the heating of traffic surfaces is optional, these factors have to be considered and valuated additionally:

- snow / ice removal cost to be saved
- the cost of salt and grit distribution and removal
- damage to structures from salt
- damage to the environment from salt
- reduced risks of accident
- if the installation is used for surface cooling in summer:
  - increased life expectancy of concrete structures due to reduced heat expansion
  - decreased formation of lane grooves in tarmac

The economic comparison for the train platform surface heating in Bad Lauterberg (see chapter 5.2.1) proves that surface heating is not only convenient, but can also be economically feasible (Table 26).

Table 26: Economic comparison for the train platform heating in Bad Lauterberg

<table>
<thead>
<tr>
<th></th>
<th>Conventional Platform</th>
<th>Heated Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>900.000 EUR</td>
<td>1.100.000 EUR</td>
</tr>
<tr>
<td>Operation Cost incl. snow + ice removal</td>
<td>3.750 EUR/a</td>
<td>1.500 EUR/a</td>
</tr>
<tr>
<td>Life expectancy</td>
<td>25 years</td>
<td>32.5 years</td>
</tr>
<tr>
<td>Interest</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Cash value</td>
<td>265.772 EUR</td>
<td>225.289 EUR</td>
</tr>
</tbody>
</table>
5.3 Geothermal Train Switch Heating

Train switches have to be heated in winter. The disadvantage of the commonly used electrical heaters are a high electrical power demand and punctual heat transfer.

In Germany, 64,000 switches are being heated, resulting in an electrical power demand of 230 GWh/a [11]. The utilization of geothermal reservoirs via heat pumps reduces the demand of electrical power by up to 80 % and allows a larger heat transfer area.

Train switches coupled with standard borehole heat exchangers (see picture below) have proven to be a reliable technology and have been installed at eight locations all over Germany as well as one location in St. Petersburg, Russia. Apart from one installation in Oberstdorf, all installations perform perfectly according to specification. In Oberstdorf, the bedrock parameters have been over-estimated, resulting in an insufficient BHE capacity.

Installed Systems

- Holzminden – Niedersachsen 2007
- Vilseck – Bavaria 2009
- Farchant – Bavaria 2010
- Sulzbach am Inn – Bavaria 2011
- Sankt Petersburg – Russia 2011
- Oldenburg – Niedersachsen 2014
- Heimbach – Rheinlandpfalz 2014
- Oberstaufen – Bavaria 2016
- Oberstdorf – Bavaria 2016

Figure 72: Electrical vs. Geothermal switch heater (above). Principle of geothermal switch heater (below).
5.4 Heat Pipe Borehole Heat Exchangers

Heat Pipe Borehole Heat Exchangers are operated without circulation pump based on the thermosiphon effect. The pipes are filled with party liquid, partly gaseous CO\textsubscript{2} under high pressure, about 30 to 40 bar. The basic principle is that the liquid CO\textsubscript{2} evaporates in the (relatively warm) Borehole heat exchanger, while the gaseous phase condenses in the (relatively cold) surface heating system and flows back into the BHE. This creates a self-sustaining circulation within the system making the circulation pump dispensable. Hence, these systems are extremely reliable and fail-safe, even in case of a power outage. Heat Pipe Borehole Heat Exchangers are installed in several cases as de-icing and snow melting system of road surfaces. For other fields of implementation, like bridges or switch heating this system has not been successfully tested yet.

REFERENCES OF THIS SECTION

### Table 27: List of thermal conductivity values from literature and measured by GeoZS and by Leoben Univ.

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<thead>
<tr>
<th>Rock type 1</th>
<th>Rock type 2</th>
<th>λ value range [W/m*K]</th>
<th>Guide value for calc.</th>
<th>Source</th>
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<td>2 3 2,4</td>
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<td>1,1 3,4 2,2</td>
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<td>Clay marl</td>
<td>1,73 2,57 2,04</td>
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<td>Siltstone (a bit quartzitic?)</td>
<td>Siltstone (a bit quartzitic?)</td>
<td>2,94 3,86 3,43</td>
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<td>Siltstone and claystone</td>
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<td>Siltstone to mudstone</td>
<td>Siltstone to mudstone</td>
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<td>Mudstone</td>
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<td>1,63 2,12 1,84</td>
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<td>Kappelmeyer &amp; Haenel, 1974; Zoth &amp; Haenel, 1988</td>
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<td>2,1 3,5</td>
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<td>Sandstone</td>
<td>1,9 4,6 2,8</td>
<td>UNI 11466</td>
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<tr>
<td>Sandstone and fine-grained siltstone</td>
<td>Sandstone and fine-grained siltstone</td>
<td>1,44 2,63 1,95</td>
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<td></td>
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<tr>
<td>Sandstone quartzitic</td>
<td>Sandstone quartzitic</td>
<td>4,89 5,74 5,30</td>
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<tr>
<td>Sandstone quartzitic with conglomerate</td>
<td>Sandstone quartzitic with conglomerate</td>
<td>3,47 4,35 3,91</td>
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<tr>
<td>Tuffitic sandstone</td>
<td>Tuffitic sandstone</td>
<td>2,11 2,82 2,45</td>
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<tr>
<td>Tuff (also sericitized)</td>
<td>Tuff (also sericitized)</td>
<td>2,11 3,50 2,88</td>
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<tr>
<td>Tuff, keratophyric and porphiric</td>
<td>Tuff, keratophyric and porphiric</td>
<td>3,74 4,31 4,04</td>
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</tbody>
</table>
### Catalogue of operational criteria and constraints

