Potential of near-surface geothermal heating on houses in Graz with graphic charts

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Abstract

This report presents a comprehensible overview of the potential and challenges of the use of near-surface geothermal heating in Graz, with especial emphasis in Borehole Heat Exchangers and Ground Sourced Heat Pumps, which have more potential in areas more densely populated.

In order to predict how self-sufficient can be a residential building under variable conditions, this work includes an spreadsheet with graphic representation of the results. Some of the variables that can be modified include the Floor Area Ratio, the performance and number of boreholes, and energy consumption of the building.

In addition, are included chapters of introduction to understand how the Ground Sourced Heat Pump work, and which are the factors that influence their performance. Additional chapters delve into more technical issues of this technology, and on comparisons with other strategies that can reduce the energy dependance of a building.

The results obtained from this research suggest that the near-surface geothermal heating is a real alternative for highly insulated buildings, new or refurbished. In buildings with high Heating Energy Requirements, the potential is however limited. The presence of a permeable aquifer and high underground temperatures in Graz are opportunities for the deployment of the technology. The presence of the advection in some areas, the eventual perturbations on underground temperature and the high costs of refurbishment and installation are the main obstacles for the implementation of Ground Sourced Heat Pumps.

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Acronyms

BHE:	Borehole Heat Exchanger
BTES:	Borehole Thermal Energy Storage
CER:	Cooling Energy Requirements
CDD:	Cooling Degree Days
COP:	Coefficient of performance
CSPF:	Cooling Seasonal Performance Factor
DHW:	Domestic Heat Water
EER:	Energy Efficiency Ratio
FAR:	Floor Area Ratio
GHE:	Ground Heat Exchanger
GSHP:	Ground Source Heat Pump
HDD:	Heating Degree Days
HER:	Heating Energy Requirements
PV:	Photovoltaic
SPF:	Seasonal Performance Factor
TS:	Thermosolar

Chapter 1

Introduction

Environmental concerns and economic savings motivate the pursue of energy efficiency at different levels. One of the areas with more room for improvement is the residential heating, which consumes up to 80 % of the residential energy requirements in Europe. In order to reduce the energy expenses of the buildings, one of the strategies consists in finding alternatives more sustainable and energy-efficient than the traditional boilers run with fossil fuels.

One of these technologies is based on heat pumps, devices able to move heat from the surrounding environment to inside a building – or the other way around. The heat pumps can extract heat from several sources, and as underground temperatures remain relatively stable along the year, the Ground Sourced Heat Pumps (GSHP) become an interesting option to provide heating requirements in a sustainable way. There are however limitations to consider, regarding for instance on the heat available in the underground, or the cost of the technology.

Graz is the second biggest city of Austria, and has the will to improve its sustainability during the future decades, thanks to the "I live Graz" project [53]. The present report tries to determine which role can have the near-surface geothermal energy in general, and in particular the GSHPs, in the sustainable future of the city. To support the report, it is included an spreadsheet with two sheets: a first one to determine at a glance the potential of heating self-sufficiency in function of the Floor Area Ratio of a building, its Heating Energy Requirements (HER) and the features of the Borehole Heat Exchangers (BHEs); and a second one that seeks for a more detailed evaluation of the sustainability potential including solar technologies into the calculations.

This report strives also to be a reference guide, and a work to serve as introduction to the topic of GSHPs. From the neophyte, who will find support in the broad introduction, to the technician, who will find deeper understanding about the engineering principles behind the GSHPs, it tries to offer a concise yet complete overview of the potential of the near-surface geothermal energy.

This report is organized in seven chapters; after this introduction, the second chapter will delve on the generalities of both the geothermal heating and the residential requirements for heat demand; a section that can serve as a theoretical introduction for those not familiarized with the topic.

Chapter three (page 24) frames the research question on the specific case for Graz, describing its particularities and the physical setting of the city. Through the rest of the report, the data gathered will nuance the threats and opportunities the near-surface geothermal energy has in the city.

Chapter four (page 30) constitutes the core of the report: the descriptions of the spreadsheets that help to calculate the self-sufficiency by means of GSHPs. This is a tool that can be helpful both at the city-level decision making and in a particular application in an specific building.

Chapter five (page 46) gathers important engineering-based information about GSHPs which, because of its complexity, was not included in the spreadsheets. It is a non-essential part, that anyway can be used as a reference guide, and to understand better the engineering principles behind the work of GSHPs.

Chapter six (page 55) offers an overview to the retrofitting and its costs, a necessary inclusion in the report because the installation of GSHPs is often associated with retrofitting of buildings. It also includes a mention about different alternatives to heat pumps, and the tools used to optimize the refurbishment measures taken.

Last, chapter seven (page 7) offers a number of conclusions, final thoughts and recommendations based on the preliminary results obtained, including some personal comments of the author.

Chapter 2

Geothermal heating in residential buildings

The present chapter is a basis of knowledge to understand both how a GSHP works, and which are the factors than influence the HER in residential buildings.

2.1 Heat pumps and geothermal energy

2.1.1 Heat pump: definition

A heat pump is a device that provides heat energy from a source of heat to a destination. Heat pumps are designed to move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses some amount of external power to accomplish the work of transferring energy from the heat source to the heat sink.

2.1.2 How it works and types

Mechanical heat pumps exploit the physical properties of a volatile evaporating and condensing fluid known as a refrigerant. The heat pump compresses the refrigerant to make it hotter on the side to be warmed, and releases the pressure at the side where heat is absorbed (Figure 2.1). This can operate both for cooling and for heating. The cooling application is the usually find in an air conditioning system, or a refrigerator. For the purpose of this report, the focus will be mostly on heating mode of the heat pump; but being able to work on cooling mode too will be regarded as an advantage, to provide cooling energy during summer.

Talking about heating mode, the heat pumps can be classified on relation with the sources of heat (the underground is only one of the possible sources of heat). The simplest option in houses is using the air as heat source. The air-sourced heat pumps require low installation costs, but are comparatively not very efficient in the use of energy, because the outdoor air to extract the heat from can be at very low temperature in winter (see table 2.1 on page 15)

To increase their performance, the Ground Source Heat Pumps[1] use Ground Heat Exchang-

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[1] GSHPs are also known as geothermal heat pumps, earth energy systems, or geoexchange systems.

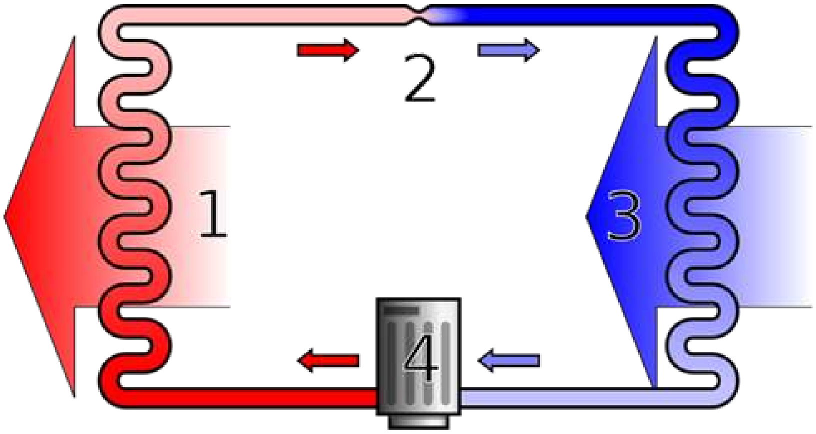

Figure 2.1: A simple stylized diagram of a heat pump's vapor-compression refrigeration cycle: 1) condenser, 2) expansion valve, 3) evaporator, 4) compressor.

ers (GHEs), that reach usually a maximum depth of 200 meters. The underground temperature remains constant around the annual average air temperature at a depth of about 15 m and then increases by 3K per 100 meters[2]; with these moderate and constant temperatures along the year, the underground can be used perfectly as a source of heat in winter, and as a sink of heat in summer.

The GHE that sources the GSHP extracts heat from a volume of ground material called aestifier, and can be horizontal or vertical (Figure 2.2). The horizontal type consists in a net of pipes buried at relatively low deep, and make use mainly of the warmth that receives the ground in summer to provide heat during winter. This system requires a significant non-constructed surface to work properly (as a garden or a parking lot), so it is not suitable to supply areas with high density of buildings, where this free space is scarce.

The vertical Ground Heat Exchangers solve in part this problem; do not require free space, and indeed can be placed right below a building. Because this last system is more suitable for urban centers, this report will focus almost exclusively on it, though with minor modifications the spreadsheets described in chapter 4 can also be adapted to horizontal GHEs. The BHEs of the vertical system encompass a greater volume of underground material, but cannot rely always on natural flows of energy to recharge thermally the underground. Each BHE produces around it a "heat cone" of decreasing temperature, and running the system over years can cause a permanent decrease on the underground temperature that compromises the performance of the GSHP. As will be described below, there are many factors that can attenuate this effect; the simplest of which is designing the heating system of the building with caution, in the way it extracts as much heat in winter as it rejects in summer for cooling purposes.

Because in any case the GHE is practically inaccessible once finished, are usually employed materials of the maximum quality in the construction. In addition, for vertical GHEs it has to be used specialized drilling machinery. This makes the GSHP a heating system with fairly expensive

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[2] In some areas with geothermal anomalies the temperature gradient can be as high as 10K per 100 meters, which naturally leads to higher performance [17].

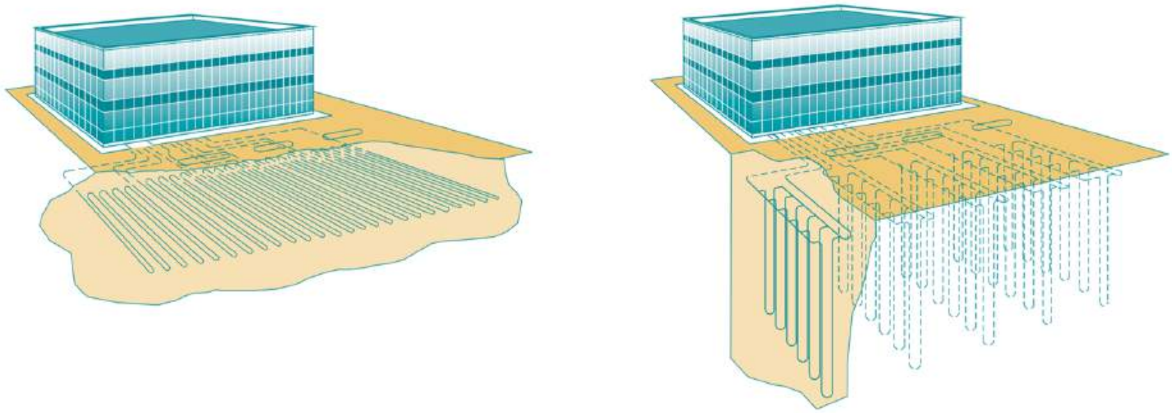

Figure 2.2: Ground Heat Exchanger; horizontal (left) and vertical (right) [50]

installation costs (see table 6.1 on page 58), which is probably its main disadvantage. Also, the thermal disturbances in hydrogeological structures can be a problem of this technology.

2.1.3 Advantages

As aforementioned, the heat pumps are characterized for using external power to transfer heat. This external power must be supplied by high quality energy (high exergy), which in the vast majority of times is electricity; however fossil fuels can be used also to run the compressor.

The main advantage of the Heat Pumps over other heating technologies is that the amount of high-quality energy used is smaller than the amount of final heat obtained, because most of the final heat comes from the heat source, in form of low quality energy. This smaller consumption of high quality energy leads to smaller running costs and smaller environmental impact, especially if green electricity is used. Field studies in Germany showed that the use of geothermal heat sources improve the Seasonal Performance Factor (see below) from 2.6 for an ambient air heat pump to 3.3 in existing buildings. For new buildings with low-temperature heating systems the SPF increases from 2.9 to 3.9 [40]. The electricity consumption is thus reduced by 21% in existing and 26% in new buildings.

Making use of low-quality energy has additional sense under the environmental point of view. As it is the form of energy with lowest quality, heat is frequently wasted when no further work can be produced with it. By using heat pumps, streams of waste heat can be put on good use even when these have low temperature, for instance less than 30° C. If this heat comes from industry, it can be said under an industrial ecologist perspective that there is a maximization of the primary energy source. In addition, there are interesting possibilities as using water heated remotely with thermosolar modules, or making use of the heat contained in the residential waste water [52].

2.1.4 Performance

Below are described a number of considerations revolving around the performance of the heat pumps; a theoretical background that can help to understand the particularities of the technology:

Coefficient of performance (COP)

When comparing the performance of heat pumps, it is best to avoid the word ”efficiency”, which has a very specific thermodynamic definition. The term Coefficient Of Performance (COP) is used instead, to describe the ratio of useful heat movement per work input. For instance, when a compressor consuming 1 kWh delivers 4 kWh or heat, then the COP is 4. Somehow, it is like the heat pump would have 400% efficiency. In mathematical terms, we can refer to the following equation:

$$COP = \frac{\Delta Q_{hot}}{\Delta A} \leq \frac{T_{hot}}{T_{hot} - T_{cool}} \tag{2.1}$$

Where ΔQ_{hot} is the amount of heat extracted from a cold reservoir at temperature T_{cool}; ΔA is the compressor dissipated work; and all temperatures are absolute. The last term of the equation also expresses the theoretical limit on the COP, expressed by Carnot efficiency limits, following the second law of thermodynamics.

Energy Efficiency Ratio (EER)

As a heat pump can work in cooling mode, there is also an Energy Efficiency Ratio (EER), equivalent to the COP for heating. The EER is smaller than the COP because in heating mode the heat dissipated when running the compressor is added in the final heat output; meanwhile in refrigeration mode, this dissipated heat has to be countered with additional work of the compressor.

Seasonal Performance Factor (SPF)

The Seasonal Performance Factor (SPF) is a measure of a heat pump’s performance, that works in a similar way that the COP but considering the whole year. It is defined as the total yearly heat energy output, divided by the total input electricity per year. It is important to define the advantages of the heat pump in the mid and long term.

As the COP has its cooling equivalent in the EER, the cooling version of the SPF is the Cooling Seasonal Performance Factor (CSPF).

Forward heating gradient

As it was stated in the equation 2.1, the maximum theoretical COP is higher as the difference between T_{hot} and T_{cool} is smaller. In other words, the heat pump will consume less electricity as smaller is the difference between the temperature on the source and the desired temperature on the heating system; difference also know as forward heating gradient. Because the underground

Table 2.1: Coefficient of performance (COP) of heat pumps [51]

Temperature of heating water (°C)	Heat sources (°C)						
	Air					Ground-Water	Ground
	-15	-5	0	+5	+15	~+10	~0
30	-	-	3.1	3.2	3.5	5.8	5.0
35	2.5	2.7	2.9	3.0	3.4	5.2	4.4
40	2.2	2.4	2.6	2.8	3.2	4.7	3.9
45	2.0	2.3	2.4	2.6	3.0	4.3	3.5
50	1.9	2.1	2.3	2.5	2.9	4.0	3.3
55	1.8	2.0	2.2	2.4	2.8	3.8	3.1

temperature is higher than the typical air temperature in winter, and thus closer to the desired room temperature, the COP of the GSHP is higher in comparison with the air-based heat pumps.

The importance of low-temperature heating systems

As the COP is improved when the temperature of the heating system is lower, the use of a heating system that operates at low temperature is important to highlight the advantages of a GSHP. For a given desired room temperature, the temperature on the heating system can be very different depending on the technology used. In the case of a classic oil or gas-fired system with ribbed radiators, the typical temperature is 60°C; meanwhile with surface heating[3], the temperature is around 30°C. In short, using a low-temperature heating system improves vastly the COP of a heat pump. Table 2.1 summarizes how the COP changes in function of the forward heating gradient.

On the other hand, it is important to remember that a low-temperature heating system will only suffice if the Heating Energy Requirements (HER) of the building are low enough; and that these heating systems are hard to install. In the case of a refurbishing, an alternative to the floor heating is a similar system placed in the wall, or in some cases it is possible to install large conventional radiators, or a low energy fan heater system [51].

Physical properties of the underground

The COP of a GSHP will be higher as easy is to extract heat from the underground material; and this is not only function of the underground's temperature.

Two parameters that have important influence are the thermal conductivity and the heat capacity. The thermal conductivity λ indicates how easily the heat flows through a material. The

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[3] Surface heating systems are based on a network of tubes embedded on the floor or walls, through which runs warm water.

Table 2.2: Properties of the materials on soil [17, 16]

	Density (1000 kg/m^3)	Thermal conductivity (Wm-1K-1)	Heat capacity (kJ/ kg·K)	Extraction rate (W/m) for 1800 operating hours	Extraction rate (W/m) for 2400 operating hours
Sedimentary rocks					
Limestone	2.6 - 2.7	2.5 - 4.0	0.81 - 0.89		
Marl	2.5 - 2.6	1.5 - 3.5	0.88		
Quartzite	2.7	3.6 - 6.6	0.78 - 0.81		
Salt	2.1 - 2.2	5.3 - 6.4	0.56		
Sandstone	2.2 - 2.7	1.3 - 5.1	0.73 - 1.04	65 - 80	55 - 65
Claystone, siltstone	2.5 - 2.6	1.1 - 3.5	0.84 - 0.92		
Unconsolidated rocks					
Gravel, dry	2.7 - 2.8	0.4 - 0.5	0.52 - 0.57	< 25	< 20
Gravel, wet	2.7	1.8	0.89	65 - 80	55 - 65
Sand, dry	2.6 - 2.7	0.3 - 0.8	0.50 - 0.59	<25	< 20
Sand, wet	2.6 - 2.7	1.7 - 5.0	0.85 - 1.07	65 - 80	55 - 65

higher the thermal conductivity, the heat will flow easier to the BHE, increasing its performance. The heat capacity c_p expresses how much heat can store a material per unit of mass. Essentially, higher values of heat capacity mean that there is more heat available to be extracted by the BHE.

