Increased ground temperatures in urban areas: Estimation of the technical geothermal potential

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Abstract

Many cities leave a considerable thermal footprint in the subsurface. This is caused mainly by accelerated heat fluxes from warmed basements, pavements and buried infrastructures. Even though rough estimations of the theoretical heat content in urban ground exist, there is no insight available on the technical potential of such subsurface urban heat islands. By considering borehole heat exchangers (BHEs) for geothermal exploitation, new opportunities arise for planning sustainable systems within cities through utilization of accelerated ground heat input from urban structures. This is feasible at moderate heat extraction rates even without any active (seasonal) recharging of the BHEs. For typical conditions in central Europe and a given system's life time, each additional degree of urban ground heating could save around 4 m of the borehole length for the same heating power supply. We inspect implications for a single BHE as well as complete coverage of cities, which is approximated by an infinite field of BHEs. The results show that shallower systems favour renewable operation, and urban technical potential of geothermal use increases by up to 40 % when compared to rural conditions.

27 *Keywords:* geothermal energy; low-enthalpy; heat transport; technical potential; subsurface urban
28 heat island

29 Nomenclature

a	thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)
F_o	Fourier number
g	g-function
H	borehole length (m)
H^*	for a given rate q , this is the length corresponding to the maximum ΔT_{GST} (m)
k	geothermal gradient ($^{\circ}\text{C m}^{-1}$)
q	heat flow rate per unit length (W m^{-1})
Q_T	dimensionless number
r_b	borehole radius (m)
R	transient total thermal resistance (m K W^{-1})
R_b	effective thermal resistance of the borehole (m K W^{-1})
t	time (s)
t_s	characteristic time (s)
t_{urb}	time of preexisting urban warming before BHE operation (s)
T	temperature in the porous medium ($^{\circ}\text{C}$)
T_{BHE}	temperature change induced by BHE operation ($^{\circ}\text{C}$)
T_{BW}	temperature at the borehole wall ($^{\circ}\text{C}$)
T_{FLS}	temperature associated with the FLS solution ($^{\circ}\text{C}$)
ΔT_{GST}	net increased temperature at the ground surface ($^{\circ}\text{C}$)
T_k	unaffected ground surface temperature ($^{\circ}\text{C}$)
T_{IC}	temperature associated with the IC solution ($^{\circ}\text{C}$)

T_{TBC}	temperature associated with the TBC solution (°C)	30
x, y, z	single space coordinates where temperature is evaluated (m)	
x_a, x_b, y_a, y_b	boundary coordinates of the specific land use (m)	
Greek symbols		
λ	thermal conductivity of porous medium ($\text{W m}^{-1} \text{K}^{-1}$)	
φ	intermediate or substitution variable	
τ	time at which a heat pulse is released (s)	
θ	dimensionless temperature	
Abbreviations		
BHE	borehole heat exchanger	
BW	borehole wall	
FLS	finite line source	
GIS	geographical information system	
GST	ground surface temperature	
IC	initial conditions	
MFLS	moving finite line source	
SIA	Schweizerischer Ingenieur- und Architektenverein	
SUHI	subsurface urban heat island	
TBC	top boundary condition	
TDP	temperature depth profile	
VDI	Verein Deutscher Ingenieure	
Conventions		
$\bar{X}$	depth-averaged value of the quantity X	

1 Introduction

The shallow ground is considered as a large energy reservoir, and the thermal capacity of low-enthalpy geothermal installations shows global growth rates of around 7 % at present [1]. Most common devices are borehole heat exchangers (BHEs), where a heat carrier fluid exchanges heat with the ambient ground by circulation in vertical boreholes. Although much more energy is stored in the ground than is used, local geothermal energy availability might be limited. Especially in areas with dense populations and high installed capacities, competition for the ground is high [2-4]. In Switzerland, for example, with the highest density of BHEs worldwide, local authorities caution overexploitation of the ground [5].

Previous works implemented GIS-based models to estimate the spatially distributed geothermal potential in specific regions or cities ([6-12]). Common to these regional models is that they consider the variability of the thermal properties of the subsurface and expected heat extraction rates, which are specified by guidelines such as the German VDI [13]. Schiel et al. [7], for instance, applied this to the city of Ludwigsburg, Germany. They compared the spatially distributed heating demands and the energy supplied by BHEs fields. In the same manner, Zhang et al. [14] estimated the spatial variability of the capacity and electricity consumption for different BHEs distributions in the city of Westminster, London. Both studies reveal how the specific heating demands may be fully or partially supplied by multiple BHEs, employing assumptions and simplifications that restrict the model.

One common simplification is related to the way these models account for urban heat sources such as heat losses from basements, underground infrastructure (e.g., tunnels, district heating and sewage networks) and heat input from increased ground surface temperature [15-19]. Generally, these influences exhibit a high variability in space and time that is commonly neglected in GIS-supported models. Depending on their strength and timing, these man-induced thermal alterations can significantly change the ground temperature down to several tens of meters in the subsurface [20]. Bayer et al. [21], for instance, employed analytical models to estimate the relative contribution of climate forcing and urban sources such as paved areas and buildings to urban ground. For this, four measured temperature-depth-profiles (TDPs) taken in areas with different degrees of urbanization in the city and suburbs of Zurich were inspected. It was demonstrated that urban structures are responsible for at least 50 % of the additional energy stored in the subsurface. This is consistent with earlier work on other central European cities, which reveal large thermal anomalies in the upper urban ground, known as subsurface urban heat islands (SUHIs). These indicate accelerated heat flux from the basements of buildings and paved ground as the main drivers [22-24]. Zhu et al. [25] compared the additional energy stored in urban ground with the annual heating demand in

several cities to calculate the geothermal potential of SUHIs. They focused on the total anthropogenic heat accumulated beneath cities (theoretical geothermal potential), However, the practically extractable energy (technical potential) of the urban subsurface is not addressed [26]. The present work intends to provide this. The objective here is the estimation of the increased technical potential of the shallow urban ground, which could be exploited by vertical ground source heat pump (GSHP) systems equipped with BHEs. As in previous GIS-based approaches, groundwater effects are neglected.

Various analytical and numerical approaches exist for simulating BHEs [27-30]. Among these, the unitary response factor approach based on g -functions [31, 32] is widely employed. In a BHE, the circulating fluid exchanges heat with the ground through conduction. The g -functions yield the relationship between the mean borehole wall temperature and the heat extraction rate [33, 34].