**Rock type 1** | **Rock type 2** | **$\lambda$ value range [W/m*K]** | **Guide value for calc.** | **Source**
---|---|---|---|---
Conglomerate/breccia | 1.3 | 3.1 | 2.6 | SIA 384
Conglomerate quartzitic | 3.85 | 5.37 | 4.82 | GeoZS
Marl | 1.5 | 3.5 | 2.1 | SIA 384
Marl | 2.33 | 3.23 | 2.7 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Marl | 1.8 | 2.9 | 2.3 | UNI 11466
Limestone | 1.86 | 3.07 | 2.64 | GeoZS
Limestone | 1.7 | 2.68 | 2.5 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Limestone | 1.7 | 5.2 | | ASHRAE
Limestone | 1.7 | 3.9 | 2.7 | UNI 11466
Compact limestone | 2.34 | 3.51 | 2.82 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Marl limestone | 1.405 | 3.05 | 2.39 | GeoZS
Lime marl | 1.84 | 2.4 | 2.12 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Marl black limestone, almost coalish | 1.70 | 2.44 | 2.01 | GeoZS
Dolomite | 3.34 | 5.94 | 4.87 | GeoZS
Dolomite | 2.52 | 4.65 | 4.14 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Dolomite | 2.8 | 6.2 | | ASHRAE
Dolomitic limestone | 2.78 | 3.15 | 3.03 | GeoZS
Salt | 5.3 | 6.4 | 5.4 | VDI 4640_1_2000
Salt | 4.48 | 5.79 | 5.52 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Salt slate | 1.24 | 4.19 | 2.76 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Sylvinite | 4.6 | 5.78 | 5.29 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Sulphate rock (anhydrite) | 4.1 | 6.07 | 5.28 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Sulphate rock (anhydrite, gypsum) | 1.3 | 2.8 | 1.6 | SIA 384
Wet shale (25% quartz) | 1.7 | 3.1 | | ASHRAE
Wet shale (no quartz) | 1 | 4 | | ASHRAE
Dry shale (25% quartz) | 1.4 | 2.4 | | ASHRAE
Dry shale (no quartz) | 0.9 | 1.4 | | ASHRAE
Rock Salt | / | 6.4 | | ASHRAE
Anhydrite, phylitic | 4.8 | 5.3 | 5.02 | GBA
Anhydrite | 5.49 | | | GBA
Limestone | 2.77 | 3.26 | 3.06 | GBA
Granite | 2.1 | 4.1 | 2.8 | SIA 384
Granite | 2.1 | 4.1 | 3.2 | UNI 11466
Granite (10% quartz) | 1.9 | 5.2 | | ASHRAE
Granite (25% quartz) | 2.6 | 3.6 | | ASHRAE
Rhyolite | 3.1 | 3.4 | | VDI 4640_1_2000
Rhyolite | 3.1 | 3.4 | 3.3 | UNI 11466
Syenite | 2.2 | 3.16 | | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988
Diorite | 2 | 2.9 | 2.3 | SIA 384
Diorite | 2.1 | 2.9 | | ASHRAE
Diorite | 2 | 2.9 | 2.5 | UNI 11466
Granodiorite | 1.64 | 3.47 | 2.6 | Kappelmeyer & Haenel, 1974; Zoth & Haenel, 1988