Table 2.2 summarizes the properties of thermal conductivity and heat capacity for different types of materials; it can be observed that the higher extraction rates match with the higher values of both parameters. Chapter 5 will retake the explanation about how the thermal conductivity and the heat capacity affect the behavior of BHEs.

Influence of groundwater

Until now have been commented the advantages of GSHP without considering the existence of groundwater. Certainly, this last can have a major influence in the performance of the BHE, as can be appreciated in Table 2.2: the unconsolidated rocks present much higher yield when are saturated. This is due the high thermal conductivity and heat capacity (4.18 kJ/kgK) of the water; as it occupies the pores of a material, it changes the overall physical properties to a more favorable for the heat extraction ones.

In addition, the flow of groundwater can provide an additional source of heat different than

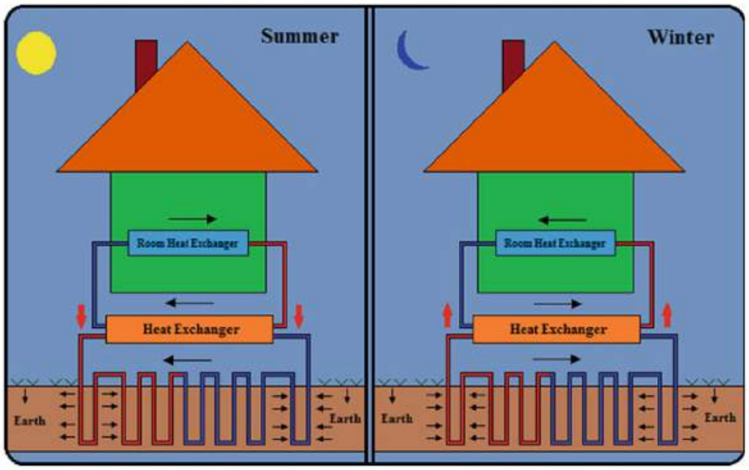

Figure 2.3: Schematic representation of the BTES system [46]

the conduction, by a process called advection. This process can increase easily the performance of a BHE over 10%, and will be addressed in detail in later chapters, especially from page 51.

Last , the presence of an aquifer allows for the construction of a called open-cycle system. The GHEs depicted in figure 2.2 consist in water (or a mixture of water and antifreezer) running through a closed system of pipes. When there is enough groundwater, an alternative is to extract water by a well, and return it back with different temperature by another well into the underground. Naturally, this system can lead to local changes on the groundwater temperatures, so should be used with caution. In the case of Graz, the excessive use of open-cycle system for cooling use is producing a significant rise on the underground temperature [26] (see page 28).

Storage and thermal regeneration

It has been hinted that the influence of the GHE can change locally the temperature of the underground. This phenomenon is a double-edge sword; on one hand, it has been observed that imbalanced extraction of heat can reduce the temperature of the underground in 6ºC as fast as in 5 years [17], which can render the GSHP unusable. On the other hand, this same effect can be used to thermally recharge the underground when needed, or even to store heat. Indeed, Richarz and Schulz [51] argue that near surface geothermal energy should, depending on the usage and regeneration ability of the ground, not be considered as an energy source, but as an energy storage. There are also showcases of thermal storage based on boreholes, and that dispense with heat pumps [56]. On section 4.2 it will be proposed the use of a Borehole Thermal Energy Storage (BTES) [46] in combination with GSHP and thermosolar (TS) technology to compensate the energy balance over the year.

The best way to guarantee a long term proper working of the GSHP is by balancing the heat load and cooling load of the building; if the energy extracted in winter equals the energy rejected in summer, then the underground temperature should remain stable. Whether the thermal loads and the cooling loads match is very climate dependent; it seems to happen in large areas of the

United States [50], but it is definitely not the case of Austria, where the heating days clearly outnumber the cooling days (see Table 3.1 on page 27).

There are also natural ways of ground heat regeneration. There exists a small flow of energy coming from the lithosphere that recharges thermally the ground in a natural way, but this flow is very small (0.06 W/m^2, around 1/1000 of the incoming energy from the sun); additional mechanisms of natural heat regeneration are advection and solar irradiation (described further on page 38)

Integration with solar technologies

As mentioned, the solar energy can be used in combination with heat pumps to further increase the energy self-sufficiency of the buildings, up to the point to produce the same amount of energy that is consumed, achieving in this way a zero-energy building (see below).

An ideally zero-energy building counts both with photovoltaic (PV) modules and TS ones installed on the roof. The PV modules feed the heat pump and supply the rest of electricity demand for lightning and house appliances. On the other hand, the TS modules produce Domestic Hot Water (DHW) and heat to support the heat pump. Also, can serve to regenerate thermally the underground with the excess of heat produced during the summer. An interesting alternative is the PV/T technology; that combines in a single module the production of electricity and heat [60] (see page 36).

Providing DHW is an application where the solar technology has a clear advantage over the heat pumps. Rising the temperature of the water up to 60°C with a heat pump would be very energy consuming due to the principle of the forward heating gradient, so other solutions are preferable. Unfortunately producing and storing DHW with thermosolar panels has also caveats. Richarz and Schulz [51] discuss that storing DHW is a rather inefficient and expensive system when compared with gas burners, which warm the water instantly, “on demand”. This is a not very elegant solution, as depending from a fossil fuel burner contrast with the efforts on implementing renewable energies on buildings, but can be a better option depending on the criteria considered. On the other hand, the solar systems can be easily implemented and are useful when are aimed at just backup the heating system.

The integration with TS energy provide advantages that have been observed already. An study in Austria shows that combined systems achieved an average SPF increase from 2.0 to 2.6 when including all auxiliary consumption; and with a good temperature control, the SPF was raised up to 3.94 [17].

Legal and institutional issues

The use of near-surface geothermal energy can lead to unexpected issues when the technology is used in two adjacent plots of land. In principle, it is easy to assume that each owner has the right over the ground heat placed exactly under his or her plot; but this apparently simple notion can be easily challenged for several causes:

First, to safeguard the “right over the underground’s heat” it should be assured that the borehole remains in the vertical of the plot area. It is normal a deviation of one meter in the horizontal for hundred meters even in well executed boreholes, so BHE poorly executed nearby a neighbor can easily deviate and benefit from a heat flow that in principle belongs to this neighbor, limiting in this way his or her possibilities of heat extraction. Also, a borehole with horizontal deviation will be less deep, and thus will not benefit of the increased temperatures due to the geothermal gradient. In areas where the GSHPs are increasingly popular, like Switzerland, this problem is motivating already the use of technologies that minimize the horizontal deviation meanwhile drilling the borehole.

In addition, even when the borehole is drilled exactly vertical on a certain parcel, the drop of underground temperature produced by this borehole can extend easily over the limits of the parcel, which effectively limits, again, the amount of heat available for neighbors. Possible solutions to palliate this problem are careful design of the BHEs, and mutual agreements between neighbors about the distance from the border to place the boreholes, and the maximum rate of heat extraction. Anyway, it is important to consider also the effect of the advection; as described in section 5.3, the groundwater flow produces a "heat plume" that can reach significant distances, affecting the performance of the boreholes placed downstream the groundwater flow.

2.2 Residential Heating Energy Requirements

Buildings require of a certain amount of energy in form of heat to maintain their comfort temperature during winter. In order to allow comparison between consumptions, these requirements are normalized with the surface of the building. The HER of a building is expressed, thus, on kWh/m^2 yr.

2.2.1 Passive buildings and zero-energy buildings

Currently there is an important trend towards the called "passive buildings" and the "zero energy buildings". Although both are aimed to reduce the environmental impact of the residential buildings, there are conceptual differences about the goal they seek for.

The zero energy buildings strive to produce locally the same energy that produce, using renewable energies. The objective of the passive houses is not as ambitious, focusing more on energy efficiency. The three main parameters to be fulfilled by a passive house are [47]:

- HER (and cooling energy requirements) below 15 kWh/m^2 yr, OR Heating load below 12,73 W/m^2.
- Primary energy demand (the total energy demand including HER, DHW and electricity) below 120 kWh/m^2 yr
- In terms of air-tightness, a maximum of 0.6 air changes per hour at 50 Pascals pressure.

There are also differences in economic terms. Right now in Austria, the extra cost of constructing a passive house is marginal, in comparison with the much more expensive zero-energy ones [33]. In any case, the HER of a zero-energy or a passive building is very low, around 10-15 kWh/m^2 yr, in comparison with the 150 or 200 kWh/m^2 yr that can have houses constructed

Table 2.3: U-values required to reach passive standard for different European climates [17]. The data for Austria is obtained extrapolating the results with the HDD for Italy and Finland [20].

U-values (W/m^{2}K)	Rome Passive Building	Helsinki Passive Building	Austria Passive building
Wall	0.13	0.08	0.11
Window	1.4	0.7	1.1
Roof	0.13	0.08	0.11
Ground	0.23	0.08	0.17
Mean	0.33	0.16	0.26
Heating Degree Days	1970	5849	3573

around 1900. The demand of electricity is in the same order of magnitude; the average household consumption in Germany is around 3600 kWh/yr , giving a value of 31 kWh/m^2 yr. In a passive energy buildings, with special saving measures, can be reached 11,6 kWh/m^2 yr [17].

Because of this potential, these kind of new constructions receive broad institutional support. For instance, in 2009 the EU tightened the EPBD (Energy Performance of Buildings Directive) to demand zero energy standards for new buildings by 2020 [17].

2.2.2 Factors influencing the HER

How much energy requires a residential building to maintain its comfort temperature depends on several factors, including the quality of the insulation and the climate regime where it is placed.

This last it is an important notion; reaching a particular HER will be more difficult and costly in climates with colder and longer winters. To standardize and compare the exigence of a place's climate, are used the Heating Degree Days (HDD). The HER of a building is supposed to be proportional to its amount of HDD; Eurostat [20] calculates the amount of HDD as as $(18 - T_m){\cdot}d$ if $T_m \leq 15$°C (heating threshold) and zero if $T_m > 15$°C, where T_m is the mean $(T_{min} + T_{max}/2)$ outdoor temperature over a given period of d days.

Following the previous, the construction requirements to reach a passive house standard are very place-dependent. Table 2.3 illustrates the differences between a city with typically milder winters (Rome), a city with typically colder winters (Helsinki) and Austria. It can be observed the striking difference between the construction requirements of Rome and Helsinki; the average insulation requirements (U-value) of the first halves the one of Helsinki.

The U-value U (also known as overall heat transfer coefficient) is an easy way to evaluate the level of insulation of the construction materials, and it expresses the heat is able to transmit per square meter of surface and Kelvin degree of difference between room and outdoor temperature (W/m^{2}K). It depends both on the thermal conductivity of the material λ and its thickness L , relating as $U = \frac{\lambda}{L}$. This means that a particular insulation on a house can be both improved by decreasing its thermal conductivity, or increasing its thickness.

The typical U-values of different materials of construction are showed in the tables 2.4, 2.5, 2.6, 2.6 and 2.8. Comparing the U-values of the different parts of the house, as the costs of retrofitting them, it is an important step to consider the costs of thermal refurbishment against the costs of installing a new heating system like heat pumps. This discussion will be retaken on chapter 6.

A note about the influence of user behavior

Another important factor influencing the HER, sometimes dismissed, is how the inhabitants of the house make use of the energy. This behavioral factor can be very influential; Eicker [17] mentions a German case in which for identical building types the standard deviation on energy consumption due to the user influence was up to 35%. This remarks the importance of the user sensitization and the environmental awareness in the pursue of reducing the energy demand in the residential sector.

Table 2.4: Typical U-Values (W/m^{2}K) for exterior walls [51].

pre-1918	Brick or rubble masonry	2.2*
	Timber frame with loam infill	2.0*
1919 - 1948	Brick wall 25 - 38 cm	1.7*
	Single leaf masonry 38-51 cm or two-leaf wall	1.4*
1949 - 1968	Lightweight masonry with hollow blocks, honeycomb bricks, aerated concrete	1.4*
	Masonry with pumice concrete blocks	0.9
1969 - 1978	Lightweight masonry with porous brick and normal weight mortar	1.0
	Precast concrete elements with core insulation or lightweight concrete	1.1
	Timber stud walls with 6 cm insulation	0.6
1979 - 1983	Masonry with lightweight or perforated brick and lightweight mortar	0.8
	Masonry with aerated concrete	0.6
	Precast concrete elements with core insulation or lightweight concrete	0.9
	Timber stud walls with 6 cm insulation	0.5
1984 - 1994	Masonry with lightweight or perforated brick and lightweight mortar	0.6
	Masonry with aerated concrete	0.5

* When retrofitted with at least 20 mm thick insulated boards, global U-value of 1.0 W/m2K

Table 2.5: Typical U-Values (W/m^{2}K) for topmost floor / flat roof [51].

pre-1918	Timber joist floor with straw loam infill	1.0
1919 - 1948	Timber joist floor with false floor and loam infill	0.8
1949 - 1968	Concrete slab, ribbed slab, hollow block floor	2.1*
	Timber joist floor with false floor	0.8
1969 - 1978	Concrete slab with 5 cm topside insulation	0.6
	Flat roof; concrete slab with 6 cm topside insulation (cold roof)	0.5
	Timber joist floor with 4 cm insulation	0.8
1979 - 1983	Flat roof; concrete slab with 8 cm topside insulation	0.5
	Timber joist floor with 8 cm insulation	0.5
1984 - 1994	Flat roof; concrete slab with 12 cm topside insulation	0.3
	Timber joist floor with 12 cm insulation	0.3

* When retrofitted with at least 20 mm thick insulated boards, global U-value of 1.0 W/m2K

Table 2.6: Typical U-Values (W/m^{2}K) for pitched roof [51].

pre-1918	Without insulation, plaster on reed mats or lathing	2.6*
	Straw loam infill between rafters, plaster to underside	1.3*
1919 - 1948	Without insulation, plaster on reed mats or lathing	2.6*
	Straw loam infill between rafters, plaster to underside	1.3*
1949 - 1968	3.5 cm woodwool panel, plastered	1.4*
	Pumice concrete blocks between rafters	1.4*
	5 cm insulation between rafters	0.8
1969 - 1978	3.5 cm woodwool panel, plastered	1.4*
	Pumice concrete blocks between rafters	1.4*
	5 cm insulation between rafters	0.8
1979 - 1983	8 cm insulation between rafters	0.5
1984 - 1994	12 cm insulation between rafters	0.4

* When retrofitted with at least 20 mm thick insulated boards, global U-value of 1.0 W/m2K

Table 2.7: Typical U-Values (W/m^{2}K) for floor over basement / ground floor[51].

pre-1918	Timber joist floor with straw loam infill	1.0
	Stone floor on soil or vaulted basement	2.9*
1919 - 1948	Timber joist floor with false floor and loam mill	0.8
	Solid brick arch floor	1.2
1949 - 1968	Concrete slab, ribbed slab, hollow block floor with minimum impact sound insulation	1.5*
	Timber joist floor with false floor	0.8
1969 - 1978	Concrete slab with 2 cm impact sound insulation	1.0
1979 - 1983	Concrete slab with 4 cm impact sound insulation	0.8
1984 - 1994	Concrete slab with 5 cm impact sound insulation	0.6

* When retrofitted with at least 20 mm thick insulated boards, global U-value of 1.0 W/m2K

Table 2.8: Typical U-Values (W/m^{2}K) for glazing [13, 18]

	Single glazing	5
	Double glazing	2.8
	Double glazing - energy saving	2

Chapter 3

The case of Graz

3.1 Overview and energy policy

Graz is the second biggest city of Austria, a medium-sized one with more than a quarter million inhabitants. Capital of Styria, university city and also known for its cultural heritage, and its very well preserved city center.

Graz is also a city with a political will on reducing the dependence from fossil fuels, and in this context the heat pumps can play a major role in the future energy scheme of the city.

Among this future energy scheme, the network of district heating has a pivotal role. Graz counts on with an extensive grid (Figure 3.1) that connects most of the inner city, and it is regarded as an strategy to eliminate the burners in the urban center, improving the air quality. The city center is characterized also by the abundance of old buildings from the "Gründerzeit" period (Gründerzeithäuser), constructions generally poor insulated and that present limitations for refurbishing, which adds a challenge to reduce their HER (see page 56). The district heating system is an especially good election for these kind of buildings that require high heat loads, but as can be observed it is not limited to them, and indeed an expansion of the grid is planned in the following years. For the areas not covered by the district heating network, gas is the choice by default for heating.

In addition, Graz has assessed already the potential for solar energy in the city, developing a "Roof Solar Cadastre" basing upon the area and orientation of roof surfaces [32], making also this information available online[1]. The cadastre states the potential both for PV and TS technologies with high accuracy: it estimates for instance the lost of surface due to structures in the flat roofs, meanwhile considers that only part of a tilted roofs is properly oriented, too. It also recognizes the difficulties with installing solar modules in the center of the city, because of the aesthetic protection of the historical building's roofs.

According with the performed predictions of the cadastre, the maximum yield per square meter of TS installation in Graz is around 355 kWh, and the one of PV is around 85 kWh per year. Accounting for 14 million square meters of roofs, 28% could be used for solar thermal systems, and 30% could be appropriate for photovoltaic. Taking into account the protection of historical buildings, the total surfaces are reduced to 25% and 27% respectively [32].