The g -functions are formulated depending on the boundary conditions at the borehole wall [35, 36]. In the original formulation, uniform temperature was assumed, requiring an expensive and less flexible numerical solution. To improve this, analytical finite line source (FLS) models were explored [37-41]. FLS models have been proven as acceptable approximation, especially in the case of single BHEs and extended time scales [33, 42, 43]. Within the scope of this study, the FLS-based g -function is convenient for two main reasons. First, high-frequency signals of the heat extraction rate are not relevant here, because the focus is set on the long term performance of the BHE and the role of land-surface effects (rather than the BHE design itself). Second and more importantly, the FLS model enables the superposition of existing analytical expressions to account for increased ground surface temperatures. Consequently, this work presents a fast and analytical framework that incorporates the time-dependent interaction between the natural geothermal reservoir, urban land surface effects and technological use. Moreover, the analytical formulation facilitates direct implementation within GIS-based models as the ones described above.

In the following, we first present the modified formulation of the mean borehole wall temperature that incorporates the dynamics induced by increased ground surface temperatures (GSTs). This formulation enables the analysis of different operation schemes, including renewability criteria. The analysis is carried out for two extremes: for a single installation and for an infinite field, rendering a massive exploitation at the city scale. As a result, the technical potential of BHEs in cities with SUHIs is motivated and the methodology is demonstrated for an example case in the city of Zurich, Switzerland.

96 2 Methodology

97 2.1 Model description

98 We consider the urban subsurface as a semi-infinite space with thermal conductivity λ and thermal
 99 diffusivity α . In this space, BHEs are represented by line sources and the increased ground surface
 100 temperature (GST) by continuous doublets distributed over the top boundary [44, 45]. The thermal
 101 changes induced by these modeling entities, together with the initial thermal conditions, determine
 102 the temperature at any point and time. Of special interest is the temperature at the borehole wall
 103 T_{BW} since it influences the heat extraction rate q from the BHE [31]. This temperature can be
 104 obtained by superposing the thermal changes induced by the interacting sources. For this, the heat
 105 conduction problem should be solved for its homogeneous and non-homogenous boundary value
 106 components [46, 47]. On the one hand, the homogeneous boundary value problem considers that the
 107 temperature at the top boundary is zero (no increased GST). Thus, the borehole wall temperature is
 108 only driven by the thermal changes induced by BHE operation, T_{BHE} . For these conditions, the g -
 109 function g relates the mean borehole wall temperature $\overline{T_{BW}}$ and the heat extraction rate q by [31]:

$$\overline{T_{BW}(t)} = \overline{T_{BHE}(t)} = \frac{q}{2\pi\lambda} g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) \quad (1)$$

110 where t is the time, $t_s = H^2/9\alpha$ is a characteristic time, H is the borehole length and r_b is the
 111 borehole radius. In the original formulation by Eskilson [31], the g -function is numerically
 112 evaluated for a specific system configuration. Alternatively, by calculating the mean borehole wall
 113 temperature with the FLS model, the following semi-analytical expression is obtained ([33, 38]):

$$\begin{aligned} \overline{T_{BHE}(t)} = \overline{T_{FLS}(t)} = & \\ & = \frac{q}{8\lambda\pi} \int_{\frac{r_b^2}{4\alpha t}}^{\infty} \frac{1}{\varphi} \exp(-\varphi) \left\{ 4\operatorname{erf}\left(\frac{H\sqrt{\varphi}}{r_b}\right) - 2\operatorname{erf}\left(\frac{2H\sqrt{\varphi}}{r_b}\right) \right. \\ & \left. + \frac{r_b}{H\sqrt{\pi\varphi}} \left[4\exp\left(-\frac{H^2\varphi}{r_b^2}\right) - \exp\left(-\frac{4H^2\varphi}{r_b^2}\right) - 3 \right] \right\} d\varphi \end{aligned} \quad (2)$$

114 On the other hand, if the temperature at the ground surface is not zero, the solution of the
 115 nonhomogeneous boundary value problem T_{TBC} should be superposed to T_{BHE} , as verified by
 116 Rivera et al. [44, 45] for urban land surface effects. It was also implemented by Bandos et al. [38]
 117 for estimating the influence of ambient temperature in thermal response tests, and by Duan and
 118 Naterer [48] for estimating the temperature beneath power transmission towers.

119 The mean borehole wall temperature is obtained by averaging the superposed solutions over the
 120 depth H as follows:

$$\overline{T_{BW}(t)} = \overline{T_{BHE}(t)} + \overline{T_{TBC}(t)} + \overline{T_{IC}} \quad (3)$$

121 where T_{IC} refers to the initial or undisturbed temperature. If this temperature is roughly
 122 approximated by a geothermal gradient k , and surface temperature T_k , the associated mean
 123 temperature along the length H is $\overline{T_{IC}} = T_k + kH/2$. In the original g-function, the temperature
 124 T_{BHE} is computed for a constant background temperature [49]. In contrast, this work considers the
 125 transient effect of the increased GST (e.g. T_{TBC}) on the long term evolution of the borehole wall
 126 temperature and associated heat extraction rates. To provide the T_{TBC} solution, it is necessary to
 127 consider the spatial variability of land use in cities. For this, the solution provided by Rivera et al.
 128 [44] can be formulated for selected urban areas with specified land use. These formulations are then
 129 superimposed to the global solution (application examples are shown in [44, 50, 51]). Here, it is
 130 assumed that each land use scenario can be characterized by its own constant or time dependent
 131 increased ground surface temperature, $\Delta T_{GST}(t)$ [21, 52]. The depth-averaging of this solution over
 132 the length H yields:

$$\begin{aligned} \overline{T_{TBC}(x, y, t)} = & \frac{1}{8\sqrt{\pi}} \int_{\frac{H^2}{4at}}^{\infty} \Delta T_{GST} \left(t - \frac{H^2}{4a\varphi} \right) \left[\frac{1 - \exp(\varphi)}{\varphi^{3/2}} \right] \left[\operatorname{erf} \left(\frac{y - y_b}{H} \sqrt{\varphi} \right) \right. \\ & \left. - \operatorname{erf} \left(\frac{y - y_a}{H} \sqrt{\varphi} \right) \right] \left[\operatorname{erf} \left(\frac{x - x_b}{H} \sqrt{\varphi} \right) - \operatorname{erf} \left(\frac{x - x_a}{H} \sqrt{\varphi} \right) \right] d\varphi \end{aligned} \quad (4)$$

133 where x, y are the coordinates of the evaluation point in the horizontal plane and y_a, y_b, x_a, x_b are
 134 the coordinates of the specific land use area with temperature $\Delta T_{GST}(t - H^2/(4a\varphi))$.