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GRETA is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme. See more about GRETA at [www.alpine-space.eu/projects/greta](http://www.alpine-space.eu/projects/greta).
<table>
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<th>Rock type 1</th>
<th>Rock type 2</th>
<th>λ value range [W/m*K]</th>
<th>Guide value for calc.</th>
<th>Source</th>
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<td>high</td>
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<td>Granodiorite</td>
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<td>3.5</td>
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<td>Gabbro</td>
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<td>2.0</td>
<td>SIA 384</td>
</tr>
<tr>
<td>Gabbro</td>
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<td>2.9</td>
<td>2.0</td>
<td>UNI 11466</td>
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<td>Gabbro (Cen. Plains)</td>
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<td>2.8</td>
<td>2.0</td>
<td>ASHRAE</td>
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<td>Gabbro (Rocky Mtns.)</td>
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<td>3.6</td>
<td>2.0</td>
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<td>2.16</td>
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<td>2.4</td>
<td>2.0</td>
<td>ASHRAE</td>
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<td>Basalt</td>
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<td>2.3</td>
<td>1.7</td>
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<td>2.95</td>
<td>GeoZS</td>
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<td>SIA 384</td>
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<td>2.94</td>
<td>Kappelmeyer &amp; Haenel, 1974; Zoth &amp; Haenel, 1988</td>
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<td>Amphibolite</td>
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<td>3.6</td>
<td>2.9</td>
<td>UNI 11466</td>
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<td>Phyllite: carbonate, limestone, quartz, graphite, sericite, gray, black, green, etc..</td>
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<td>3.116</td>
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<td>Rock type 1</td>
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<td>(\lambda) value range [W/m*K]</td>
<td>Guide value for calc.</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>low</td>
<td>high</td>
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<tr>
<td>para, phyllite, fine-coarse-grained, ortho, etc.</td>
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<td>Greenschist: also with mica schist, also prasinite</td>
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<td>3.661</td>
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<td>Chert and Quartzite</td>
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<th>Guide value for calc.</th>
<th>Source</th>
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<tr>
<td>Concrete</td>
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<td>2,2</td>
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<tr>
<td>Ice (-10 °C)</td>
<td>2,1</td>
<td>2,32</td>
<td>2,32</td>
</tr>
<tr>
<td>Polyethylene (PE100)</td>
<td>0,4</td>
<td>0,4</td>
<td>0,4</td>
</tr>
<tr>
<td>Air (0 °C – 20 °C)</td>
<td>0,02</td>
<td>0,02</td>
<td>0,02</td>
</tr>
<tr>
<td>Steel</td>
<td>60,0</td>
<td>60,0</td>
<td>60,0</td>
</tr>
<tr>
<td>Water (10 °C)</td>
<td>0,6</td>
<td>0,6</td>
<td>0,6</td>
</tr>
<tr>
<td>Anchor grout</td>
<td>1.14</td>
<td>1.55</td>
<td>1.55</td>
</tr>
</tbody>
</table>

**Table 28: Thermal conductivity values for rocks from the Molasse basin.**

<table>
<thead>
<tr>
<th>Molasse</th>
<th>Type of rock / soil</th>
<th>Thermal conductivity (\lambda) [W/(m*K)]</th>
<th>Value range</th>
<th>Guide value for calc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper freshwater Molasse</td>
<td>Claystone - pelite</td>
<td>2.3</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Pelite</td>
<td>2.3</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Sandstone fine-grained</td>
<td>2.3</td>
<td>2.6</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Sandstone middle-grained</td>
<td>2.5</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Sandstone coarse-grained</td>
<td>2.5</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Upper marine Molasse</td>
<td>Claystone - pelite</td>
<td>2.6</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Pelite</td>
<td>2.6</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Sandstone fine-grained</td>
<td>2.7</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Sandstone middle-grained</td>
<td>2.7</td>
<td>3.2</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Sandstone coarse-grained</td>
<td>2.6</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Lower freshwater Molasse</td>
<td>Claystone - pelite</td>
<td>2.2</td>
<td>2.7</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Pelite</td>
<td>2.3</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>Sandstone fine-grained</td>
<td>2.4</td>
<td>2.8</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Sandstone middle-grained</td>
<td>2.7</td>
<td>3.2</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>Sandstone coarse-grained</td>
<td>2.2</td>
<td>3.1</td>
<td>2.4</td>
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</tbody>
</table>
The main trends are summarized below (open loop):

- Influence of ground thermal conductivity
- Influence of underground water flow
- Influence of initial temperature
- Influence of ground thermal capacity
- Influence of number of boreholes

**Figure 73**: Case A (Genoa, 29 BHE): Sensitivity analysis for SPF$_2$ at the 10$^{th}$ year of operation

**Figure 74**: Case A (Genoa, 29 BHE): Sensitivity analysis for the minimal inlet temperature in the BHE field

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Figure 75: Case A (Genoa, 29 BHE): Sensitivity analysis for the maximal inlet temperature in the BHE field

Figure 76: Case B (Genoa, 22 BHE): Sensitivity analysis for SPF$_2$ on the 10$^{th}$ year of operation
Figure 77: Case B (Genoa, 22 BHE): Sensitivity analysis for the minimal inlet temperature in the BHE field

Figure 78: Case B (Genoa, 22 BHE): Sensitivity analysis for the maximal inlet temperature in the BHE field

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Figure 79: Case C (Davos, 64 BHE): Sensitivity analysis for SPF₂ on the 10th year of operation

Figure 80: Case C (Davos, 64 BHE): Sensitivity analysis for the minimal inlet temperature in the BHE field
Catalogue of operational criteria and constraints

GRETA is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme. See more about GRETA at www.alpine-space.eu/projects/greta.
Figure 83: Case D (Davos, 48 BHE): Sensitivity analysis for the minimal inlet temperature in the BHE field

Figure 84: Case D (Davos, 48 BHE): Sensitivity analysis for the maximal inlet temperature in the BHE field
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Catalogue of operational criteria and constraints


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[38] VDI, VDI 4640 - Thermal use of underground, 2010.


Partner’s involvement

<table>
<thead>
<tr>
<th>No.</th>
<th>Partner</th>
<th>Contact</th>
<th>E-mail</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>7</td>
<td>EURAC</td>
<td>Pietro Zambelli</td>
<td><a href="mailto:Pietro.Zambelli@eurac.edu">Pietro.Zambelli@eurac.edu</a></td>
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</tbody>
</table>