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[1] http://www.geoportal.graz.at/cms/ziel/5163127/DE/

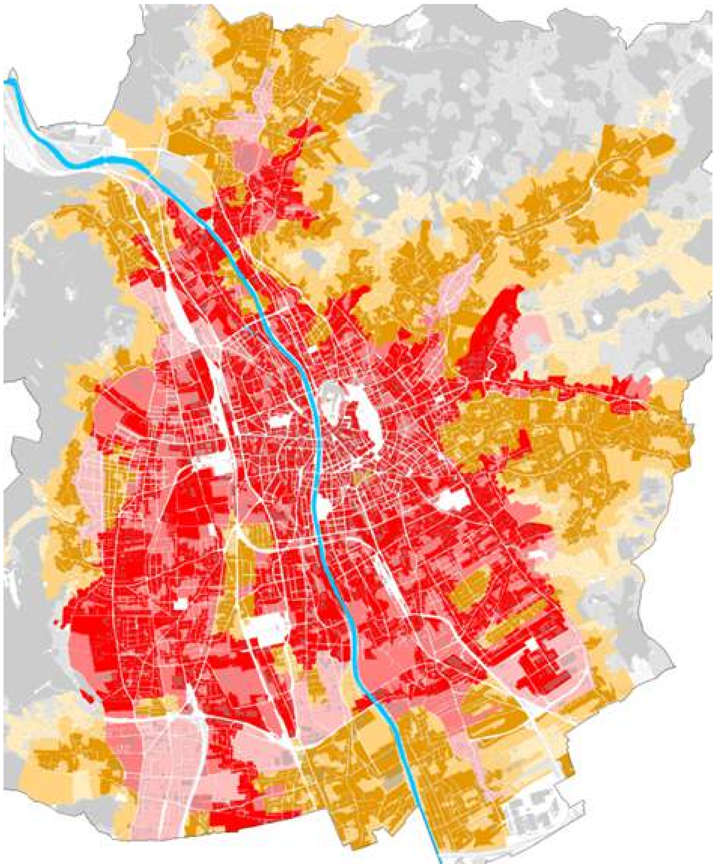


Figure 3.1: District heating and gas supply - or expanding areas [54]. Red areas mark the current extension of the district heating network, with lighter red for the extensions planned for short-mid term (up to 2015), and mid-long term (from 2020). Dark orange areas are currently supplied by natural gas, meanwhile lighter orange marks future planned expansions of the network.

3.2 Climate regime

Graz has a typical central European climate regime with severe winters, warm summers, strong seasonality and no dry season. The average temperature over the year is between 9 and 10º C, and there is a yearly solar irradiation of 1127 kWh/m^2 [44]. The amount of Heating Degree Days has been quoted to be 3499 [31], but Table 3.1 offers different data taken from RETScreen International [49].

There are also some sources that disagree with the data of RETScreen International [49], from NASA international database. For this reason, Table 3.1 substitutes the data of temperature gathered from the NASA database by the one gathered by the Austrian Service of Meteorology [59], showing an average record of temperatures from 1970 to 2000 somehow different. In the last decades it has been observed a rise in the temperature according with the registers of temperature made in the city [34].

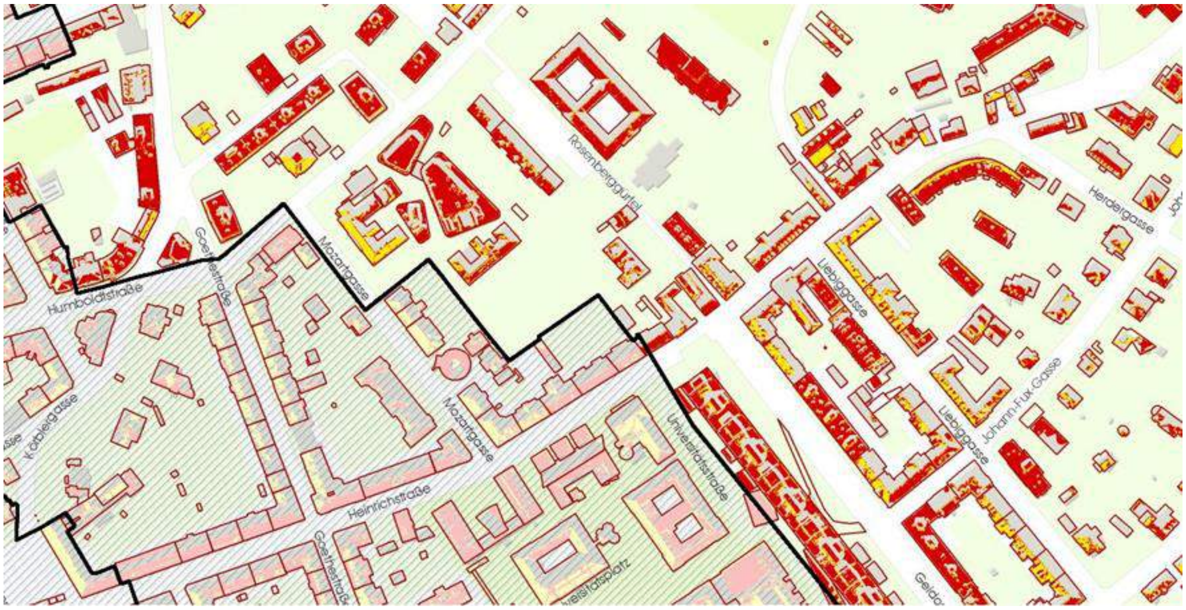


Figure 3.2: Screenshot from the Roof Solar Cadastre for thermosolar potential. Note the buildings enclosed by the black line are colored in pale tone, to signal the limitation of solar installations for aesthetic reasons, as are historical buildings.

3.3 Geology and hydrogeology

It has been mentioned already the influence of the different underground's conditions over the performance of heat pumps; knowing the particularities of Graz is, thus, important to have an idea of the potential of GSHP in the city.

Graz is placed on the edge of a greater geological unit called "Neogene Styrian Basin"[15]. At smaller scale, Graz occupies a valley crossed by the Mur river, and filled with Neogene sedimentary materials (Figure 3.3a). Flanking these materials, there are other sedimentary rocks of different nature; a mixture of clays, sands and gravel dominate the east and northeast of the city, meanwhile carbonate rocks emerge at the west, and in the center of Graz at the iconic Schlossberg [7].

Groundwater presence

With this rough description it is already possible to predict different potential performance of BHE in the area of Graz, due to the irregular presence of groundwater. The sedimentary Neogene materials are very permeable [26] and are marked as areas of high groundwater productivity by the Austrian Geological Survey [6], constituting an aquifer that extends over part of the city. In contrast, the materials flanking this aquifer are categorized as areas with limited groundwater resources (aquicludes). Naturally, the placement of a BHE in one are or other will determine partially its performance.

Moreover, the aquifer of Graz has not an uniform thickness. As there are impermeable materials adjacent to the permeable ones on surface, they can also be found at certain depth

Table 3.1: Climate data in Graz [49, 59]

Month	Air temperature (°C)	Daily solar radiation - horizontal (kWh/m^2d)	Heating degree-days 18°C	Cooling degree-days 10°C
January	-1.0	1,13	688	0
February	1.0	1,93	568	0
March	5.1	2,99	483	0
April	9.6	4,01	307	0
May	14.6	5,12	143	105
June	17.7	5,39	40	200
July	19.5	5,34	0	280
August	18.9	4,60	0	270
September	14.7	3,46	136	104
October	9.4	2,26	310	0
November	3.7	1,23	496	0
December	0.1	0,90	653	0
Annual	9.4	3,20	3.823	959

forming an aquiclude under the aquifer (Figure 3.3b). Combining this information with the average depth of the watertable level, it is easy to map the thickness of the saturated material layer on Graz (Figure 3.3c).

It can be observed how the saturated material's thickness varies greatly over the basin. Precisely in the area where the old city is placed, this thickness is of five meters maximum. At the northwest of Schlossberg, the aquifer practically disappears, as emerge the materials with low permeability. In the historical center, the saturated layer keeps a maximum thickness of 10 meters. On the other hand, the aquifer reaches its maximum of 30 meters at the west of the Mur, in the area of Reininghaus.

It cannot be ignored the additional effect of the advection: the aquifer has a high porosity [26] and the groundwater flow is fairly fast, from 4 to 10 m/day [28], so higher yields can be expected in BHEs placed over the saturated layer (see section 5.3 on page 51). From the previous it can be stressed the place dependance of a borehole performance in Graz; meanwhile in some parts of the city the presence of groundwater is irrelevant, in others it can occupy a significant part of the boreholes' length, reducing installation and operation costs and making GSHP a much more suitable technology. For instance, the GSHP can have an important role in the area of Reininghaus, where is planned the construction of new buildings and the thickness of the aquifer is higher.

The Styrian Government offers in [24, 23, 25] a database with a large number of boreholes drilled in the city, showing their position and yield. A comprehensive comparison could be done to confirm the different performances in function of the hydrological conditions.

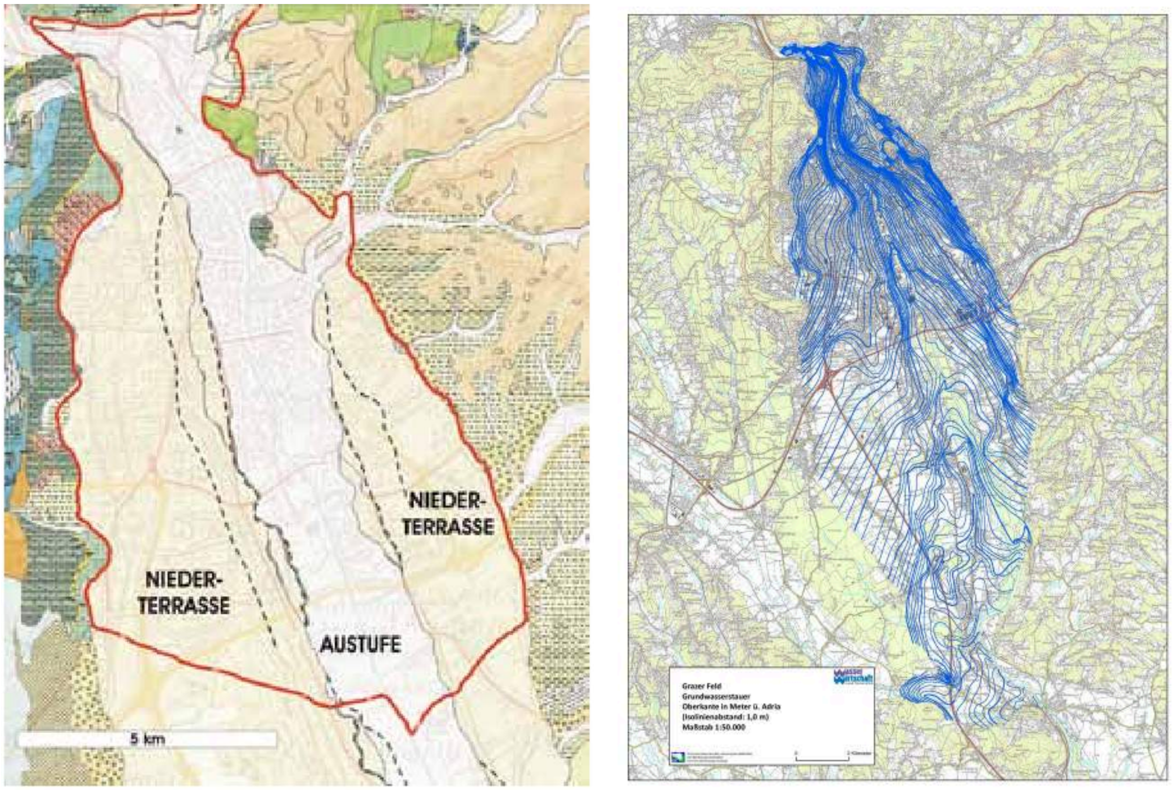
Temperature on the underground

As it has been mentioned in the previous chapter, the temperature on the underground is an important factor that determines the overall COP of the GSHP, and remains constant over the year at certain depth, at a temperature of 9°C or 10 °C according with the average air temperature from table 3.1. However, Giuliani et al. [26] detected important thermal anomalies in the center of Graz, with underground water up to 20º C (Figure 3.3d, see too [24]). This phenomenon of "Subsurface Urban Heat Island" is not exclusive of Graz, and has been reported numerous times (see for instance [38, 61, 37]). It is produced by several anthropogenic processes, among them the flow of energy to the ground from district heating systems, cellars, underground parking or sewers. At least in the case of Graz, another cause is the use of underground water for cooling purposes, without balancing the cooling and heating loads [26]. This would explain why the highest temperatures are registered after summer, in November.

The overheat of the city center is a problem for the cooling technologies; up to the point that Giuliani et al. [26] propose to limit by law the use of groundwater for cooling purposes in the center of the city. On the other hand, it is evident that the enhanced temperature of the city center is an opportunity for the installation of GSHP. As suggested by the principle of forward heating gradient, extracting heat from 20º C instead that 10º C can lead to great saving in running costs. So far there is no study in the specific case of Graz, but Zhu et al. [61] estimate the energy stored in the underground of several cities and argue that this reservoirs can be used to support the HER of a city for years.

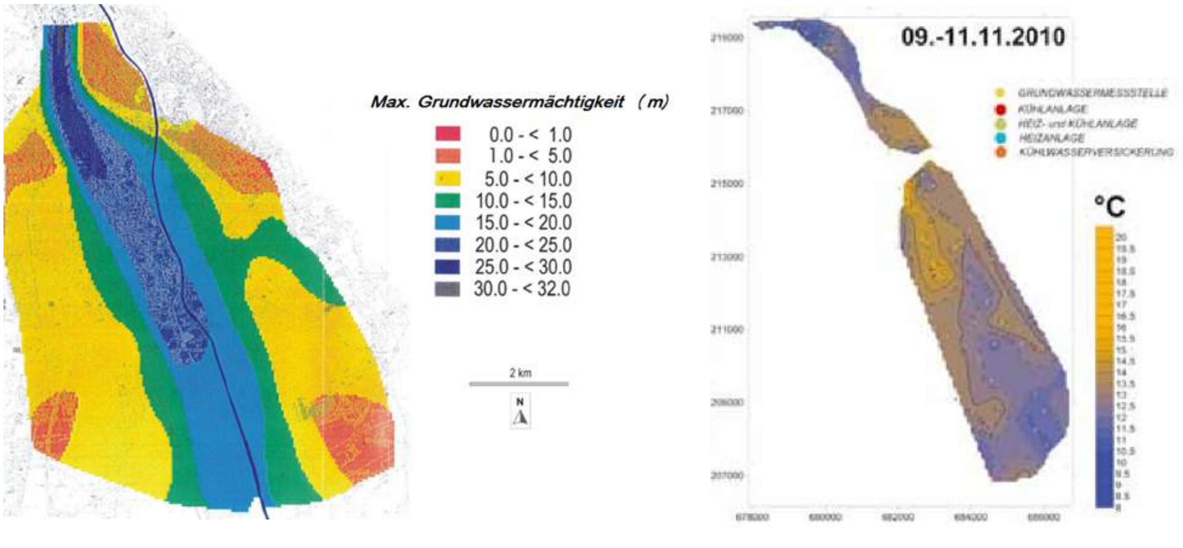
Last, it is interesting to mention that Graz has a slight anomaly on the heat flow from the lithosphere, heritage of the volcanic past of the Styrian basin. The heat flow in the area is of 80 mW/m^2; still very small, but significantly high in comparison with the standard value of 60 mW/m^2 [15].

Figure 3.3: Hydrological and Geological maps of Graz



(a) Geological map of Graz. The named materials correspond to recent sedimentary materials. [26].

(b) Aquiclude in the underground of Graz. height above sea level [55].



(c) Thickness of the aquifer under Graz [30]

(d) Temperature at a depth of 1,5 meters in the aquifer at the east of the Mur. The warmest areas reach 20°C [26]

Chapter 4

Spreadsheets: methods and calculations

The spreadsheet enclosed with this report is an essential piece for the decision making. It consists on two sheets:

1. The first one is aimed to provide with information about the self-sufficiency achievable with GSHP for a given Floor Area Ratio (FAR), HER and parameters of boreholes.

2. The second one provides detailed calculations introducing the electricity production and consumption, the DHW consumption, and TS and PV technologies. It serves to assess if a building can reach an standard of zero-energy, or up to which point it can be energetically independent.

4.1 Sheet 1: Ground Source Heat Pump (GSHP) self-sufficiency

The aim of this sheet is determine whether the heating demand of a building can be supplied using GSHP in its plot area, and depending on certain properties of the BHE installed. Two features are fundamental about the building: its FAR and its HER.

4.1.1 Sources of information

Floor Area Ratio (FAR)

The Floor Area Ratio is defined as the ratio between surface of floor space in a building A and the surface of the plot in which is placed the building A_p .

$$FAR = \frac{A}{A_p}$$

For instance, a building of one floor that occupies the totality of the plot has a FAR equals to one. The FAR is higher than one in compact urban tissue, where are predominant the buildings of several stories, and it is typically lower than one in areas of individual houses with a parcel of land, as shown if Figure 4.1.