135 Initially, for the purpose of generality, it is assumed that the spatially variable GST can be
 136 represented by a mean constant value, ΔT_{GST} . For a specific location, with given land use
 137 distribution, this value could be an area-weighted GST that renders the mean annual ground surface
 138 temperature. According to this, the land use effect is represented by an infinite plane that induces a
 139 transient vertical heat flux into the ground. An analytical expression for this effect can be derived
 140 from the solutions presented in [38, 46], which after being averaged over the reference length H ,
 141 reads:

$$\begin{aligned}
\overline{T_{TBC}(t)} &= \frac{1}{H} \int_0^H \left[\frac{z}{2\sqrt{\pi a}} \int_0^t \frac{\Delta T_{GST}}{(t-\tau)^{3/2}} \exp\left(-\frac{z^2}{4a(t-\tau)}\right) d\tau \right] dz \\
&= \Delta T_{GST} \left\{ \operatorname{erf}\left(-\frac{H}{\sqrt{4at}}\right) + \sqrt{\frac{4at}{\pi H^2}} \left[1 - \exp\left(-\frac{H^2}{4at}\right) \right] + 1 \right\} \\
&= \Delta T_{GST} \cdot f\left(F_o = \frac{at}{H^2}\right)
\end{aligned} \tag{5}$$

142 where F_o is the Fourier number. To accurately superpose $\overline{T_{TBC}(t)}$ to $\overline{T_{IC}}$ in Eq. (3), ΔT_{GST} represents
 143 the excess in ground surface temperature above T_k . This means that the absolute urban ground
 144 surface temperature is $T_k + \Delta T_{GST}$. In Eq. (2) and Eq. (5), the time is specified by the same variable
 145 t . This means that both processes, increased GST and BHE operation, start at the same time.
 146 However, a time lag between those processes may exist. In city centers for instance, the thermal
 147 forcing associated with land use changes had been acting for several decades before the installation
 148 of any BHE. If this time lag is t_{urb} and the BHE starts operation at $t = 0$ then the time in Eq. (5)
 149 should be $t_{urb} + t$.

150 Taking the original g -function as a reference, it is necessary to obtain a dimensionless form of Eq.
 151 (3) to generally describe the effect of elevated ground surface temperature. This dimensionless form
 152 can be derived as follows:

$$\begin{aligned}
\left[\overline{T_{BW}\left(\frac{t}{t_s}\right)} - \overline{T_{IC}} \right] \frac{2\pi\lambda}{q} &= \overline{\theta_{BW}\left(\frac{t}{t_s}\right)} = g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) + 2\pi \frac{\lambda\Delta T_{GST}}{q} f\left(F_o = \frac{t_{urb} + t}{9t_s}\right) \\
&= g\left(\frac{t}{t_s}, \frac{r_b}{H}\right) + 2\pi Q_T f\left(\frac{t_{urb} + t}{t_s}\right)
\end{aligned} \tag{6}$$

153 where the dimensionless number $Q_T = \lambda\Delta T_{GST}/q$, compares the strength of the surficial forcing
 154 ΔT_{GST} , to the heat extraction rate q , of the BHE.

155 According to Eq. (6), urban land surface effects increase the mean borehole wall temperature and
 156 allow a higher extraction rate q . By comparing these affected rates with those ones obtained under
 157 undisturbed conditions, the increased technical geothermal potential is estimated. For this, different
 158 system configurations and exploitation scenarios will be analysed.

159 At this point, it is worth to discuss some assumptions in the model that suggest a limited scope of
 160 applicability at first glance. One is the assumption of a homogenous porous medium. However, for
 161 conduction dominated conditions, using average or effective thermal properties (homogenization),
 162 has proven to be a good approximation [32, 49]. Another constraining assumption is the omission of

groundwater flow in the model. On the one hand, several studies have demonstrated that thermally unaffected groundwater flow enhances the performance of GSHP systems (e.g. [53, 54]). On the other hand, significant groundwater flow close to the ground surface also promotes higher heat losses from surficial sources [55]. Preliminary analysis implementing the moving finite line source (MFLS [56]), indicates that a rather low effective thermal velocity easily overprints any ground surface temperature effects on the mean borehole wall temperature. In these cases, (thermally) undisturbed groundwater flow shapes the thermal plumes without changing significantly the overall energy balance [57, 58]. A few studies have been carried out in urban areas significantly influenced by dynamic aquifers where the presented analytical models have limited applicability. These studies necessarily rely on measurements and numerical simulations of the interaction of these aquifers and near-surface urban sources [59-62].

2.2 Scenarios of analysis

There are diverse standards for BHE installation and planning in different countries [63] that typically restrict induced ground temperature variations, heat extraction rates and/or the lifetime of the geothermal system. This work considers the regulations for planning and construction provided by the Swiss Society of Engineers and Architects (SIA). Specifically, its norm 384/6 defines the lowest allowed temperature in the circulating fluid of ground coupled heat pumps. According to the norm, the mean fluid temperature should not be lower than -1.5 °C after 50 years of operation [64]. If this mean fluid temperature is $\overline{T_{fluid}}$, then it is possible to relate this temperature and Eq. (3) as follows [32]:

$$\overline{T_{fluid}} = \overline{T_{TBC}(t_{urb} + t)} + \overline{T_{IC}} + qR(t) = \overline{T_{BW}(t)} + qR_b \quad (7)$$

where the sum $\overline{T_{TBC}(t_{urb} + t)} + \overline{T_{IC}}$ is usually referred to as the undisturbed ground temperature, $R(t)$ is the transient total thermal resistance and R_b is the effective thermal resistance of the borehole. For an unbalanced extraction rate q , $\overline{T_{BHE}(t)} + qR_b$ acts against the background temperature provided by $\overline{T_{TBC}(t_{urb} + t)} + \overline{T_{IC}}$.

Two scenarios are discussed in the following:

- The “depleting scenario”, which corresponds to a finite operation period of 50 years.
- The “renewable scenario”, which corresponds to an infinite operation period, where the heat extraction rate is balanced by natural sources [3, 65].

191 Results for both scenarios are discussed along with their corresponding ‘base case’, which refers to
 192 the undisturbed conditions. In this way, the net energy gain is associated with urban effects, and
 193 thus the related technical potential can be quantified and discussed.

194 The analyses are carried out for a reference site, specified by the parameters listed in Table 1. The
 195 given values of the geothermal gradient, the thermal diffusivity and the thermal conductivity are
 196 representative for the city of Zurich [21] and are characteristic for unconsolidated sediments
 197 typically found beneath many central European cities [66]. The magnitude of R_b is within the
 198 expected range of values for long term BHE operation [49]. Finally, the value for T_k is site specific
 199 and corresponds to the estimations for the city of Zurich described in [21].

