The geothermal potential of cities

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ABSTRACT

What is the heat beneath our feet? There is a growing interest in the geothermal resources available at shallow depth beneath cities. However, there exists no general procedure for quantifying the low-temperature geothermal potential in urban ground and groundwater. This review categorizes previous work based on different definitions of the geothermal potential and compares the different assessment methods used. It is demonstrated that the theoretical potential of the available heat at a shallow depth is enormous, especially when not only the heat in place, but also compensating heat fluxes are considered. The technical potential describes the extractable heat by a specific technology. The methods to evaluate the extractable heat are manifold, including the use of technical performance standards, analytical and numerical simulation tools and mathematical regression procedures. These are different for groundwater well based open-loop systems and heat-exchanger-based closed loop systems, and the results depend on variable local factors, the density of systems applied and whether heat and/or cold is utilized. We contrast the published findings based on the power density and the relative contribution to the demand of a city. The broad span of the results highlights the need for a more consistent framework that distinguishes between the conceptual assumptions for calculating the technical geothermal potential and the local city-specific factors. This will be the basis for a reliable analysis of the economic geothermal potential of low-temperature geothermal applications on a local, district or city scale. This will also enhance the reliability and the trust in these technologies, and thus the public acceptance reflected in the acceptable geothermal potential.

1. Introduction

In this study, we focus on low-temperature geothermal energy which is known to provide a robust, decentralized and renewable energy source for cities [1]. Special interest is in the direct use of the endogenic geothermal resources accessible at shallow depths beneath cities, which is broadly discussed to offer a great potential for decarbonisation of the heating sector [2–6]. Continuously increasing numbers of shallow geothermal installations during the last decades demonstrate growing relevance, but the simultaneously increasing density of installations in residential areas exhibits also a potential for conflicts. This means a rising challenge for regulators and city planners, who have to balance optimal use and minimum interference between neighbouring installations [7–12]. In fact, despite an overall good knowledge of physical processes acting in the ground, such as heat transfer in soil and the dynamics of groundwater in porous media [13,14], the long-term impacts of diverse coexisting geothermal devices on ground and groundwater are not fully understood yet. On the one

hand, this lack of knowledge can stimulate a highly precautionary attitude and a strict regulation, in which case the geothermal potential of cities remains underused [15]. On the other hand, the lack of knowledge may promote ignorance of ground thermal evolution, which generates under-regulated use of shallow geothermal energy with a high risk of interference between neighbouring installations.

Another barrier for progress in urban geothermal energy use is the concurrent need of the urban subsurface as a freshwater resource and for vertical infrastructure development. As urban underground space is acknowledged to be rich in diverse resources, such as in geomaterials, geothermal energy and drinking water [16–18], it plays a fundamental role in urban development [19]. Until now, however, urban underground regulations and utilization strategies do rarely consider the potential and consequences of managing the combined use of different resources [20]. Consequently, this leads to a lack of coordination and non-sustainable exploitation of urban underground space, illustrated by conflicts of use detrimental to different compartments of urban underground space [21,22].

A premise of integrating geothermal energy use in both urban management plans and modern concepts of underground space management is understanding its potential. During recent years, research on thermal conditions beneath cities has made great progress, offering multifaceted insights into crucial processes and governing factors in urban subsurface environments worldwide [23–29]. However, there exists a heterogeneous understanding of the relevance of the geothermal potential, which is often interpreted in different ways depending on the scope of a specific case study.

The present work reviews previous studies on the shallow geothermal energy situation in cities, and based on this provides a refined understanding of the urban geothermal potential. A consistent definition is considered elementary for funnelling the widespread, diverse knowledge of subsurface urban energy reservoirs. This will finally support the optimization of integrated and holistic urban geothermal energy management. In the following, after describing the specific geothermal conditions beneath cities, the main shallow geothermal technologies are shortly introduced. This leads to a hierarchical definition of geothermal potential, which is based on environmental, technical, economic and acceptance principles. In an outlook, we discuss the future needs for a more consistent assessment and thus optimal utilization of this often still untapped resource underneath us.

2. Urban geothermal conditions, processes and technologies

2.1. Shallow geothermal systems

Shallow geothermal ground and groundwater use typically focuses on the top hundreds of meters, and it is realized as closed- and open-loop systems [14,30,31] (Fig. 1). Mostly, these geothermal applications extract energy for running a heat pump and supplying the heating system of buildings. In many cities, however, cooling with the ground as a source for cold is of growing interest [32].

Closed-loop systems are most frequently applied, and here the principle is ground heat exchange by circulating a heat carrier fluid through tubes installed in horizontal collectors, vertical boreholes or energy piles. Ground source heat pump (GSHP) systems with horizontal ground heat exchangers (GHE) (Fig. 1a), are usually very shallow systems (< 5 m depth), used in the framework of individual dwellings. GSHPs with vertical borehole heat exchangers (BHEs, Fig. 1b) access depths of tens to several hundreds of meters. These represent the by far most popular technological variants, implemented as single or multiple BHEs. Energy piles (Fig. 1c), are vertical heat exchangers incorporated in foundation piles and thus limited to new buildings.