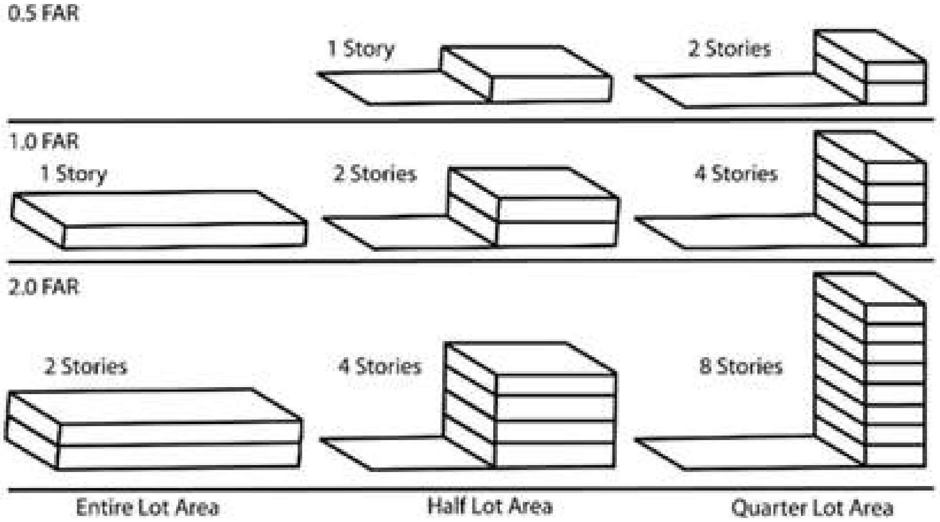


Figure 4.1: Floor Area Ratio

The FAR is important because it defines the amount of ground surface available for heat extraction for each square meter of heated surface[1]. A higher FAR means that the heat has to be obtained from a comparatively smaller surface, and to reach the self-sufficiency the building should have lower heat demand. For this study, will be considered values of FAR between 0,1 and 6, to reflect both the situation of single houses in a significant plot of land, and the situation of buildings in the city center, up to six stories high and without garden. Specifically, the values of FAR considered are 0,1, 0,2, 0,35, 0,5, 0,75, 1, 1,5, 2, 2,5, 3, 4, 5 and 6.

Heating Energy Requirements(HER)

The HER depends on several factors, as described on section 2.2. Naturally, for the specific case of Graz the HER is considered to be only dependent to the construction quality of the building, as the climate is the same and the behavior of the residents is considered also the same for the sake of the comparison. For the graphic displaying, the maximum value of HER is 250 kWh/m^{2}yr; equivalent to old buildings constructed without insulation measures. The lowest value is set at 10 kWh/m^{2}yr; that is, lower than the standard for passive housing. The Environmental Department of Stadt Graz counts with an online tool to estimate the HER and the cost for heating in Graz[2]. In any case, the value of HER introduced on the spreadsheet should take into account the internal and solar gains, as well as the ventilation loses.

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[1] To generate more accurate results, it would be more proper to consider in the FAR not the floor surface in a building, but the heated surface of that building. This last data is however more difficult to obtain, so the process is simplified considering that all the floor area of the building is heated.

[2] Familie Grazer: http://www.umwelt.graz.at/cms/beitrag/10087544/4849665/

Borehole Heat Exchanger (BHE) features

The spreadsheet displays a graph that presents the self-sufficiency both as function of FAR and HER; however the technical features of the boreholes have also major influence here. Each graph displayed is unique for the same following parameters of the BHE:

- Borehole performance: measured as W/m. The amount of power that is extracted from a single meter of BHE, on average. It varies largely depending on the temperature of the underground, the flow of underground water and the lithology (see Table 2.2 on page 16). Moreover, the performance of a BHE is dependent also on other parameters that are included in the calculations of the spreadsheet:

- Working hours: the time the BHE is working. The working hours affects the overall borehole performance, because the temperature around the BHE drops over time following the equation 5.5 on page 49. The number of hours per year a heat pump has to work is climate-dependent. A number between 800 and 1200 is a reasonable assumption.

- Length of the BHE. The depth of a BHE uses to range between 100 and 200 meters. The maximum depth is limited by geological impediments, or by depth-dependent drilling costs. The depth of a BHE also influences slightly its overall performance, as the underground increases its temperature in depth around 3 Kelvin degrees for 100 meters.

- Borehole spacing. Smaller the distance between boreholes, higher will be number of BHE that will fit in a plot area, higher will be the power than can be extracted from the underground, and faster will be the decrease of temperature on the underground, affecting in turn the overall performance of the GSHP. Determining the ideal spacing is not an straightforward task. Gultekin et al. [27] found out that the decrease in performance on boreholes does not depend too much on the physical properties of the underground (thermal conductivity), but on the disposition of the boreholes and the distances between them, as shown in Figure 4.2. Depending on the number of boreholes in the plot, a distance between them between six and ten meters is a good assumption. Mustafa Omer [43] mentions that in North America can be considered the absolute minimum spacing of 4.6 meters in northern climates, and 6.1 meters in southern climates.

4.1.2 Calculations

The graph is elaborated by plotting the results of a matrix of both heat demand and FAR values. For each value obtained, it is performed the following operation:

$$Self-sufficiency = \frac{\left(\frac{\frac{A}{FAR}}{BH_{area}}\right)(BH_{perf}HP_{worktime}BH_{lenght})}{A{\cdot}HER} \tag{4.1}$$

Where the number of boreholes n_{BH} in the area is calculated dividing the total area of the plot $\frac{A}{FAR}$ by the area covered by each borehole BH_{area} ; the output energy of a single borehole

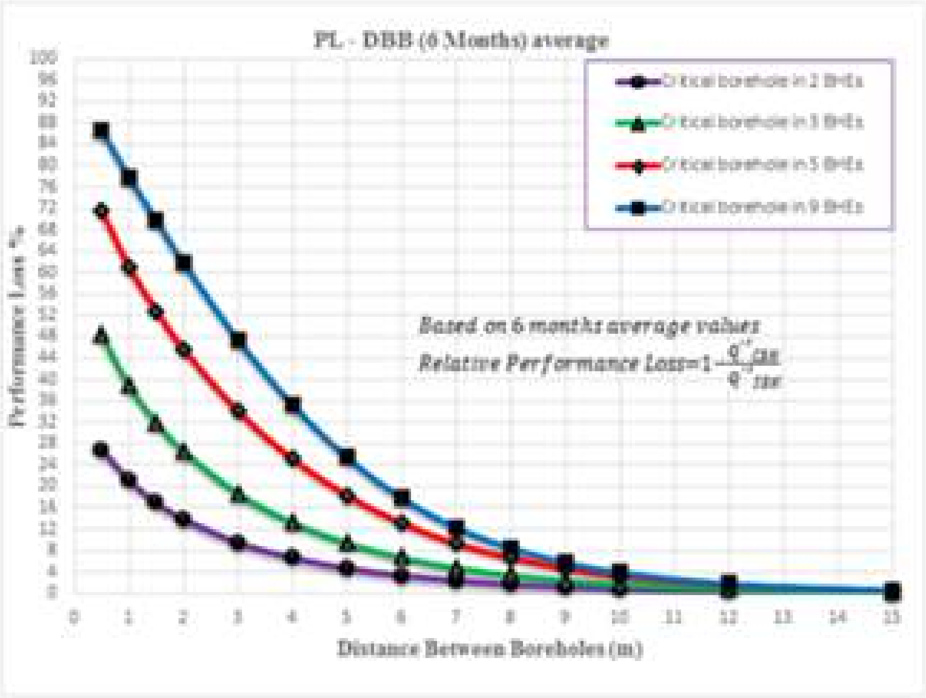

Figure 4.2: Performance loss over six months, in function of the number of boreholes considered and the distances between them [27].

is calculated by the product of the average power in kW([3]) per meter BH_{perf} , the working time of the heat pump $HP_{worktime}$ and the length of the borehole BH_{lenght} ; and the demand is calculated multiplying the constructed area A by the heating energy requirements HER .

Simplifying this operation, it can be observed that the constructed area A can be suppressed, which means the self sufficiency is independent on the constructed area considered; and depends only on the FAR, the HER and the technical features of the boreholes. Equation 4.1 can then be better expressed as

$$Self - sufficiency = \frac{BH_{perf} HP_{worktime} BH_{lenght}}{HER{\cdot}FAR{\cdot}BH_{area}} \tag{4.2}$$

Note that the numerator corresponds to the supply of energy, and the denominator to the demand. When the self-sufficiency equals one or is higher to one, the building can supply itself with the heat from the underground, given for granted that this is regenerated in some way. When the self-sufficiency is lower than one, it expresses the percentage of heat that can be obtained in this way.

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[3] Note for practical reasons the input value in the spreadsheet is in W/m, so the spreadsheet appropriately multiplies it by $1{\cdot}10^{-3}$

4.1.3 Results and discussion

As a function $\frac{1}{x}$, the graph obtained (Figure 4.3) has two asintotes: the self-sufficiency tends to the infinite when the HER is low enough, and as the HER increases the self-sufficiency approaches infinitely to zero. From here it can be observed that the highest gains in self-sufficiency can be achieved when the HER is comparatively low. The reduction on HER from 50 to 40 kWh/m^{2}yr can signify the difference between 80% and 100% in self-sufficiency; meanwhile this difference is not as acute in a reduction of HER from 150 to 140 kWh/m^{2}yr, for instance. Thus, the use of GSHP has sense especially at low HER, where also low-temperature heating systems can be used.

Equation 4.2 shows that the self-sufficiency increases linearly with the the BHE performance, length or working hours. In other words, the self-sufficiency increases proportionally with the output energy of a single borehole. In can also be observed how the self-sufficiency decreases linearly with an increase on the HER, the FAR, and the area covered by each borehole. As the area covered by borehole depends by the square of the radius between boreholes, this means that the self-sufficiency is affected by the distance between boreholes following a quadratic function; having a weight disproportionate in comparison with the other factors. This reinforces the importance of defining the distance between boreholes and the numbers of boreholes on the plot.

Equation 4.2 has the inconvenience of not considering the described influences of $HP_{worktime}$, BH_{lenght} and BH_{area} over BH_{perf}. As the performance of the borehole is not independent variable, it should be determined in relation of the depth of the boreholes, the distance between them and the working time of the heat pumps.

4.2 Sheet 2: Detailed self - sufficiency calculator

The detailed calculator is aimed to provide assessment about the potential of near-surface geothermal technology, in combination of solar technologies to estimate the degree of potential self-sufficiency achievable on yearly basis. This calculator can be used to check whether or not a building can reach a zero-energy standard with the application of sustainable technologies, or to estimate the savings that can be achieved.

4.2.1 Sources of information

Input values

This section includes the technical data of interest for the building:

- Floor area: unlike in the first sheet, the total floor area of the building has this time importance.

- Floor Area Ratio: the FAR works in combination with the floor area to calculate the Plot area, or in other words, the area available to place the BHEs.

- Heating Energy Requirements; as explained on page 31.

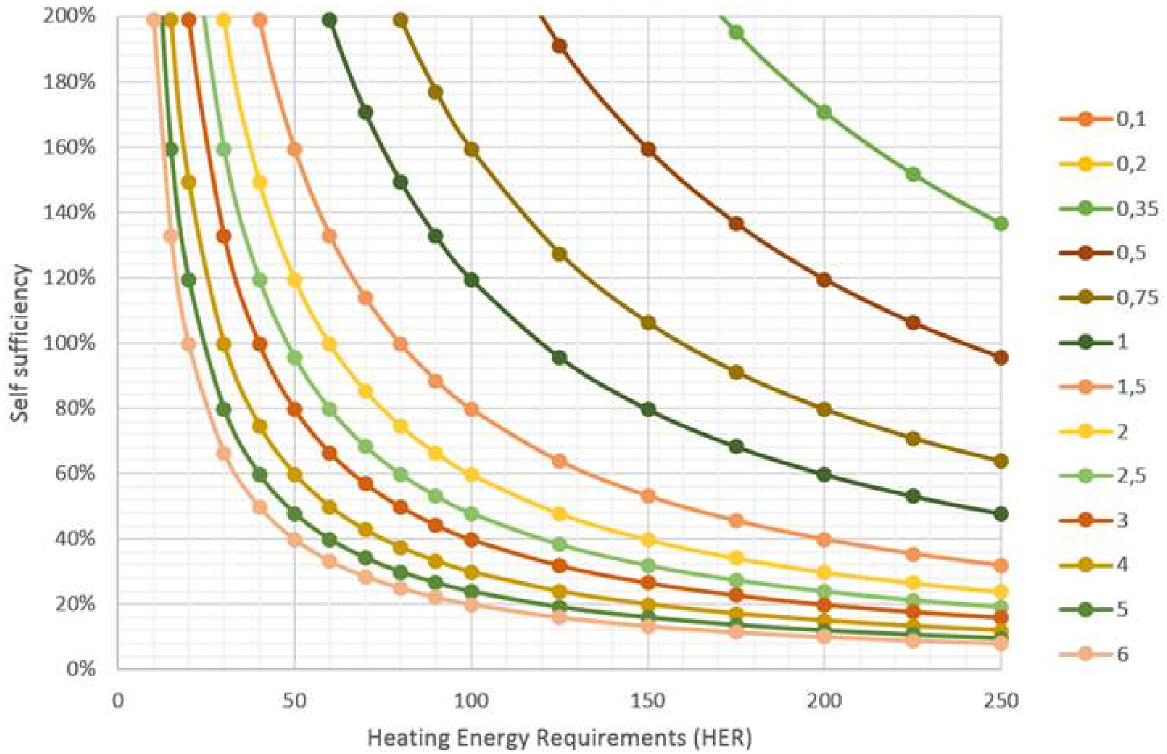

Figure 4.3: Self sufficiency in function of HER and FAR. Example from the spreadsheet calculations, considering boreholes with an average performance of 40 Wm-1, of length 150 meters, working over 1000 hours and spaced 8 meters.

- Cooling Energy Requirements: for well insulated buildings, it can be the case the heat pump has to work in reverse mode to cool the building and keep the thermal comfort during summer. This parameter accounts for the total yearly energy that should be extracted from the building to maintain the thermal comfort, in kWh/m$^{2.}$

- DHW demand: The spreadsheet includes the possibility to include the DHW demand for the calculations, expressed in kWh/m^{2}. This means it should be calculated accounting both the daily requirement of DHW per person (between 30 and 60 liters at 45°C), and the average living space per person in the building. In case it serves as reference, the value of the German standards is about 12,5 kWh/m^{2}yr, and in Switzerland around 14 kWh/m^{2}yr [17]. Note that as explained on 18, it is unclear if renewable energies are the most appropriate way to produce DHW; in the case it is considered not, this field should be set to zero.

- Electricity demand: Without account for the consumption of the heat pumps, and expressed in kWh/m^{2}. Different ways can be taken to estimate it, as it depends on the efficiency of the appliances on the building, and the number of people living in it. In Germany the average electricity consumption is about 31 kWh/m^{2}yr, but in passive energy buildings with special measures, this figure can be reduced to 11.6 kWh/m^{2}yr [17].

Borehole Heat Exchanger (BHE) features

As in the first spreadsheet, there are introduced some parameters of the BHE. The BHE performance, length and working time are as described on page 32. In addition are considered:

- Seasonal Performance Factor (SPF): Knowing the SPF allows to account for the long term heat pump electricity consumption.
- Energy Efficiency ratio: In a similar way than the SPF, it is used to calculate the electricity spent on cooling mode of the heat pump. Note that as mentioned on page 14, the Cooling Seasonal Performance Factor should be worse than the SPF one.
- BHE spacing, area covered by borehole and number of boreholes on plot area: As in the case of the first spreadsheet, the area covered by borehole is calculated as a circle of radius as half the distance between boreholes. Then, is it calculated the number of boreholes that can fit into the plot area dividing it by the area covered by borehole. Note here that this number is rounded down; this means that a number of 3.98 boreholes (as was calculated in the first sheet) is then rounded to three, as otherwise there would be a withdraw of energy from nearby plots (see page 18). The distance between boreholes should be adjusted in the way this rounding is more favorable, or otherwise the formula used can be changed easily in the spreadsheet.

Solar technology efficiency

Here are introduced the efficiency of both TS and PV technologies.

- Thermosolar efficiency refers to the proportion of incoming energy that can be converted into available heat for hot water production or thermal regeneration of the borehole. The efficiency of the system usually is about 50% [51] in a regular installation and this is the default value used, but using the heat for regenerate the underground can lead to higher inefficiencies, as suggested by experiences with BTES [19].
- Photovoltaic efficiency: refers to the efficiency of the photovoltaic modules, accounting for the proportion of incoming solar radiation that can convert into electricity including the operational loses by temperature and the orientation of the modules. PV technology has underwent significant improvements both in price, and in efficiency and continue to evolve; the commercial efficiencies are in a range between 9% and 20% [48](Figure 4.4). For this calculator, it is assumed a default value of 15% efficiency, but due to the broad differences between photovoltaic technologies (the c-Si technology is more expensive and efficient than the thin-film one, for instance), this value should be reviewed in a particular case in order to obtain reliable results.