200 Table 1: Parameters for the reference site taken from [21, 66].

Parameter	Value
Thermal diffusivity, a ($\text{m}^2 \text{s}^{-1}$)	1×10^{-6}
Thermal conductivity, λ ($\text{W m}^{-1} \text{K}^{-1}$)	2.5
Borehole radius, r_b (m)	0.1
Effective borehole thermal resistance, R_b ($\text{W}^{-1} \text{m K}$)	0.15
Background surface temperature, T_k ($^{\circ}\text{C}$)	10
Vertical geothermal gradient, k ($^{\circ}\text{C m}^{-1}$)	0.03

201

202 For the following analysis, a range of borehole lengths (H) between 50 m and 200 m is considered.
 203 The upper limit is chosen based on observed urban temperature-depth-profiles (TDPs) that typically
 204 show thermal anomalies reaching up to 150 m depth [17, 20]. Moreover, the upper limit of 200 m
 205 minimizes the effect of inaccuracies in the analytical model related to the assumption of an uniform
 206 heat extraction rate along the depth [67]. This assumption may be critical for deeper applications
 207 because with higher ground temperatures (due to the geothermal gradient) it is expected that heat
 208 extraction rates also increase with depth. Finally, for specification of increased urban ground-
 209 surface temperature, ΔT_{GST} , a range of 0.5-5 K is chosen according to the findings in [22, 23].

210

211 3 Results and discussion

212 3.1 Single BHE

213 3.1.1 Effect of land surface forcing on mean borehole wall temperature

214 The dimensionless mean borehole wall temperature ($\overline{\theta_{BW}}$) is crucial for estimating the technical
 215 geothermal potential, and it is scrutinized first. Figure 1a shows the influence of increasing ground-
 216 surface warming (expressed by Q_T), assuming that urban ground heating and BHE operation start
 217 simultaneously ($t_{urb} = 0$). The curve $Q_T = 0$ corresponds to the original g-function without the
 218 transient effect induced by ΔT_{GST} . In this case, the sustained drop in $\overline{\theta_{BW}}$ is due to the continuous
 219 heat extraction q . For $\Delta T_{GST} > 0$, the quantity $Q_T = \lambda \Delta T_{GST} / q$ increases proportionally to its
 220 magnitude. The associated curves depicted in Figure 1a exhibit a characteristic minimum in $\overline{\theta_{BW}}$.
 221 The time at which this minimum occurs indicates the instant when GST effects balance the
 222 temperature drop induced by q such that the heat flux from the surface compensates the heat
 223 extraction. At later times, continuously high ground-heat flux replenishes the cooled ground.
 224 Pronounced ΔT_{GST} is associated with a higher mean borehole wall temperature.

226 Figure 1: Dimensionless mean borehole wall temperature over dimensionless time: a) $t_{urb} = 0$
 227 years and b) $t_{urb} = 100$ years (the magnitudes in $^{\circ}\text{C}$ and years correspond to the parameters
 228 shown in Table 1 with $q = 20 \text{ W m}^{-1}$ and $H = 100 \text{ m}$). A higher Q_T indicates a stronger effect
 229 from ΔT_{GST} relative to the heat extraction rate q . $Q_T = 0$ is the original g-function neglecting
 230 urbanization effects.
 231

232 Figure 1b examines the same conditions as in Figure 1a, but assumes that urbanization has started
 233 100 years ago ($t_{urb} = 100$ years). In this case, a subsurface urban heat island (SUHI) pre-exists
 234 before the BHE operation. The influence of increased ground-surface temperatures as expressed by

235 Q_T is clearly enhanced, especially at early operation times. This is a consequence of the linear
236 superposition of the different solutions indicated in Eq. (3). For a given borehole length H , there is a
237 time when SUHI covers this depth and the changes in the mean borehole wall temperature start to
238 diminish. If the operation time of the BHE is several times longer than this characteristic time, then
239 at the end of the time window, $\overline{\theta_{BW}}$ becomes insensitive to t_{urb} (Figure 1b).

240 The described temporal dynamics of the mean borehole wall temperature can be transferred to the
241 mean fluid temperature $\overline{T_{fluid}}$ via Eq. (7). In this way, it is possible to estimate the heat extraction
242 rates that fulfil the conditions of the depleting and renewable scenarios as discussed in the
243 following.

244 3.1.2 Depleting scenario

245 The depleting scenario assumes that the reservoir is exhausted after 50 years of operation. For this
246 condition, Figure 2 depicts the technical geothermal potential for different timings and intensities of
247 surface warming.

248 Figure 2a shows the heat extraction rates for $t_{urb} = 0$ and 100 years. These rates are mean annual
249 values and are of the same magnitude as those discussed in [7, 49, 68]. While these rates have
250 values between 26-27 W m⁻¹ for the lowest assumed ground surface warming ($\Delta T_{GST} = 0.5$ K), they
251 reach values higher than 30 W m⁻¹ at the upper limit of $\Delta T_{GST} = 5$ K. Clearly, the rates are more
252 sensitive to ΔT_{GST} for the shallower BHEs.

253 The characteristic curvature is the result of the complementary effect between the initial thermal
254 conditions given by the geothermal gradient and the increased GST on top. For a given iso-rate
255 curve q , there is a length H^* above and below which the extraction rate q can be kept at lower
256 ΔT_{GST} . For a BHE with $H > H^*$, the natural geothermal gradient dominates and thus, the rate q is
257 sustained by decreasing ΔT_{GST} .

Figure 2: Single BHE in the depleting scenario: a) heat extraction rates q (W m^{-1}), b) ratio $q(t_{urb} = 100)/q(t_{urb} = 0)$ for the rates shown in a), c) extracted power (W), and d) ratio between the rates shown in a) and the ones from the base case (excluding the urban effect). Exemplarily, H^* is the length that requires the maximum ΔT_{GST} keeping $q = 27.5 \text{ W m}^{-1}$.

For any selected point in the domain of Figure 2a, the extraction rates are higher for $t_{urb} = 100$ years than for $t_{urb} = 0$ years. For better insight, the ratio of the rates $q(t_{urb} = 100 \text{ years})/q(t_{urb} = 0 \text{ years})$ is depicted in Figure 2b. It is shown that the gain in q due to 100 years of urbanization ranges between 1 % and 6 %. The minimum ΔT_{GST} for a given curve is an indicator for the penetration depth of ΔT_{GST} in the 100 years period. Taking for example $\Delta T_{GST} = 3 \text{ K}$, the maximum relative gain from this preexisting GST is obtained for a BHE with borehole length of $H \approx 112 \text{ m}$.