Distribution of PV and TS production, and HDD and CDD over year

It is well known that the performance of a PV modules decreases when are subject to high temperatures: Meral and Dinçer [39] estimate that the lost on efficiency accounts for 0.05%

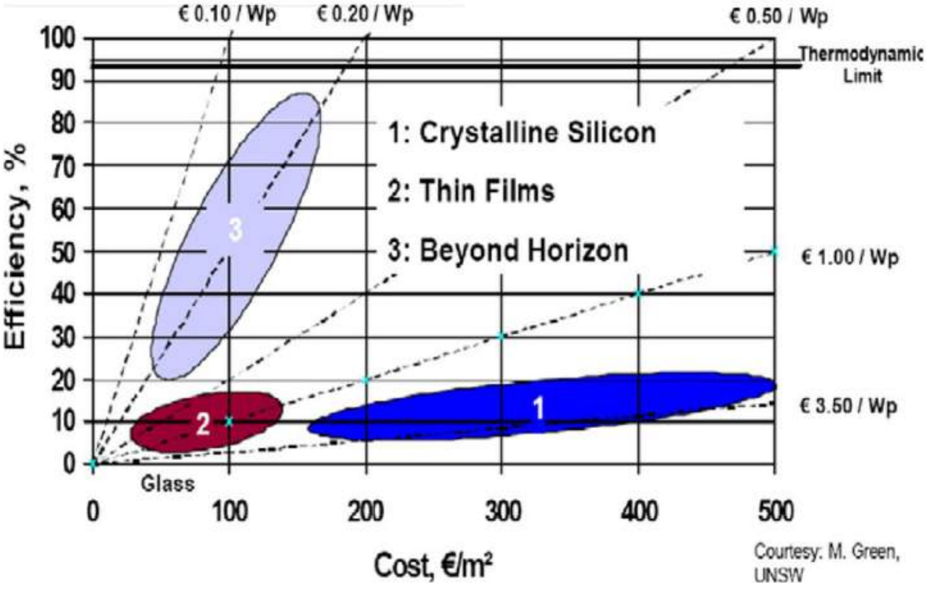

Figure 4.4: Cost-efficiency for PV modules based on c-Si technology (1), thin-film technology (2) and the potential "third generation" technologies (3) [48]

for each degree over 20°C, which is the standard temperature at the manufacturer's measure of efficiency (Figure 4.5). As the calculation of the global performance over the year requires of rather complex calculations, instead a web-based calculator is used. According to this [8][4], in Graz is dissipated because of the temperature around 8% of the energy in case of free standing modules, and around 12.5% in case of building integrated ones, when are oriented optimally 37 degrees on the vertical.

Given this, Table 4.1 offers a summary of how the production of energy with TS and PV distributes along the year. In the case of TS, the distribution is proportional with the data of daily solar irradiation, gathered from RETScreen International [49] and summarized on Table 3.1 on page 27. The distribution of PV production along the year is calculated in a different way, making use of the previously mentioned web-based calculator [8].

As expected, both technologies exhibit a different behavior along the year. The production of TS is concentrated in summer, when the incoming energy is higher. In case of PV, the production is also higher in summer, but it is somehow "shaved". The performance in summer does not match with the incoming energy because higher temperatures lead to a decrease on the performance. As consequence, the proportion of electricity produced during winter is also higher in comparison with the proportion of TS energy produced in the same season.

Besides the application of PV modules and TS ones, it is worth to consider the existence of the PV/T technology, consisting in collect heat from a PV surface, increasing in this way the efficiency of the PV cells at the time than producing heat. Water-based PV/T is a very popular technology and has gained growing application in practical projects. This type of system can

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[4] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php

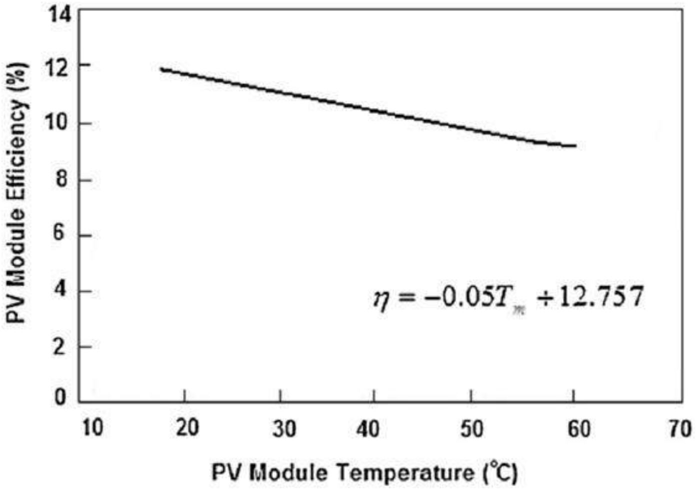


Figure 4.5: Relationship of the PV module efficiency η and PV module temperature T_m . In this case, the efficiency of the module at standard temperature of 20ºC is 12% [39]

achieve maximum electrical efficiency of around 9.5 % and thermal efficiency of about 50% [46].

To know how the heating and cooling energy requirements distribute along the year, it is used data from [50] showed in table 3.1 on page 27. Using this data it is elaborated the table 4.2, that shows the percentage distribution of HDD and CDD over the year. Note that despite being official NASA data, it was commented that the data of temperature from Stadt Graz differ from them; it is also significant that according with the data used, May and September have both significant cooling requirements.

Assumptions about environment

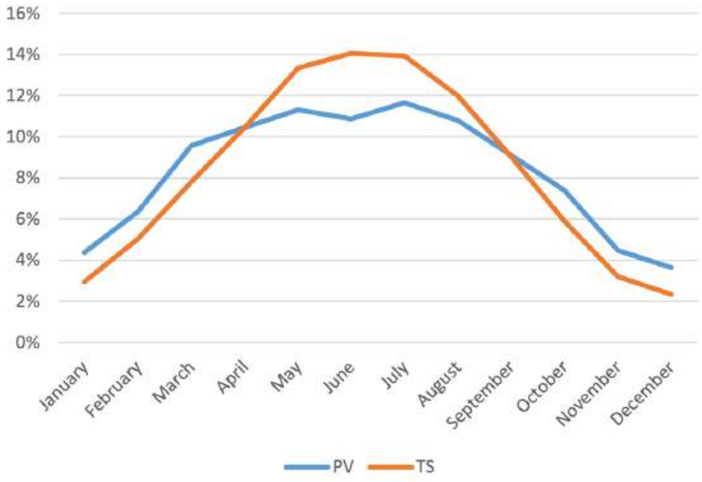
Some data from the environmental conditions are necessary to estimate the influx of energy to the system:

- Solar irradiation: It is defined as the power in form of solar energy that reach the surface of the earth. The total irradiation per year serves to know the performance of solar technology; meanwhile the irradiation per month allows to know the monthly performance. In Graz, the Global Horizontal Radiation is about 1127 kWh/m^{2}yr [44], which results in a mean solar irradiation of 129 W/m^2. How this incoming power is distributed over the months matches with how the output of TS heat distributes over the year, according with table 4.1.

- Natural ground heat regeneration: Expressed as W/m^2. It has been mentioned that the imbalances of heat extraction can lead to changes in underground temperatures, but this does not always has to be the case, especially when the FAR is low, because the ground also regenerates by itself the temperature. The mechanisms by which this natural regeneration is produced are diverse. First, there exist a natural heat flow from the inner layers of the earth, which as mentioned is very small: 60 mW/m^2 is an standard value, that in the case

Table 4.1: Proportion of production of Thermosolar (TS) and Photovoltaic (PV) technologies over the year [50, 8]

	TS (%)	PV (%)
January	2.9	4.4
February	5	6.4
March	7.8	9.6
April	10.5	10.5
May	13.3	11.3
June	14.1	10.9
July	13.9	11.6
August	12	10.8
September	9	9.1
October	5.9	7.4
November	3.2	4.5
December	2.3	3.6



of Graz is somewhat higher, of about 80 mW/m^2 . When the ground is not covered by some construction, it absorbs 46% of the incoming sun energy [50], which constitutes a flow of energy orders of magnitude larger than the heat flow from lithosphere. Indeed, it has been commented how horizontal and superficial GHEs take advantage of this sun energy absorbed by the ground during summer. Moreover, the effect of the groundwater advection can replenish also effectively the heat during the summer period, when the GSHP is not working. In short, the rate of natural ground regeneration can be very variable depending of the plot; from a minimum where there is no advection and the land is used for building and thus receives no sunlight; to the case of a broad open area where there is advection. For this calculator, a default value of 2 W/m^2 has been taken, but this should be properly assessed for each specific case.

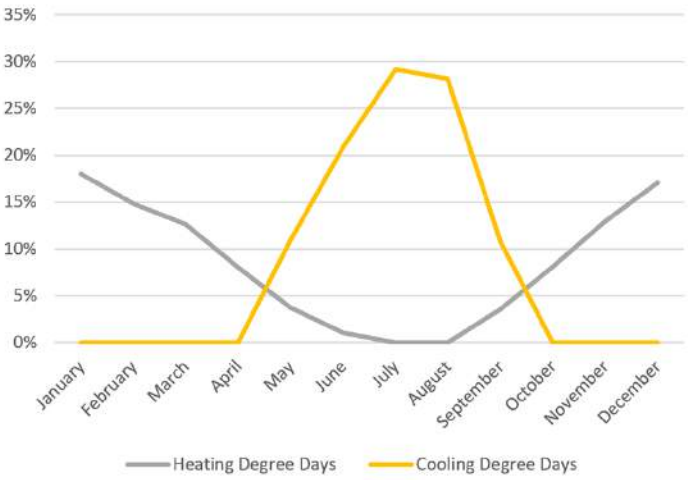
Constants

In order to avoid fixed values in the operations of the spreadsheet, are introduced two constants that there is no reason to change:

- Number of months per year: It is used when splitting some values evenly among months.
- Factor to convert from W to kWh/yr: This number, 8.76, serves to covert directly a constant power in W to energy produced in a year, in kWh. Effectively, $1W\frac{1kWh}{1000W}\frac{8760h}{1yr} = 8.76$

Table 4.2: Proportion of Heating Degree Days (HDD) and Cooling Degree Days (CDD) over the year [50]

	HDD (%)	CDD (%)
January	18	0
February	14.9	0
March	12.6	0
April	8	0
May	3.7	10.9
June	1	20.9
July	0	29.2
August	0	28.2
September	3.6	10.8
October	8.1	0
November	13	0
December	17.1	0



4.2.2 Regular calculations

Total heat production by Heat Pump

The total yearly heat production by heat pump $HP_{P,yr}$ is calculated in a similar way as in first spreadsheet. The number of boreholes in the plot is $n_{BH} = \frac{\frac{A}{FAR}}{BH_{area}}$ and then rounded down, as explained on page 36. Then, $HP_{P,yr} = n_{BH} BH_{perf} HP_{worktime} BH_{lenght}$.

Total heat for Domestic Hot Water (DHW)

The total yearly requirements of DHW DHW_{yr} is calculated multiplying A by the DHW demand per square meter and year.

Total heat for room heating

In a similar way, the total yearly requirements of room heating RE_{yr} are calculated multiplying A by the requirements per square meter and year.

Total heat demand

Thus, the total head demand HER_{yr} of the building over the year account for the sum of DHW requirements and room heating requirements. $HER_{yr} = DHW_{yr} + RE_{yr}$

Total cooling energy requirements

When cooling is required to keep an adequate room temperature, the GSHP enters in cooling mode. The total yearly cooling requirements CER_{yr} are calculated multiplying A by the cooling requirements per square meter and year. As the GSHP is working in rejecting mode, it is assumed that this same amount of energy is injected into the underground, recharging it thermally.

Degree of potential heat self-sufficiency with heat pumps

The heat self-sufficiency HER_{SS} that can be achieved with heat pumps equals to the total heat demand by the total heat production of a heat pump. $HER_{SS} = \frac{HER_{yr}}{HP_{yr}}$.

Proportion of heat regenerated yearly

The amount of heat yearly regenerated HER_R equals to the product of the Natural Ground Heat Regeneration and A_p, plus the amount of heat CER_{yr} rejected into the underground due to cooling requirements. The HER_R is divided by the Total heat demand HER_{yr}, to obtain the proportion of heat that is regenerated on a yearly basis.

TS panels to supply heat and regenerate ground

In order to avoid changes in the underground temperature, it may be necessary to supply extra heat in summer, in a way similar to the BTES depicted on page 17. The amount of heat to supply by thermosolar energy on a yearly basis TS_{yr}equals to the Total heat demand minus the energy regenerated both naturally and by heat rejection: $TS_{yr} = HER_{yr} - HER_R - CER_{yr}$. Then, the surface needed to generate this amount of heat is calculated dividing TS_{yr} by the yearly production of a single square meter of module (which equals to the product of the average solar irradiation and the efficiency of the TS module). Last, the amount of square meters obtained is rounded up to one.

Consumption of electricity to run GSHP

The total electricity consumed by the GSHP will equal to the sum of $\frac{HP_{P,yr}}{SPF}$, which represent the electricity consumed for heating purposes, and $\frac{CER_{yr}}{EER}$, which represents the electricity consumed for cooling.

Domestic consumption of electricity

This value represents the energy consumed by the buildings in concept other than GSHP. It is the product of A and the electricity demand per square meter.

Total consumption of electricity

The total amount of energy consumed by the building on yearly basis $Elec_{yr}$ equals to the sum of the electricity consumed by the GSHP and the domestic consumption of electricity.

PV panels to supply 100% of electricity

In this calculator it is supposed that the objective is achieving a zero-energy house; so it is calculated the amount of PV modules in square meters needed to supply the electricity demand. For this, it is divided $Elec_{yr}$ by the amount of electricity generated by a single square meter of PV module, calculated as the product of the yearly irradiation and the efficiency of the PV module. Then, the amount of square meters obtained is rounded up to one.

Roof/plot surface covered by solar technology

Expresses the proportion of plot surface covered by PV and TS modules. When the FAR is higher than one, this area is instead the roof surface. Naturally, if are excluded alternatives as solar modules mounted on facades, when the proportion of roof area covered surpasses the 100% there is no space to install all the modules, but this limitation can be evident at smaller proportions. There is always a part of the roof which cannot be used efficiently for the production of solar energy, as described by the solar cadastre commented on page 24. This cadastre can indicate if there are physical limitations to the installation of the calculated module surface on the roof.

4.2.3 Monthly calculations

In order to provide with an even more accurate depiction of energy balances in a building, the calculations of the previous section are combined with the monthly production of energy by TS and PV modules on table 4.1 and the monthly proportion of HDD and CDD according with table 4.2[5]. With this data it is possible to calculate and represent graphically the following data in monthly basis:

Heat requirements

The heating requirements encompass both the consumption of heat for room heating and the consumption of heat for DHW. The monthly calculation is done by multiplying the HER_{yr} by its monthly fraction of HDD, and adding to this $DHW_{yr}/12$, as the consumption of DHW is considered constant along the year.

Cooling requirements

The calculation is done by multiplying CER_{yr} by its monthly fraction of CDD.

Electricity demand

The electricity demand comes from three sources, that add to each other:

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[5] It is assumed that the distribution of HER matches with the distribution of HDD. In theory this should be true, but in practice the highly insulated buildings are also more able to regulate in a passive way their demand of heating and cooling; in practice this means that for highly insulated houses the HER tends to concentrate more in winter, meanwhile the CER concentrates in summer.

First, there is the electricity demand for other sources than GSHP; thus, for each month there is $Elec_{yr}$/12.

Second, there is the electricity spent by the heat pump. To obtain this figure, it is divided the heat produced monthly by GSHP (see below) by the SPF of the GSHP.

Third, there is electricity spent by the GSHP in cooling mode. This corresponds for each month with CER_{yr} multiplied by its monthly fraction, and then divided by the EER.

Heat produced by TS

The calculation is done by multiplying TS_{yr} by its monthly fraction.

Heat produced by GSHP

It is known the yearly production of heat by GSHP, but this energy produced is not distributed evenly according with the heating requirements; but instead with the heating requirements that are not covered by the production of TS heat.

To know accurately when is produced the heat by means of GSHP, it is necessary an auxiliary monthly table, in which is subtracted to the value of heat requirements the heat produced by TS. When the value is higher than zero, the proportion of heat generated over the total is expressed in percentage. The monthly production of heat by GSHP will be the product of this percentage with $HP_{P,yr}$.

Electricity produced by PV

The calculation is done by multiplying $Elec_{yr}$ by the monthly fraction of production of PV electricity.

Monthly heat balance

The monthly heat balance indicates if heat is subtracted from the underground or if it is rejected, using it as storage. This balance accounts for heat consumption as loses, and as heat generated by TS, heat regenerated naturally, and cooling requirements, as gains.

Monthly electricity balance

In a similar way, the monthly electricity balance accounts for the electricity demand as loses, and the electricity produced by PV as gains

4.2.4 Results and discussion

With the previous calculations it is possible to estimate the yearly behavior of a house theoretically supplied only with renewable energies. An example of the graphic results that can be achieved is showed on figure 4.6.

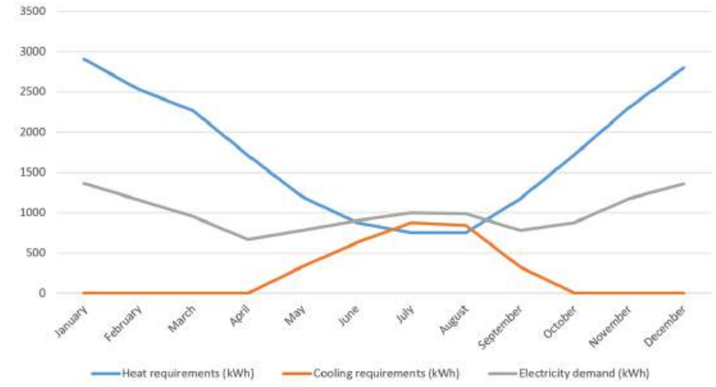
Changing the different parameters on the spreadsheet is easy to see how decreases the need of artificial thermal recharge of the underground when the cooling and the heating requirements of the building are similar. This means that less TS panels are needed, especially if the DHW demand is covered with gas burners (and then is accounted as zero in the calculator).