Figure 2c indicates the total power extracted from a single BHE. The power is mainly controlled by H . However, for a given power, elevated ground surface temperature tends to decrease the required BHE length at an approximate rate of 4.5 m for 1 K. For a 2 kW demand (annually averaged) and assuming $\Delta T_{GST} = 0.5 \text{ K}$, for instance, a BHE has to be drilled 80 m. This is reduced to 60 m given a value of $\Delta T_{GST} = 5 \text{ K}$. Note that in practice, planning of appropriate BHE configuration also has to consider high frequencies in the energy demand (daily and hourly loads), which may appreciably

276 increase the required length [69]. These results imply that an optimized use of the stored energy in
277 urban areas can be achieved by combining more shallow BHEs to supply the base demand and
278 fewer deep exchangers for buffering peak loads. An analogous strategy combining exchangers with
279 different lengths is shown in [67] for very deep BHEs ($H > 600$ m).

280 Figure 2d shows the gain on total power (or heat extraction rates) by considering urban ground
281 surface effects relative to the undisturbed base case ($\Delta T_{GST} = 0$). This is the increased technical
282 geothermal potential associated with urban ground warming. For very low ΔT_{GST} , this gain is less
283 than 5 % while it could reach up to 30 % depending on the time lag t_{urb} and the strength of ΔT_{GST} .
284 As expected, the shallower the BHE is, the higher the relative gain in power. For a BHE with 200 m
285 length, this gain for the studied depleting scenario ranges between 5 % and 13 %, even after 100
286 years of urban ground heating.

287 Menberg et al., Benz et al. and Zhu et al. [22, 61, 70] have studied the subsurface urban heat island
288 phenomenon in several German cities. Zhu et al. [61] for instance, specifies for the city of Cologne
289 magnitudes of ΔT_{GST} ranging between 2-4 K in build-up areas and more than 5 K in the city center.
290 Taking into account that downtown cities are generally the oldest areas, the increased geothermal
291 potential of a single BHE with $H = 100$ m could be between 10 % and 25 % higher than in less
292 affected rural environments (Figure 2d). Besides, its inherent spatial variability, ΔT_{GST} changes
293 significantly with time. It is also influenced by multi-scale climate conditions, evolution in land use,
294 surficial characteristics of pavements, and insulation of basements. The increased geothermal
295 potential shown in Figure 2d therefore represents an averaged first-order estimation. Application to
296 a specific site with temporally and spatially variable conditions is demonstrated later in Chapter 3.3.

297 The ratios depicted in Figure 2d depend on the initial thermal conditions, minimum allowed fluid
298 temperature and thermal diffusivity. Considering for instance a representative $\Delta T_{GST} = 4$ K and $H =$
299 100 m, the ratio is around 1.20. If the thermal diffusivity is between 50 % and 200 % of the
300 reference value (Table 1), this ratio could vary between 1.21 and 1.26 for a low $T_k = 8$ °C or
301 between 1.16 and 1.21 for a high $T_k = 12$ °C. This means that within the feasible ranges for
302 diffusivities and non-affected GST in central European cities [70], the ratios in Figure 2d are still
303 robust estimates.

304 3.1.3 Renewable scenario

305 Given the conditions of the previous depleting -scenario, the reservoir will be exhausted after 50
306 years of operation. Of similar interest are the conditions under which an unlimited exploitation in
307 time can be achieved. The analysis is motivated by the response of $\overline{T_{BW}}$ to ground surface
308 temperature effects characterized in Figure 1. Taking for example the curve with $Q_T = 0$, which

309 corresponds to the original g -function that ignores urbanization, it is shown that a ‘renewable
 310 operation’ is feasible approximately for $\ln(t/t_s) > 2$. At these times, axial effects and heat input
 311 from the ground surface compensate the continuous drop in the mean borehole wall temperature as
 312 discussed in [57]. However, reaching this state would require an operation time longer than 260
 313 years for the parameters of Table 1 with $H = 100$ m.

314 As can be seen also in Figure 1, for $Q_T > 0$, i.e. when accounting for urbanization, a sustainable
 315 operation can be achieved from the time when $\overline{\theta_{BW}}$ gets minimal. This minimum is reached earlier
 316 depending on the strength of ΔT_{GST} relative to q (measured through the dimensionless number Q_T).
 317 Figure 3a depicts how this minimum changes as a function of t_{urb} and Q_T . With the lowest $Q_T \approx 0$,
 318 the minimum is reached at $\ln(t/t_s) > 2$ as discussed earlier. However, taking a realistic $\Delta T_{GST} = 4$
 319 K and $q = 20 \text{ W m}^{-1}$, we obtain $Q_T = 0.5$. Then, for $H = 100$ m, the minimum is reached after 32
 320 years for $t_{urb} = 100$ years ($\ln(t/t_s) \approx -0.1$) or even after 12 years if $t_{urb} = 0$ years ($\ln(t/t_s) \approx -$
 321 1.1). The larger t_{urb} is, the longer ΔT_{GST} has been acting before the BHE. Thus, it takes longer for
 322 the line source to balance the positive thermal effect of ΔT_{GST} (see also Figure 1b). However, when
 323 reaching the minimum $\overline{\theta_{BW}}$ faster, this means lower mean borehole temperatures.

324

325 Figure 3: a) Minimum dimensionless borehole temperature, $\min(\overline{\theta_{BW}})$, and associated
 326 dimensionless time $\ln(t/t_s)$, referential absolute magnitudes for time (years) and $\overline{T_{BW}}$ ($^{\circ}\text{C}$) can
 327 be seen in Figure 1b; b) schematic $(\overline{\theta_{BW}})$ (left axis) and corresponding heat extraction rates q
 328 (right axis) for the depleting (qd) and renewable (qr) scenarios. Rates qr are distinguished for
 329 the short term (qr_{st}) and for the long term (qr_{lt}). $Q_T = \lambda \Delta T_{GST}/q$ and t_{urb} is the time lag (in
 330 years) between the start of BHE operation and the pre-existing ΔT_{GST} effect.
 331

332 During simulation, the minimum temperature $\overline{T_{fluid}}$ can be set to the SIA’s temperature threshold,
 333 and the corresponding maximum possible extraction rates can be computed (Eq. (7)). In the

334 following, these rates are called “renewable rates”. The ratios of these rates relative to the
 335 renewable ones obtained from the base case ($\Delta T_{GST} = 0$ K) are shown in Figure 4a. These ratios are
 336 very similar to the ones shown in Figure 2d (depleting operation), especially for $t_{urb} = 100$ years
 337 with values between 1.05 and 1.30. Figure 4a however suggests a lower sensitivity to H that can be
 338 inferred from the depicted gradient, particularly for longer BHEs. This means that for obtaining a
 339 similar ratio as in Figure 2d, a lower ΔT_{GST} is needed under renewable conditions. Still, the absolute
 340 renewable heat extraction rates are generally lower compared to the depleting scenario. This is
 341 summarized in Table 2.