In contrast, the amount of PV required to supply the electricity and run the GSHP is relatively high, even with good HER and electricity demand. Achieving electricity self-sufficiency with the current PV efficiencies might be challenging , just because of the physical space available on roof. Also, it is important to notice that some kind of storage of electricity would be also needed, as the electricity balance is negative during winter months. The most efficient option might be to sell the excess of electricity during summer and later take this same amount during winter, but doing this requires also a favorable legal framework.

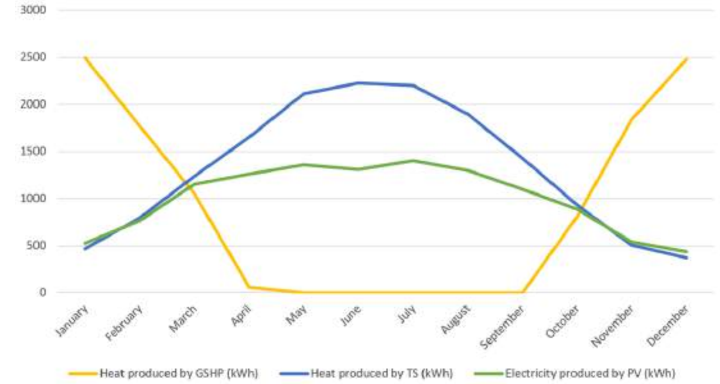
Also, the efficiency on regenerating the underground heat should be checked case by case. In the calculator it is considered that 50% of the energy received by the TS modules during summer is usable during winter, but there might be a number of variables that reduce this efficiency, as can be groundwater flow. In a similar way, it is considered that the efficiency on storing and delivering DHW is also 50%, but there can be a variable amount of loses here.

With all, the results of the calculator are consistent with the general rule that a house can self-supply energetically up with a FAR of 4 (four storeys high). In the data run in figure 4.6, the surface covered by PV and TS modules on the roof is about two thirds of the roof, which is approximately the maximum usable space in a flat roof for solar technologies purposes. Note that according with the spreadsheet, optimizing the HER to 15 kWh/m^2 yr and suppressing the DHW demand (supplying it with gas) would reduce the surface occupied with solar modules to 51%. In these circumstances, it could be possible to achieve the energy self-sufficiency even in buildings of five storeys.

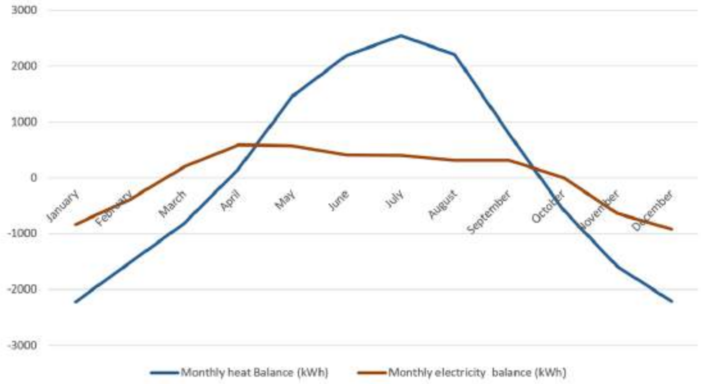
Figure 4.6: Results of detailed calculation according with following parameters: Building of 600 m^2; FAR of 4; HER of 20 kWh/m^2 yr; CER of 5 kWh/m^2 yr; DHW demand of 15 kWh/m^2 yr; Electricity demand of 13 kWh/m^2 yr; Boreholes of 100 meters spaced 7 meters, working 1000 hours at a performance of 35 W/m, with a SPF of 3.5 and an EER of 2.5; TS efficiency of 50%; PV efficiency of 15%; Average solar irradiation of 129 W/m^2, and Natural ground heat regeneration of 2 W/m^2; and monthly distributions of PV and TS production, and HDD and CDD according with tables 4.1 and 4.2 respectively.



(a) Heat, cooling and electricity demand



(b) Electricity demand and supply



(c) Heat and electricity balance over year

Chapter 5

Modeling of Borehole Heat Exchangers

So far the importance of physics and engineering principles about BHEs has been addressed rather superficially. This chapter is dedicated to the detailed description of BHEs according to these physical and engineering principles.

To model the behavior of these systems, the possible solutions come essentially in two forms:

- Numerical solutions: Use iterations of algorithms to approximate to the solution of a system. This is the called computer modeling, because the number of operations required can reach the number of thousands in order to obtain a good approximation. It is an expensive and time-consuming method, but allows for detailed simulations with many variables involved.

- Analytic solutions: Use mathematical expressions as equations, and apply physical laws, to obtain a discrete and exact value of the solution; there is certainty that the model will behave and it is a fairly faster method, but does not allow for complex simulations.

This chapter will focus exclusively on the analytic solutions, as the aim is to provide an insight of the physical principles that rule the behavior of BHEs, and to serve as a reference guide to perform quick engineering calculations when needed. The numerical solutions, computer-based, require in comparison complex software that is beyond the scope of this work.

From now and following the aims of this report, it will be assumed by default that the GSHPs works in heating mode and the BHEs are a source of heat. The equations are indifferent for absorption or rejection of heat; and when figures refer to cases of heat rejection, it will be mentioned.

5.1 Thermal properties of the underground

Two properties of the materials important to understand how accumulate and diffuse heat are density ρ (kg/m^3)and heat capacity c_p (kJ/kgK)(see table 2.2 on page 16). From here it can be obtained easily the volumetric heat capacity $v_p = \rho c_p$(kJ/m^{3}K). The volumetric heat is usually more practical because it allows to know the behavior of the underground in a more direct way than the heat capacity, that is measured by unit of mass. Knowing the volumetric heat capacity and the temperature of the underground, it is easy to approximate the heat that can

Summary of nomenclature

ρ	Density (kg/m^3)	H	BHE depth (m)
λ	Thermal conductivity (W/m·K)	t	Time (s)
c_p	Heat capacity (kJ/kgK)	r	Radius (m)
v_p	Volumetric heat capacity (kJ/m^{3}K)	v	Velocity (m/s)
a	Thermal diffusivity (m^2/s)	$_{BHE}$	Borehole heat exchanger
q	Heat flux (W)	$_{AES}$	Aestifer
T	Temperature	$_F$	Heat carrier fluid
R	Thermal resistance (m·K/W)	γ	Euler's constant (0.5772)

be extracted with a borehole of certain length and that occupies a certain area as described in chapter 4.

Another important property is the thermal conductivity λ (W/mK), defined as the capacity of a material to conduct heat. As was hinted, higher values of λ lead usually to higher performance of the BHE.

Last, the thermal diffusivity a (m^2/s) measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. Thus, $a = \frac{\lambda}{v_p}$.

5.2 Modeling of heat flow in stationary conditions

To model the flow of heat in the aestifer towards the heat carrier fluid in the BHE, the simplest models postulate two thermal resistances, one fixed resistance corresponding to the thermal resistance of the BHE structure itself R_{BHE} and, one resistance corresponding to the thermal resistance of the aestifer R_{AES} , as represented in Figure 5.1. The difference of temperature between the average one on the heat carrier fluid T_F and the input temperature T_0 is

$$T_F - T_0 = qR_{BHE} + qR_{AES} \tag{5.1}$$

The value of R_{BHE} is typically around 0.1 m K/W for double U-tubes and up to 0.2 m K/W for single U-tubes in bentonite, where no special precautions are taken to keep the tubes close to the borehole wall [22]. The value of R_{AES} can be considered static, or otherwise changing in function of time (see below).

Given this, the simplest model to calculate the heat flux per unit length of borehole q_{BHE} (W/m) is

$$q_{BHE} = \frac{T_F - T_{BHE}}{R_{BHE}} \tag{5.2}$$

Where T_F is the fluid temperature. From here, two well different approaches can be taken, depending on if R_{AES} is time-dependent or not:

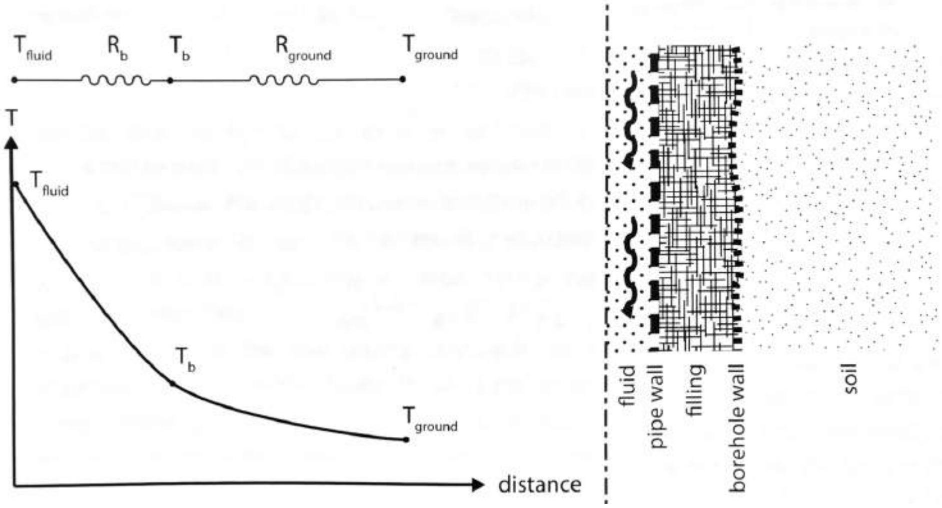


Figure 5.1: Temperature levels and resistances of BHE. R_b and T_b refers to the temperature and resistance of the BHE. Note that in this case, the BHE acts as a rejector of heat, instead than extractor [17]

1. "Finite source model": time-independent model that is supposed to be realistic when the cone of heat reaches an stationary state (after 20 or 30 years of use, as seen on Figure 5.2). The length of the borehole H and the exchange of heat with the ground surface limits the eventual size of the heat cone.

2. "Infinite source model": time-dependent (the thermal resistance of the aestifer is time variable) and based on the mathematical premise of an infinitely extended "line source" or sink of heat. In this model, the temperature never reaches a steady state, but continues to evolve with the logarithm of time (as seen on Figure 5.2).

5.2.1 Heat flow in stationary conditions: finite source model

In order to evaluate the long term influence of a BHE it is needed to use a "finite source model", independent of time. The model assumes that the heat cone produced by the BHE grows, but stabilizes at some point after years of operation. Claesson and Eskilson [11] provide a solution for the steady-state temperature $T_{s,F}$ approached by the heat transfer fluid in a borehole heat exchanger of finite depth H and radius r_{BHE}

$$T_{s,F} - T_0 = qR_{BHE} + \frac{q_{BHE}}{2\pi\lambda} ln\left(\frac{H}{r_{BHE}\sqrt{4.5}}\right) \; if \; H \gg r_{BHE} \tag{5.3}$$

This solution is based on considering the ground surface as a constant temperature boundary, at the long-term average annual soil temperature. It can be observed how the last term of the equation effectively substitutes R_{AES} on the equation 5.1.

Moreover, the time t_s at which is reached the the steady state on the BHE, and thus equation 5.3 is valid (also, the crossing point of the thick lines on Figure 5.2) can be obtained with

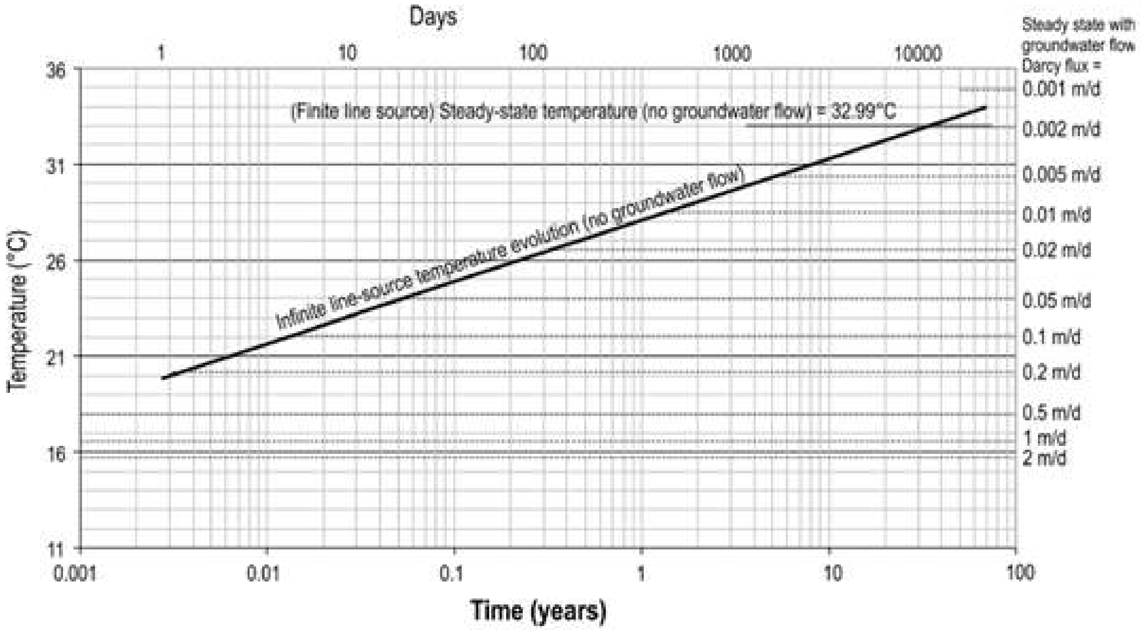


Figure 5.2: Temperature evolution of heat transfer fluid in a typical BHE, depending on model followed: Infinite line source (thick black line, showing logarithmic temperature evolution), or finite line source (thick grey line) [4]

$$t_s = \frac{e^{\gamma} H^2 V_p}{18\lambda} \tag{5.4}$$

If the BHE is shallower and the thermal conductivity of the underground is higher, then greater the interaction with the surface will be, quicker the steady state will be approached, and less extreme the temperatures in the surrounds of the BHE will be. [4].

As t_s can easily be 30 years, to describe appropriately the behavior of a BHE over shorter periods of time it is used the infinite source model, which considers R_{AES} as a function of time.

5.2.2 Heat flow in non-stationary conditions: infinite source model

The heat transfer in a BHE in function of time is defined by the equation

$$T_F - T_0 = qR_{BHE} + \frac{q_{BHE}}{4\pi\lambda}\left(ln\left(\frac{4at}{r_{BHE}^2}\right) - \gamma\right) \tag{5.5}$$

Again, it can be observed how the last term of the equation corresponds with the R_{AES} from the equation 5.1, only now its value varies with time t . This solution is an approximation of a more complex calculations involving integral equations; it has a maximum error of 10% for $\frac{at}{r_b^2} \geq 5$, and 2.5% for $\frac{at}{r_b^2} \geq 20$ [17]. The accuracy of the solution thus increases when the thermal front extends, which is faster for high thermal diffusivity a .

It should be remembered that equation 5.5 considers a BHE of infinite depth, with no heat exchange with atmosphere or underlying rocks. It assumes purely two- dimensional (horizontal) heat conduction, not taking into account three- dimensional heat flow [4]. According to this equation, the heat cone would increase indefinitely and the temperature at BHE would drop indefinitely, with the logarithm of time.

Though the two described models offer always different results, if the BHE is rather short it can be noticed a more significant difference between the finite source model and the infinite source model [41].

5.2.3 Temperature in the boundary of BHE and at any distance from the borehole.

The equations 5.3 and 5.5 can be easily adapted to calculate the temperature in the boundary of the borehole, removing the term R_{BHE} from the equation 5.1. Indeed, the temperature at the boundary of the BHE would not account for the resistance of the BHE, considering only the thermal resistance created by the aestifier. Thus, under the stationary finite source model, the stable temperature on the boundary of the borehole $T_{s,BHE}$ would be

$$T_{s,BHE} - T_0 = \frac{q_{BHE}}{2\pi\lambda} ln\left(\frac{H}{r_{BHE}\sqrt{4.5}}\right)\ if\ H \gg r_{BHE} \tag{5.6}$$

and in the case of the time-dependent infinite source model

$$T_{BHE} - T_0 = \frac{q_{BHE}}{4\pi\lambda}\left(ln\left(\frac{4at}{r_{BHE}^2}\right) - \gamma\right) \tag{5.7}$$

These equations can also be used to calculate the temperature field at other distances r from the BHE. Note however that the finite source model has to be used with caution in these cases, as its accuracy depends on the length of the BHE being much larger than the distance r to the center of the BHE.

5.2.4 Spacing of boreholes

As the heat cone produced by a BHE extends from it, it reduces the potential yield of nearby BHEs. Defining the distance at which the boreholes should be placed from each other becomes then an exercise of compromise: placing them closer allows for increased withdraw of power from the ground, but also depletes faster the energy stored in the material, and thus leads to a decrease of the underground temperature.

On page 32 it was mentioned that the typical separation between BHE is between 6 and 10 meters, and this data were properly justified with a graph of the performance's drop in function of the disposition of the borehole field. But really, a more reasoned approach can be taken, establishing for instance that the distance between BHE should be such that the decrease of temperature at a distance r from BHE is 2°C, with a working time of 1000 hours and a continuous heat extraction of 35 W/m.

Then, the equation 5.7 can be applied. Knowing the temperature drop $T_r - T_0$, the heat flow per meter q_{BHE} , the working time t and the physical properties of the ground a and λ[1], it is possible to clear the value of r , which would indicate the spacing between BHEs.

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[1] It is worth to remember that Gultekin et al. [27] showed how λ has an insignificant effect on the drop of performance of nearby BHE, so probably the physical properties of the underground are not decisive.

Table 5.1: Peclet numbers corresponding to typical values of hydraulic and thermal properties of soils and rocks, in typical borehole spaced 4.5 meters [9].

Soils	Peclet Number	Rocks	Peclet Number
Gravel	$5.72 \cdot 10^{2}$	Limestone, dolomite	$5.92 \cdot 10^{-3}$
Sand (coarse)	13.4	Karst limestone	5.28
Sand (fine)	1.15	Sandstone	$1.77 \cdot 10^{-3}$
Silt	$1.28 \cdot 10^{-2}$	Shale	$1.05 \cdot 10^{-6}$
Clay	$3.24 \cdot 10^{-5}$	Fractured igneous and metamorphic	$6.32 \cdot 10^{-2}$
		Unfractured igneous and metamorphic	$1 \cdot 10^{-7}$

5.3 Modeling of heat flow in presence of groundwater flow

Up until now it has been considered that the heat is transmitted towards the borehole by conduction; which depends on the thermal conductivity λ and it is higher in presence of groundwater. In case this groundwater is flowing, there exists a second mechanism by which the BHE can receive or reject heat, called advection.

In physics and engineering, advection is a transport mechanism of a substance or a conserved property (in this case, energy) by a fluid due to the fluid's bulk motion. Advection of groundwater flow will provide an additional heat sink (if the BHE is rejecting heat) or heat source (if the BHE is extracting heat), leading to enhanced performance (less extreme temperatures) and towards a steady state.

These predictions have been checked; Chiasson et al. [9], Fan et al. [21], Wang et al. [57], estimate roughly a 10% improvement in the performance of a BHE following numerical modeling; though Wang et al. [57] advices that the total enhancement effect depends to a great extent on the distribution and thickness percentage of the ground layer with the greatest groundwater flow. Also, for a system of underground heat recharge BTES as described in chapter 4, Fan et al. [21] concluded that too much groundwater flow is negative for the system, because it removes stored energy during summer.

A recurrent simplification of the advection is to consider that groundwater flow increases the thermal conductivity λ of the materials to an effective thermal conductivity λ_{eff} , but advection and conduction are mechanisms very different, that can be important for the BHE performance or not depending on the groundwater flow and the nature of the materials.

Technically, the relation between advection and diffusion is known as Peclet number [14]. In hydrogeology, it is considered that advection becomes important for the BHE performance when the Peclet number is higher than one. Not surprisingly, it is in the coarse sedimentary materials where the Peclet number is higher (Table 5.1). For the practical case of Graz, this means that the advection will be the predominant process of heat extraction at the aquifer level, meanwhile conduction will gain weight in the materials that do not conform the aquifer.

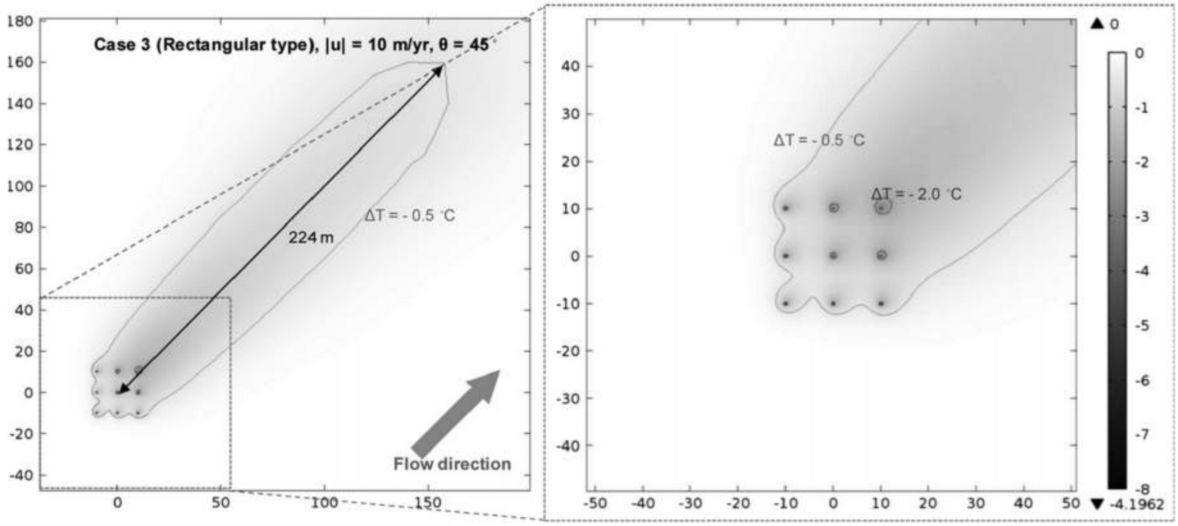

Figure 5.3: Distribution of maximum ground temperature change with fast groundwater flow (10 m/yr) in rectangular borehole arrays [10]. This figure should be taken with caution; see footnote.

The effect of the groundwater becomes important from a speed of 7 or 8 cm/day [35, 4]. In the aquifer of Graz are reached groundwater flow speeds of 10 m/day [28], which reinforces the idea that advection cannot be ignored at least in certain areas of Graz. Choi et al. [10] showed in a numerical analysis that the performance of an array of boreholes varies up to 13 % depending on its orientation with respect the main groundwater flow direction, so also the predominant flow of groundwater should be considered in areas where the advection is important. Lee and Lam [35] suggest that the performance increase due to advection is more notorious in cases when the GSHP is working in a more continued way, and there are no daily or seasonal stops.

The presence of groundwater flow modifies the shape of the heat cone around the BHE. This plume of thermal disturbance can extend for relatively long distances, as can be appreciated in Figure 5.3[2], affecting the performance of BHEs placed downstream the groundwater flow. The performance of the boreholes inside the GHE also change with their relative position inside it. It can be noted that the temperature around the upper right borehole is significantly lower, because of the influence of the nearby BHE in combination with the advection. As consequence, it performance will be reduced. To solve this problem, some researchers have proposed to use different rates of heat extraction per borehole, in order to not decrease in excess the underground temperature [5, 29].

Different matter is how these heat plumes can affect the performance of BHEs placed downstream. As advanced on page 18, this can arise legal problems when the heat plume decreases the performance of a neighbor's GSHP. To assess this problem, it is probably required a careful study or a proper legal framework.

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[2] This citation should be taken with caution; the author qualifies as "fast" a groundwater flow of 10 m/yr, orders of magnitude smaller than normal values in Graz.

5.3.1 Analytical solutions for heat flow in presence of groundwater flow

The analytical tool enabling a rapid assessment of the effect of groundwater advection is a modification of the infinite source technique termed the "continuous moving line source", which envisages an infinite line source of heat moving through a conducting medium at speed V in the direction $-x$, depositing a plume of heat behind it (along the x axis) as it moves.

Note that despite being based on the infinite source model, the following solution presented by Molina-Giraldo et al. [41] considers only the steady state, which on the other hand is reached relatively faster thanks to the effect of the advection. To model the heat flow in non-stationary conditions and with groundwater flow, numerical analysis by computer is advised, or using the advanced time-dependent equations proposed also by Molina-Giraldo et al.. The proposed equation that determines the shape of the heat plume left is

$$T(x,y) - T_0 = \frac{q}{2\pi\lambda} exp\left(\frac{v_{the}x}{2a}\right) K_0\left(\frac{v_{the}r}{2a}\right) \tag{5.8}$$

Where r = radial distance from heat source = $\sqrt{x^2+y^2}$, K_0 is the zero order modified Bessel function of the second kind and v_{the} is the thermal velocity. The thermal velocity is related to the Darcy velocity flux v_D by:

$$v_{the} = \frac{v_D V_{HCwat}}{V_p} \tag{5.9}$$

Where V_p is the volumetric heat capacity of the bulk saturated aquifer material, and V_{HCwat} is the volumetric heat capacity of water (4.2 MJ/m^{3}K). From this equation it can be observed that the temperatures will be less extreme and the steady state will be reached faster when the thermal diffusivity a is higher.

5.3.2 Performance of the BHE in function of the groundwater flow.

It has been mentioned that the advection due to groundwater flow increase the performance of the BHE around 10%, according to numerical methods. How to quantify exactly this increase in performance with analytical solutions is challenging; though with limitations, Banks [4] propose that equation 5.8 can be adapted to know the temperature of the heat transfer fluid on the BHE, by setting $r = \sqrt{x^2+y^2}$ to correspond with the borehole radius r_B; and by adding a borehole thermal resistance term, is is possible to predict the steady-state temperature of the BHE heat transfer fluid.

$$T_F - T_0 = qR_{BHE} + \frac{q}{2\pi\lambda} exp\left(\frac{v_{the}x_B}{2a}\right) K_0\left(\frac{v_{the}r_B}{2a}\right) \tag{5.10}$$

where $r_B$and x_B correspond to a point on the borehole wall. Note that this is not a wholly accurate representation, as this formulation assumes that the borehole fill has similar properties to the aquifer, and that groundwater flow takes place through it. Thus, it results in a variety of different temperatures around the borehole circumference, depending on direction with respect to groundwater flow. Following this, Banks [4] suggests that the final fluid temperature T_F is calculated as the sum of qR_{BHE} and the average of four determinations around the BHE

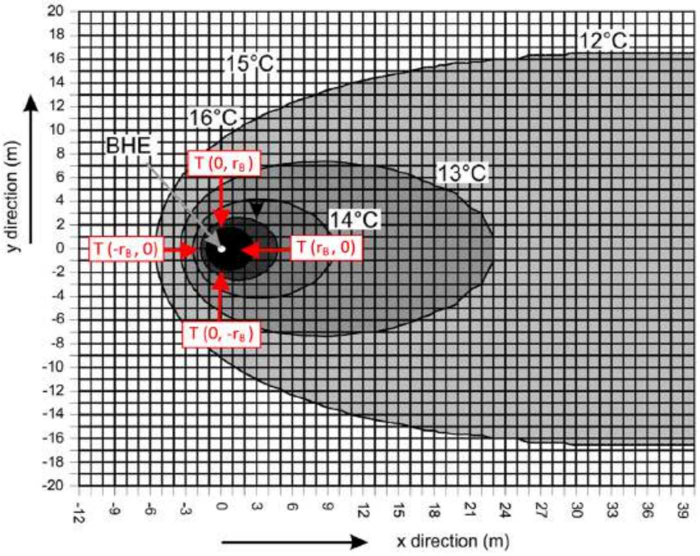

Figure 5.4: Shape of the steady-state thermal plume from a BHE following equation 5.8, rejecting heat at a rate of 35W/m, with a water flow of 6.6 cm/day and typical values for the rock of λ= 2 W/mK and V_p= 2200 kJ/m^{3}K [4]

wall (as pointed in Figure 5.4): borehole wall downstream: $T(r_B, 0)$; borehole wall lateral: $T(0, r_B), T(0, -r_B)$; and borehole wall upstream: $T(-r_B, 0)$.

Comparing the solution of the equations 5.10 and 5.3, it is possible to appreciate the theoretical increase in performance due to the advection.

5.4 Borehole sizing

Ground heat exchanger sizing is concerned mainly with the determination of heat exchanger length. The required length H is calculated by

$$H = q_l \left(\frac{\frac{COP-1}{COP}(R_{BHE} + R_{AES}F)}{T_0 - T_{F,0}} \right) \tag{5.11}$$

Where q_l is the design heat load, $T_{F,0}$ is the minimum temperature of the heat carrier fluid, and F is the load factor for heating, evaluated as the fraction of equivalent full load hours during a period to the total number of hours in that period:

$$F = \frac{\bar{q}}{q_{max}}$$

where $\bar{q}$ and q_{max} are the average load and peak load of the period, respectively. To size properly a borehole for heat extraction, normally the period of time chosen is the coldest month, January.

Chapter 6

Retrofitting and economic aspects

Retrofitting is in some way like resetting the age of the building; it is an opportunity to increase its value, comfort and implement sustainability measures, including HER reduction ones. After so much focus on passive buildings and new techniques of construction, it is worth to remember that Graz has 64 thousand buildings [32], and most of them will exist in the foreseeable future. To achieve major reductions in heating consumption at city level requires to pay attention to this whole mass of buildings, and consider different ways to reduce their HER. At the same time can be considered alternatives like heat pumps, but it is important to remember that these last are aimed at supply the heat demand, not reducing it.

Thus, in face of a large set of choices for retrofitting a building, the main issue is to identify those that prove to be the most effective in the long term. When choosing among a variety of proposed measures, the household has to reconcile environmental, energy, financial, legal regulation and social factors to reach the best possible compromise solution to satisfy the final occupant needs. [3].

In relation with the topic of heat pumps that has been developed over the report, one of the main thesis of this chapter is that GSHP are subordinated in priority to a good retrofitting; it is needed the last to maximize the advantages of a GSHP. Other topics that will be addressed are the costs of alternatives technologies, as well as a brief overview of the methodology used to know the optimal measures to implement in a retrofit.

6.1 The role of GSHP depending on building typology

The usefulness of a GSHP in a building is very dependent on the HER of this building. As seen on chapter 4, the self-sufficiency by means of GSHP is only achievable at low HER, and a low HER is also needed to combine the GSHP with a highly efficient low-temperature heating system. Following this, we can distinguish several typologies of buildings:

6.1.1 Newly constructed buildings

Given the need of reducing energy dependency, it is justified striving for highly efficient energy standards, and to use the most efficient systems for heat delivery. As the additional cost of construction of a passive building in Austria is marginal, the installation of GSHP (or a similarly efficient heating system) should be given for granted; and if it is not compulsory the city of Graz should do as possible to encourage the building's investors in this direction.

6.1.2 Buildings in need of retrofit

The buildings in need of retrofit can consume very high amount of energy. For instance, Eicker [17] comments that in Germany there are buildings with a consumption of 220 kWh/m^2 yr, that have a huge saving potential reducing the transmission heat loss of the building envelope. A typical retrofit measure is to install 16 cm insulation to create a "thermal envelope" around the building [51], including the roofs and sometimes the cellars. To keep this envelope as closed as possible are needed especial windows, and also pay especial attention to the called "thermal bridges", non-insulated surfaces that cannot prevent transmission of heat. It is also usually needed a renovation of the ventilation system, to allow proper influx of air without loosing heat.

However, the described renovations are not equally easy to do. According to this, can be distinguished two main categories of buildings:

Non-historical building, especially constructed between 1950 - 1980

This group consists in construction more or less recent, with facades without historical value. Because the facades can be covered easier with the insulation, and it is easier to pay attention to the thermal bridges, these buildings are also easier and and cheaper to retrofit.

There can be found many examples of successfully retrofitted buildings, also in Austria. For instance, Dequaire [12] mentions the case of three schools in Linz constructed in the decade of 1960 that reduced the HER in more than 80%, up to reach passive house standards. A case in Graz [31] presents a building that was retrofitted remarkably in more than one sense. First, the technique used allowed for the installation of a thermal envelope without need of clearing temporally the building. Second, the reduction on energy achieved is impressive, from 184 to 12 kWh/m^{2}yr, which means savings of 93%. Unsurprisingly, this case is also a good example of application of TS and GSHP technologies in a retrofitting.

Historical buildings: Gründerzeithäuser

The Gründerzeithäuser are historical buildings constructed between 1848 and 1918. This kind of constructions is abundant in Austria in general [52], and specially in Graz, in its well preserved historical center. These buildings are typically bad insulated, with normal HER between 120 and 160 kWh/m^{2}yr. The facades are normally subject of protection because of historical reasons, which prevents to install insulation in the outer side. This creates a problem, because insulating walls from the inside of the building is costly and difficult: the moisture that accumulates in the facade can deteriorate easily the stone [51], and the control of thermal bridges is more problematic.

Salzburger Institut für Raumordnung and Wohnen [52] quotes a case in Salzburg in which a building of this typology was refurbished to reduce its HER to less than 30 kWh/m^{2}yr. Part of the success relies in using special materials for the insulation of the building, that remove by capillarity the moisture on the walls, and the installation of a highly efficient system of ventilation. In the case mentioned, biomass in form of pellets was used to run the boiler installed[1].

Another example is the famous retrofitting of the Reichstag, in Berlin [1]. It counts with a thermal storage in an aquifer below the building, and the refurbishment has been so efficient that indeed it produces more energy than it consumes.

6.2 Costs of retrofitting

Retrofitting is expensive even when it is economically feasible, and there are several issues that can suppose an obstacle under the economic point of view:

A first important obstacle is the confusion about which is the real cost of thermal retrofitting. When a refurbishment of a building is done, there are several actions and expenses associated: maintenance (painting of walls or plastering), energy related incremental cost (incremental cost of triple glazing when replacing a window), and costs for building extensions and modernizations (modernization of the kitchen) [45, 51].

In other words, only a part of the refurbishing budget can be attributed to the incremental costs of thermal retrofits. When the different costs are appropriately accounted, then it is possible to know the real cost of the thermal retrofitting, which otherwise can be bloated. Neuhoff et al. [45] argue that in these circumstances and if the household can receive the economic advantages of the retrofit, then it is generally feasible under the economic point of view.

However, ensuring that the household perceive the economic benefits of the retrofitting can be challenging in the case of rented properties. In these cases, Richarz and Schulz [51] suggest that exist two possible solutions: a first one consists in including the refurbishment costs in the monthly bill; a second one is keep on charging the same price to the tenant, without accounting the energy savings of the refurbishment. In any case this allow the repayment to be completed during the life expectancy period.