342 After reaching the minimum $\overline{T_{BW}}$, the effect of ΔT_{GST} is more relevant than the rate q , and the
 343 borehole wall temperature increases (Figure 1). Theoretically, it would be possible to further
 344 increase the heat extraction rates (for example by increasing the heating demand associated to the
 345 specific geothermal system) so that $\overline{T_{BW}}$ is kept at the given temperature threshold from that time
 346 on. The resulting heat extraction rate would be constant in time until the minimum temperature
 347 threshold is reached and then the rate could be increased monotonically until it arrives at a
 348 maximum value (Figure 3b). At this maximum, the transient effect of ΔT_{GST} disappears, a new
 349 thermal equilibrium in the ground is reached and $\overline{\theta_{BW}}$ becomes again identical to the original g -
 350 function with $Q_T = 0$. The initial thermal conditions however are now defined by the geothermal
 351 gradient and a new equilibrated ground surface temperature, which is the superposition of ΔT_{GST}
 352 and T_k .

353
 354 Figure 4: Ratio between the renewable heat extraction rates with and without urban effects at: a)
 355 short-term or minimum and b) long-term or asymptote in the mean borehole wall temperature.
 356

357 Figure 4b presents the ratios between the long-term maximum rates and the base case. By
 358 comparing Figure 2d and Figure 4b, it is shown that in the long-term renewable rates are between 5

359 % and 10 % higher than those calculated in the depleting scenario with prescribed life time of 50
360 years.

361 **3.2 Infinite BHE field**

362 Previous analysis reveals the consequence of urban ground heating for single BHE performance, but
363 on the city scale, the concerted use of multiple BHEs has to be accounted for [7, 9, 71]. In such -
364 configurations or fields, the interaction and competition among BHEs may reduce the extractable
365 heat per BHE when compared with a single installation [72]. For estimating the full urban technical
366 geothermal potential, we therefore consider an extreme case, which is an infinite BHE field with
367 borehole spacing B (squared lattice) and length H . This field mimics the idealistic behaviour of a
368 non-optimized large scale exploitation in a city, where all BHEs are similarly operated. These
369 conditions facilitate the simulation through superimposed line sources, which invoke the linearity of
370 the heat transport equation with known or constrained heat extraction rates at the borehole wall [33,
371 37, 73]. Following analysis continues using the parameters of the reference site listed in Table 1.

372 **3.2.1 Depleting scenario**

373 In the first step, the depleting scenario again considers mean fluid temperatures above $-1.5\text{ }^{\circ}\text{C}$
374 during 50 years of operation. Figure 5 depicts the energy densities in kWh per square meter and per
375 year as a function of borehole length or installation depth H , and spacing B . The effect of long-term
376 urbanization prior to BHE installation is included by assuming $t_{urb} = 100$ years. Figure 5a
377 represents conditions of low ground heating of $\Delta T_{GST} = 1\text{ K}$, which could be found for example
378 beneath green spaces [22]. In comparison, a stronger ground heating of $\Delta T_{GST} = 5\text{ K}$ is depicted in
379 Figure 5b. As expected, in both figures, the highest energy densities are obtained for the deepest
380 and more packed configurations.

381 For a separation of 30 m between standalone installations, for instance, Figure 5b gives energy
382 densities between 13 and 33 kWh m⁻² a⁻¹ depending on the field depth. Taking the referential
383 heating energy demands specified in Schiel et al. [7] for city buildings (between 102.3 and 207.1
384 kWh m⁻² a⁻¹), this would imply that for $H = 200\text{ m}$, the shallow ground could supply between 32 %
385 (33/102.3) and 16 % (33/207.1) of these energy requirements for 50 years.

Figure 5: Energy densities ($\text{kWh m}^{-2} \text{a}^{-1}$) for the infinite field with $t_{urb} = 100$ years under the depleting scenario: a) $\Delta T_{GST} = 1$ K and b) $\Delta T_{GST} = 5$ K

In this depleting scenario where the calculation time is fixed ($t = t_{urb} + 50$ years), the ratio between energy densities, affected and unaffected (base case) by ΔT_{GST} , is independent of the separation B . Thus, the estimated increased technical geothermal potential computed for single BHE installations (Figure 2b, d) is also valid for the infinite field.

3.2.2 Renewable scenario

Renewable use refers to heat extraction that does not only guarantee regulatory limits (here minimum of -1.5 °C for heat carrier fluid) for a given time (here 50 years), but also beyond. As shown for single BHE operation (Chapter 3.1.3), continued reservoir depletion is associated with advancing replenishment, and ultimately ground heat flux can stimulate thermal recovery.

For a BHE in a field, the corresponding mean borehole wall temperature $\overline{\theta_{BW}}$ behaves similarly to the one shown in Figure 1a for a single BHE and $Q_T = 0$, but with lower magnitudes due to the interference with neighboring BHEs. The time for reaching renewable operation conditions in the base case (i.e., the curve's plateau) is also higher since influences from distant BHEs extend the transient behavior.

The effect of including an increased ground surface temperature is shown in Figure 6. The energy densities are lower and clearly different from those in Figure 5 (depleting scenario). In the latter, the highest energy density is obtained with a deeper field, while in the renewable scenario, the shallowest field is favored. This is due to the unconstrained exploitation time under renewable conditions. To fulfil this, the system is forced to take more heat from increased GST rather than

410 depleting the reservoir. In both exploitation schemes the maximum in energy densities are obtained
 411 for the most packed fields.

Figure 6: Energy densities ($\text{kWh m}^{-2} \text{a}^{-1}$): a) $\Delta T_{GST} = 1 \text{ K}$, b) $\Delta T_{GST} = 5 \text{ K}$, c) ratio of renewable rates with $\Delta T_{GST} = 1 \text{ K}$ with respect to the renewable base case and d) ratio of renewable rates with $\Delta T_{GST} = 5 \text{ K}$ with respect to the renewable base case.