This payback period can be long: for instance in the case of International Energy Agency [31] previously mentioned the project has a payback period of 30 years. Anyway, the economic benefits are only part of the advantages of the retrofitting. It is a good idea present to households and investors also the environmental advantages of the retrofitting, to give a global perspective of the benefit [36].

6.3 Alternative technologies to heat pumps

The heat pumps are regarded as a suitable alternative to produce heat; however it is worth to mention that there are alternatives to them:

6.3.1 Comparison of different technologies

Table 6.1 compares information of selected technologies for heating, including GSHP. It can be observed that its strength relies on its low operation costs.

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[1] Other examples of retrofitting on Gründerzeithäuser can be found at: http://www.gruenderzeitplus.at/ueber/index.php

Table 6.1: Comparative analysis of heating in a residential building (selected methods)[51]

	Final energy (kWh)	Primary energy (kWh)	kg CO_2 equiv.	Cost/year (€)	Cost in 20 years (€)	Investment (€)	Annuity (€)	Total (€)
Condensing boiler (2010)	9500	10,450	2309	760	27,917	8000	11,773	39,690
Gas motor HP (2010)	7500	8250	1822	600	22,071	12,000	17,659	39,730
Direct electricity (2010)	10,000	26,000	6830	2200	80,928	-	-	80,928
Air HP (2010)	4500	11,700	3074	630	23,174	14,000	20,602	43,776
Ground HP (2010)	3500	9100	2390	490	18,024	22,000	32,357	50,381
Groundwater HP (2010)	2500	6500	1708	350	12,874	22,000	32,357	45,231

Comparison to cover 10,000 kWh/year of heating energy. The energy demand incorporates the useful demand (heating) as well as the energy loss caused by distribution and transmission. The system is operated at a temperature of 50 / 40 °C
Assumptions: cost of gas 0.08 ct/kWh, electricity 0.22 ct/kWh, power for heat pump 0.14 ct/kWh. Life expectancy of the system is 20 years, financing at 4% interest rate, price increase of 5%. The Air heat pump includes buffer storage tank. The ground heat pump includes 200-m-deep earth piles. The Groundwater heat pump has a production and re-injection well.

Meanwhile, GSHPs have the the highest initial investment cost, which is clearly a disadvantage when short payback periods are considered as main criterion for the retrofitting. Table 6.1 also suggests that temporal discount of the benefits and the interest rate considered are essential to make a proper asset of the economic advantages of the heat pumps. Section 6.4 will comment further the criterion that can be used to design the measures of a retrofit.

6.3.2 A showcase of high performance without heat pumps: Drake Landing Solar Community

The mentioned Borehole Thermal Energy Storage is a system that can be used with independence of heat pumps, as demonstrate the project of Drake Landing Solar Community, a group of 52 homes in Canada that reach an outstanding 97% of heat produced with solar fraction.

It is placed in an area with significant solar resources (around 203 W/m^2, 60% more than Graz), and also has very cold winters (5200 HDD) [19].

The system consists in a total 2,293 m^2 of TS modules, which warm water that later is transferred to a short-term storage. When the short-term storage is heated, the heat is fed to the underground borehole storage, consisting on 114 boreholes about 37 meters long stretched over an area of approximately 35 meter in diameter[2]; activating thermally around 34,000 m^3 of underground [56]. It was noticed that the overall efficiency of the system has increased over time, as first the underground had to reach an appropriate temperature.

During winter, the short-term storage acts as a buffer to extract heat from the seasonal storage, and delivers heat to the houses in form of warm air. As seen, no heat pumps are involved; in turn, gas boilers warm the air in case it is necessary an auxiliary input of energy. This system of warm air delivery has the advantage of providing heat at the same time than ventilation, a need in highly insulated houses. The DHW is provided by individual TS modules backed with gas burners.

This project had an overcost that was paid in part by public institutions. It is important to notice that this is a showcase in which the economic feasibility was not a priority target. Now the project would cost three million dollar less, as this amount of money was spent for one-time research and development.

6.4 Selection of measures to apply on retrofitting

As when selecting the measures to implement in a retrofit, probably the most important concept is to understand that this is a multi-criterion optimization problem, where there is always a trade-off between capital expenditure, operating cost, and occupant thermal comfort [58].

In practice, seeking for the optimal solution is mainly attempted via two main approaches [2]:

- Different scenarios are predefined and evaluated separately. This is an iterative process in seek of the best possible solution, and can be significantly time-consuming.
- Decision-aid techniques that are usually combined with simulation to assist reaching a final decision among a set of alternative actions.

In any case, the problem faced in a multi-objective optimization model is that multiple and competing objective functions are formulated to assess feasible alternatives, which are not predefined but are implicitly defined by a set of constraints. In this way, maximizing the thermal comfort can be limited by the capital expenditure, for instance.

This can be more complicated because different results can be obtained depending on the weighting of different objectives defined for the building retrofit. Some of these objectives can be heating and cooling load, annual emissions global warming potential, thermal discomfort or payback time.

In general, today are still used many "rules of thumb" at the time of undergoing retrofitting [42]. To overcome this problem, some authors propose a curious methodology called "Genetic Algorithm", inspired from the biological principles of natural selection and genetic recombination (see [58, 42]). Each random building configuration is evaluated against an "objective

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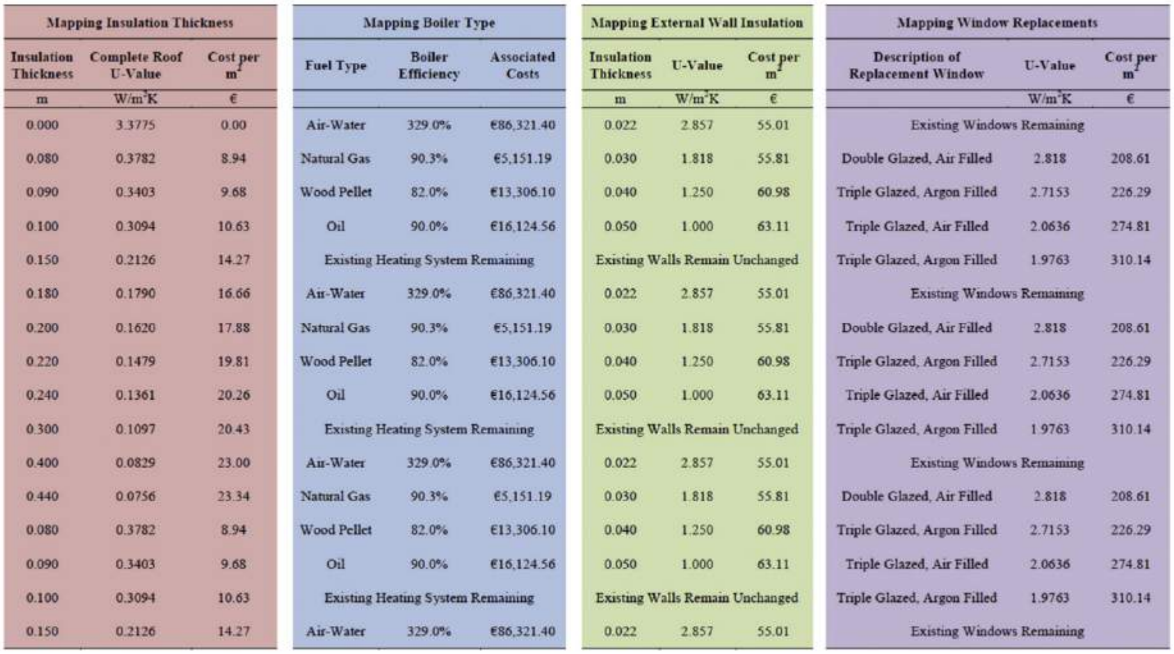
[2] This gives an approximate area covered per borehole of 8.5 m^2 , and a separation between them of 3.2 meters, approximately.



Mapping Insulation Thickness		
Insulation Thickness	Complete Roof U-Value	Cost per m^2
m	W/m^2K	€
0.000	3.3775	0.00
0.080	0.3782	8.94
0.090	0.3403	9.68
0.100	0.3094	10.63
0.150	0.2126	14.27
0.180	0.1790	16.66
0.200	0.1620	17.88
0.220	0.1479	19.81
0.240	0.1361	20.26
0.300	0.1097	20.43
0.400	0.0829	23.00
0.440	0.0756	23.34
0.080	0.3782	8.94
0.090	0.3403	9.68
0.100	0.3094	10.63
0.150	0.2126	14.27

Mapping Boiler Type		
Fuel Type	Boiler Efficiency	Associated Costs
Air-Water	329.0%	€86,321.40
Natural Gas	90.3%	€5,151.19
Wood Pellet	82.0%	€13,306.10
Oil	90.0%	€16,124.56
Existing Heating System Remaining		
Air-Water	329.0%	€86,321.40
Natural Gas	90.3%	€5,151.19
Wood Pellet	82.0%	€13,306.10
Oil	90.0%	€16,124.56
Existing Heating System Remaining		
Air-Water	329.0%	€86,321.40
Natural Gas	90.3%	€5,151.19
Wood Pellet	82.0%	€13,306.10
Oil	90.0%	€16,124.56
Existing Heating System Remaining		
Air-Water	329.0%	€86,321.40

Mapping External Wall Insulation		
Insulation Thickness	U-Value	Cost per m^2
m	W/m^2K	€
0.022	2.857	55.01
0.030	1.818	55.81
0.040	1.250	60.98
0.050	1.000	63.11
Existing Walls Remain Unchanged		
0.022	2.857	55.01
0.030	1.818	55.81
0.040	1.250	60.98
0.050	1.000	63.11
Existing Walls Remain Unchanged		
0.022	2.857	55.01
0.030	1.818	55.81
0.040	1.250	60.98
0.050	1.000	63.11
Existing Walls Remain Unchanged		
0.022	2.857	55.01

Mapping Window Replacements		
Description of Replacement Window	U-Value	Cost per m^2
	W/m^2K	€
Existing Windows Remaining		
Double Glazed, Air Filled	2.818	208.61
Triple Glazed, Argon Filled	2.7153	226.29
Triple Glazed, Air Filled	2.0636	274.81
Triple Glazed, Argon Filled	1.9763	310.14
Existing Windows Remaining		
Double Glazed, Air Filled	2.818	208.61
Triple Glazed, Argon Filled	2.7153	226.29
Triple Glazed, Air Filled	2.0636	274.81
Triple Glazed, Argon Filled	1.9763	310.14
Existing Windows Remaining		
Double Glazed, Air Filled	2.818	208.61
Triple Glazed, Argon Filled	2.7153	226.29
Triple Glazed, Air Filled	2.0636	274.81
Triple Glazed, Argon Filled	1.9763	310.14
Existing Windows Remaining		

Figure 6.1: Example of variable types used for retrofitting optimization [42]

function" to determine how fit it is, and then the best adapted "individuals" exchange features between them in a random way, like would do the genes in a wild population. To introduce appropriately the data in a table like 6.1, data from tables 2.4, 2.5, 2.6, 2.6 and 2.8 can be used, as for pricing it can be used the information contained in reference guides as "BCIS Alterations & Refurbishment Price Book". After the first selection, the Genetic Algorithm repeats the process, up to find the "individual" configuration that shows better adaptation.

As noticed, the Genetic Algorithm methodology is eminently stochastic, so requires of several runs to validate the results. Murray et al. [42] found that this methodology applied to an static simulation suits well real-world applications, but it is necessary to carry out analysis of a project before retrofit works commence to ensure an optimal approach is taken in accordance with the project specific criteria. Note also that Genetic Algorithm requires to define an "objective function" to compare different configurations, and this function is defined with criterion partially subjective. For instance, Murray et al. [42] use in their evaluation the "simple payback", "carbon emissions" and "energy cost" as criterion, but other could be used instead.

The selection of appropriate measures in a retrofit is not an straight-forward task, but it is important to determine objectively the advantages of GSHPs. Though it is hard to state it categorically, it seems clear that GSHP in retrofits should be considered also in combination with measures aimed at reducing the HER of the building.

Chapter 7

Discussion and conclusions

Ground Sourced Heat Pumps can be a feasible solution, depending on the circumstances

From the results obtained, a general conclusion is that GSHP is a feasible and reliable technology for new buildings that strive for high energy efficiency. Up to four storeys, a building can supply itself with heat from GSHP, and can potentially reach the zero-energy standard using the appropriate combination of solar technologies.

... but are not a silver bullet for buildings in need of refurbishment

In the case of buildings in need of retrofit, the application of GSHP is not an ultimate and easy solution, and it is not a suitable technology for say, an HER over 30 kWh/m^{2}yr. There are several obstacles to consider: on the one hand technical, because a GSHP is usually not able to provide the high heat loads that present a building poorly insulated. On the other hand, it can be economically hard to justify it in the long term in comparison with an energy-efficient retrofit.

The GSHPs are one more tool at disposition of households and urban planners, but will not lead Graz to the energy independence except in combination with other technologies and measures.

Embracing the passive standard, not the zero-energy one.

Though it would be need to perform a careful economic comparison, it was mentioned that passive houses are significantly cheaper than zero-energy ones in Austria, and the data from the spreadsheet calculator presented in this work seem to be in the same line with this perception. The costs to reach the energy self-sufficiency can rise when approaching the hundred percent, as for instance with the supply of DHW with TS technology. Note that even high-performers showcases like Drake Solar Landing Community chose to provide the DHW partially with natural gas, which prevent from the self-sufficiency, but might have sense under the economic point of view.

The buildings placed in Graz's historical center have additional reasons to strive for good energy standards instead that unrealistic expectations about self-sufficiency, because their historical roofs present limitations to the installation of PV and TS modules.

No refurbishment without thermal retrofitting. From now on.

This should not discourage to start working in a certain direction. The thermal retrofitting of the buildings in Graz is a project in the long term; and better results will be achieved starting sooner. There should be a focus on encouraging househlds to retrofit thermally the building when a refurbishing is going to be done. In some sense, every time a refurbishment is done without thermal retrofitting it is a lost opportunity, because there will be no chance in decades to improve the performance of a building in such deep way.

Unfortunately, not all the households decide to make this step of retrofitting; because cost, or any other reason. One of the main objectives of Stadt Graz might be ensuring that every refurbished building undergoes a thermal retrofit. To achieve this, an obvious option would be enforcing it by law, but there could be considered other “soft” alternatives. Providing the right personalized information, giving customized assessment for architecture redesign, or making available long-term low-interest loans are just some of the alternatives, but are just personal suggestions.

New technologies should be embraced

As the plans of refurbishment are in the long term, it should be kept an eye on the potential of new materials and techniques to improve the thermal efficiency. The costs of thermal retrofitting have reduced in the last years, and this is a trend that will be kept ongoing in the future, with the incorporation of new technologies (as the mentioned PV/T modules) and new materials with exceptional thermal resistance as aerogels. In the same line, the positive-energy buildings will be more usual in the future, and it is necessary to keep an open mind about the potential benefits that future developments the area of urban refurbishment can bring. It would be also desirable to count on with an appropriate legal framework, for instance to sell the excess of energy produced, or to make use of heat in waste water.

Potential of district heating in Graz

In order to achieve the highest self-sufficiency on a building, it has been proposed the use of TS modules mounted on the roof. In the case when this system is discouraged, as it can be the case of historical buildings, Graz can benefit from its extensive network of district heating to substitute these TS panels. In summer, the demand on the district heating is fairly low, and can be covered with the installation of TS panels in specific places of the network. Increasing appropriately the size of these installations, it would be possible to supply with extra heat the houses connected to the district heating network, and then regenerate the ground heat without need of TS modules installed on roofs.

Advection is not an option...

... but a reality. As it has been commented through this work, it seems the influence of groundwater flow in the Graz aquifer cannot be ignored. This comes with the advantage of the enhanced performance, but perhaps more importantly, comes also with the certainty that certain GHE will affect inevitably the performance of the nearby ones. This is mostly important in the areas where a significant proportion of the BHEs is drilled through the aquifer, like it is the case on the area of Reininghaus. If an objective is to increase the amount of GSHP in the city, then a proper legal framework should be developed to address this issue.

Thermal regeneration is needed... or perhaps not.

Among the drawbacks that have been frequently quoted in GSHP, there is the fact that an inappropriate balance of the heat and cooling loads will inevitably drive to temperature changes in the underground. In case of buildings in Graz, where the residential heating requirements are higher than the cooling ones, this would produce a decrease of underground temperature.

Because of several factors, the underground of Graz in the old city is overheated, around 10 degrees more than its natural temperature. This stored heat can become an important opportunity for enhancing the GSHP that eventually would be placed in the center of the city. Further research is needed to determine exactly the increased performance, and for how long can be enjoyed this advantage before the ground gets below its original temperature.

Focus on specific cases

Despite the clear usefulness of the tools presented in this work, it is also necessary to remark that there are some very case-specific parameters that should be addressed case by case. There are three especially significant:

The effect of the advection is probably very place dependent, and evaluating it is important to know the potential performance of the GHE, and how it can influence the nearby GHEs.

Another important factor is the rate of natural heat regeneration in an specific place. As it has been commented, this is not only dependent on the advection, but also on the land use. The presence of natural heat recharge can signify savings in TS installations, so knowing it is important.

Last, the previous have also influence in how behaves the underground as thermal storage and during the thermal recharge. The assumption that 50% of the energy received by the TS modules during summer can later on be used in winter might be inaccurate depending on the case.

Consensus is an asset

Graz is a city with high objectives, but also counts with some important consensus thanks to the “I live Graz” project. These agreements should be used to capitalize the opportunities of improvement in a number of fields, including of course energy efficiency. This can help to create the appropriate legal frameworks that benefit the sustainable technologies when needed.

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