417 Figure 6a depicts the case of $\Delta T_{GST} = 1 \text{ K}$ with minor heat flux. The ratio between these densities
 418 and those from the base case ($\Delta T_{GST} = 0 \text{ K}$) is depicted in Figure 6c, and urbanization here yields up
 419 to 8 % higher densities, and consequently, extraction rates. An increased ground surface
 420 temperature of 1 K might be associated with a loose and open development in suburban areas.
 421 Taking again the energy heating demands specified in [7] for this type of settlement (57.7 kWh m^{-2}
 422 a^{-1}), the results indicate that it would be possible to supply between 14 % - 17 % of this demand in a
 423 renewable way. To accomplish this, BHEs of around 100 m long are required with a separation
 424 between 20-30 m.

425 Figure 6b depicts the other extreme: renewable energy densities for $\Delta T_{GST} = 5 \text{ K}$, such as is
 426 common in many city centers. By relating to the densities in the base case, Figure 6d indicates that

the renewable rates in the city center would be between around 30 % - 40 % higher than outside the city.

From the comparison with the depleting densities shown in Figure 5b, it can be concluded that the latter are between 25 % - 65 % higher. The value of 25 % refers to the most shallow and packed fields, and 65 % to the deepest and more spread fields. A related analysis is presented in Table 2 in terms of absolute heat extraction rates (W m^{-1}) for both exploitation scenarios and different system configurations. In general, for single BHEs the SIA's requirements seem to be a good guideline to ensure renewability since discrepancies to the depleting scenario are not significant. For the infinite field however, the situation is different especially for longer systems. Under non-urbanized conditions ('Base case' in Table 2) for example, depleting rates could be about six times higher than the renewable ones ($H = 200$ m and $B = 20$ m). This difference declines with shallower systems and stronger urban effect (ΔT_{GST}) reaching values between 1.19 and 1.40 for $H = 50$ m and $\Delta T_{GST} = 5$ K.

Table 2: Heat extraction rates (W m^{-1}) for a single ($B = \infty$) and a representative BHE in an infinite field for different degrees of urbanization and exploitation schemes, and $t_{urb} = 100$ years. R: renewable scenario, D: depleting scenario.

		Base case		Low development		Suburban		Urban	
		$\Delta T_{GST} = 0$ K		$\Delta T_{GST} = 1$ K		$\Delta T_{GST} = 3$ K		$\Delta T_{GST} = 5$ K	
H (m)	B (m)	R	D	R	D	R	D	R	D
50	10	3.9	5.8	4.2	6.2	4.8	6.9	5.5	7.7
	20	10.6	14.7	11.4	15.6	13.1	17.6	14.8	19.4
	30	16.0	20.0	17.3	21.3	19.8	23.9	22.4	26.5
	∞	25.4	25.5	27.2	27.2	30.5	30.5	33.9	33.9
100	10	1.4	3.3	1.5	3.5	1.7	3.8	1.9	4.1
	20	4.1	10.1	4.4	10.6	5.0	11.6	5.6	12.6
	30	7.5	15.9	8.1	16.7	9.2	18.2	10.3	19.8
	∞	24.7	25.3	26.2	26.5	28.8	28.9	31.3	31.3
200	10	0.6	2.8	0.6	2.8	0.7	3.0	0.7	3.1
	20	1.5	8.9	1.6	9.2	1.8	9.6	2.0	10.1
	30	2.9	14.9	3.1	15.3	3.4	16.1	3.8	16.9
	∞	25.4	27.1	26.7	27.8	28.7	29.2	30.4	30.6

Finally, it is interesting to compare the energy densities of Figure 6b with the corresponding heating energy demand in urban settlements (between 102.3 and $207.1 \text{ kWh m}^{-2} \text{ a}^{-1}$) [7]. For the most optimistic scenario ($B < 10$ m, $H < 60$ m), it would be possible to supply 13 - 27 % (in a renewable way) of the heating demand associated with settlements, such as downtown city buildings. For more realistic BHE separation of $B = 20\text{-}30$ m, this percentage would be only between 6 % and 16 %. These numbers of course are restricted to the parameters of the presented case study (Table 1).

3.3 Case study

This case study aims at demonstrating the applicability of the methodology at a real site with specific (time dependent) land use distribution. It does not only include the effect of elevated heat flux from urban structures, but also atmospheric warming due to long-term climate change. The site is located in the suburb of Meilen in the city of Zurich (Figure 7a), where a temperature-depth profile (TDP) was measured prior to BHE operation (Bayer et al. [21]). For this site, Figure 7b shows the most influential urban structures that can be classified as buildings (B) or pavements (A). Most of the buildings were built within the period between 1959-1972. However, three on the west side (B17-B19) date back to 1884. The streets are also rather old with an age of more than 100 years.

Figure 7: a) Plan view of the site as of 2005 [74] and b) influencing buildings (B) and pavements (A). The lighter orange areas surrounded by dashed lines represent buildings demolished in 1959, whose thermal influence is included in the simulation. The red point indicates the BHE location (more details in Bayer et al. [21]).

By superposing non-homogeneous solutions for the conductive-dominated problem, Bayer et al. [21] reproduced the measured TDP (Figure 8a). Their procedure was based in a stochastic inversion that yielded estimations of the ground surface temperature of pavements and buildings. Their methodology was also capable of differentiating between the thermal influences due to climate forcing and the identified urban structures.

Figure 8: a) Measured and simulated temperature-depth profile (TDP) in the case study (Bayer et al. [21]), and b) surface air temperature (SAT) in the nearby site.

For the estimation of the increased technical potential, this work considers a BHE installed at the measuring point starting operation in 2005 (same year as the measurement). The mean temperature at the borehole wall is obtained by superposing Eq. (4) (for each urban structure) to the background effect representing undisturbed green space. According to Bayer et al. [21], the ground surface temperature for green open spaces and pavements is a function of the surface air temperature (SAT). The latter has been known for the last 130 years with a daily resolution. However, it is necessary to fit an analytical expression in order to extrapolate SAT during the operation time (2005 onwards). The fit curve is shown in Figure 8b and follows a logistic model with a maximum of 10.5 °C in 2100.

For different borehole lengths, Figure 9a depicts the extractable mean annual heat extraction rates under depleting conditions ($\overline{T_{fluid}} = -1.5$ °C after 50 years). Figure 9a distinguishes two different cases on its left axis: base case without increased ground surface effects (N) and the total effect including urban structures (N+U). On the right axis of Figure 9a, the rate ratio (N+U)/N is indicated. For $H = 100$ m for example, the total increased GST effect (N+U) allows to extract up to 18 % more energy than in the base case (N).

Figure 9: a) Depleting heat extraction rates in the case study for different scenarios: base case (N) and total GST effect (N+U); b) ratio renewable/depleting rates (left axis) and time to reach short term renewability (right axis).

Figure 9b shows the ratios between renewable and depleting rates (left axis), as well as the times to reach renewability (right axis). The results indicate that there are not significant differences between the exploitation schemes. This is a consequence of installing a single BHE in an environment with pre-existing warming and agrees with the previous discussion on renewability for single BHEs (Chapter 3.1.3 and Table 2). According to Figure 9b, with a BHE of around 145 m length, given the SIA requirements, renewable operation after 50 years is feasible.

503 4 Summary and conclusions

504 This study addresses two major aspects when operating borehole heat exchangers (BHEs) in urban
 505 environments. First, it is revealed that the technical geothermal potential of utilizing urban ground
 506 can be substantially higher (up to 40 %) than in rural, open green spaces. This is due to urban
 507 ground warming, caused by heat loss and accelerated heat flux from urban structures, which are
 508 characteristic for many cities worldwide. Second, it is demonstrated how urban ground warming
 509 enhances the renewal of BHEs operated in unbalanced way. For this, ground energy exploitation,
 510 within a given time to a given temperature threshold, is compared to long-term renewable operation.

511 A summary of the increased technical potential when comparing feasible heat extraction rates in
 512 cities to those in the rural surrounding is provided in Table 3. These values are obtained by taking
 513 the ratio of heat extraction rates under different degrees of urbanization divided by the
 514 corresponding ones of the non-perturbed base case as listed in Table 2. The increased technical
 515 potential is clearly dominated by the relative ground heating, ΔT_{GST} , while borehole length H and
 516 separation B have a secondary role. As expected, the increased potentials are higher for shallower
 517 systems. For highly urbanized conditions ($\Delta T_{GST} = 5$ K), full exploitation rates increase by 13 – 33
 518 %, and renewable rates by even 19 – 40 %. However, note that the absolute renewable rates are
 519 generally lower (Table 2). In essence, this means that either higher energy extraction is feasible in
 520 urban ground, or the borehole length can be reduced. As a rough estimate, each additional degree of
 521 ground heating saves 4 borehole meters.

522 Table 3: Increased technical geothermal potential for single ($B = \infty$) and the representative BHE
 523 in an infinite field for different degrees of urbanization and exploitation schemes and $t_{urb} = 100$
 524 years. R: renewable scenario, D: depleting scenario.

		Low development		Suburban		Urban	
		$\Delta T_{GST} = 1$ K		$\Delta T_{GST} = 3$ K		$\Delta T_{GST} = 5$ K	
H (m)	B (m)	R	D	R	D	R	D
50	10	1.08	1.07	1.24	1.20	1.40	1.33
	20	1.08		1.24		1.40	
	30	1.08		1.24		1.40	
	∞	1.07		1.20		1.33	
100	10	1.08	1.05	1.22	1.14	1.37	1.24
	20	1.08		1.22		1.37	
	30	1.08		1.22		1.37	
	∞	1.06		1.17		1.27	
200	10	1.07	1.03	1.20	1.08	1.30	1.13
	20	1.07		1.20		1.32	
	30	1.07		1.20		1.33	
	∞	1.05		1.13		1.19	

Table 4 summarizes, what share of the urban heating energy demand (according to [7]) can be covered by operating BHEs in an infinite field. In (sub)urban areas, 4 – 16 % of the heating demand could be supplied in a renewable way. Apparently, towards the city center the energy demand grows more than the stored geothermal energy. Since replenishment comes mainly from the ground surface, here shallower systems are favorable. However, when full reservoir exploitation is considered, values of up to 40 % can be achieved by deep boreholes of up to 200 m. Not only the accessed ground volume but also the ground heat flux may be decisive for the appropriate borehole depth and configuration. As another example, consider depleting exploitation of warmed urban ground ($\Delta T_{GST} = 5$ K). Here, the extractable energy is similar for $H = 50$ m and 100 m, as reflected by the similar shares of around 20 % listed in Table 4 ($B = 10$ m). This is a consequence of the competing effect between accelerated ground heat flux and the geothermal gradient. Considering the highest magnitudes of ΔT_{GST} with $t_{urb} = 100$ years, installing a BHE field with $H = 100$ m is not likely the best strategy, since almost the same power can be extracted with a shallower system that takes advantage of the cumulated urban heat. However, for longer BHE fields ($H = 200$ m) the geothermal gradient dominates and the energy yield is enhanced.

Table 4: Share of the heating demand supplied by an infinite BHE field for different degrees of urbanization and exploitation schemes and $t_{urb} = 100$ years. The considered heating demands (in kWh m⁻² a⁻¹) are as follows [7]: 60 for low development areas, 130 for suburban areas and 170 for city centers. R: renewable scenario, D: depleting scenario.

		Low development		Suburban		City center	
		$\Delta T_{GST} = 1$ K		$\Delta T_{GST} = 3$ K		$\Delta T_{GST} = 5$ K	
H (m)	B (m)	R	D	R	D	R	D
50	10	32 %	47 %	16 %	23 %	14 %	20 %
	20	22 %	30 %	11 %	15 %	10 %	12 %
	30	15 %	18 %	7 %	9 %	6 %	8 %
100	10	22 %	53 %	11 %	26 %	10 %	21 %
	20	17 %	40 %	8 %	19 %	7 %	16 %
	30	14 %	28 %	7 %	14 %	6 %	11 %
200	10	18 %	86 %	9 %	40 %	8 %	32 %
	20	12 %	69 %	6 %	32 %	5 %	26 %
	30	10 %	52 %	5 %	24 %	4 %	19 %

The findings presented here are crucial for planning geothermal systems in regions with elevated ground temperatures. Such subsurface urban heat islands, however are not only caused by heat loss from basements and accelerated heat flux through paved ground. In cities, there exist several additional sources such as sewage channels, district heating systems or tunnels. Aside from this, long-term atmospheric warming has to be accounted for. All these factors countervail ground

550 cooling from geothermal energy use, and thus facilitate renewable operation without active
551 replenishment. Strictly speaking, however, we do not tap a naturally renewable energy source. In a
552 nutshell, shallow geothermal systems recycle urban ground heat losses.

553

554 **Acknowledgements**

555 This work was supported by the Swiss National Science Foundation (SNSF) under grant number
556 200021L 144288, and the German Research Foundation (DFG), under grant number BL 1015/4-1.
557 We thank Rachael Colldeweih for language corrections.

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