Open-loop systems (Fig. 1d, f), such as groundwater heat pump systems (GWHPs), utilize the groundwater directly as a heat carrier, which is more efficient for energy transfer, but only feasible when productive aquifers can be accessed. Most installations are based on a well-doublet scheme in a shallow aquifer including an extraction well, which pumps groundwater, and an injection well where the cooled or warmed water is injected back into the same aquifer at the same rate, but at a different temperature. The depth of the wells is typically less than 50 m [14,33].

An installation that permanently extracts energy from the ground relies on natural replenishment, which is limited by the slow heat diffusion in porous media. Aside from this, heat advection caused by groundwater flow can accelerate replenishment, but also spread the thermal anomalies induced in the ground. The ideal way of utilizing shallow geothermal energy is a hybrid use for heating and cooling. Among these, borehole thermal energy storage systems (BTES) are closed-loop applications of multiple BHE fields, while aquifer thermal energy storage systems (ATES) operate wells (Fig. 1e, f).

For planning single BHEs and multiple BHE-fields, and to some extent for open systems, planning tools are available and a considerable amount of literature exists on suitable modelling and spatial planning techniques (e.g. [14,34]). However, there are no established planning tools that integrate such systems into an urban energy plan [35,36].
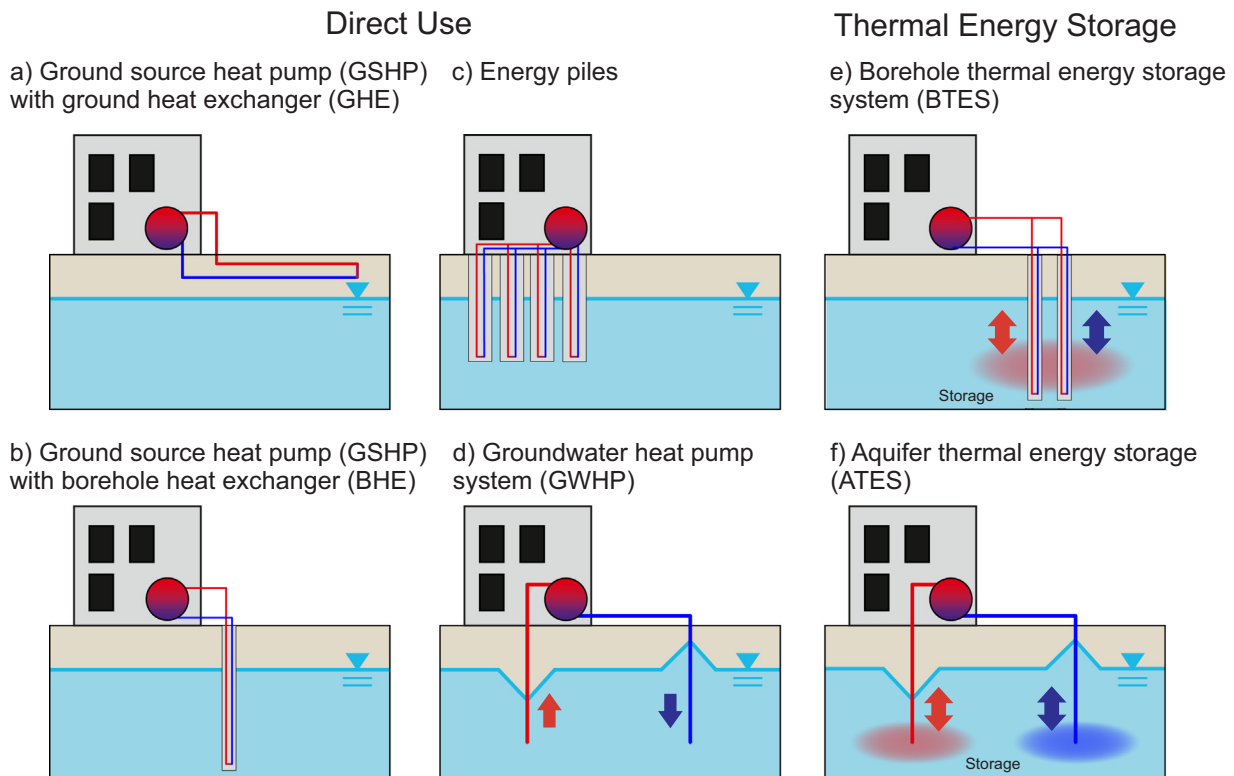

Direct Use

a) Ground source heat pump (GSHP) with ground heat exchanger (GHE)

c) Energy piles

b) Ground source heat pump (GSHP) with borehole heat exchanger (BHE)

d) Groundwater heat pump system (GWHP)

Thermal Energy Storage

e) Borehole thermal energy storage system (BTES)

Storage
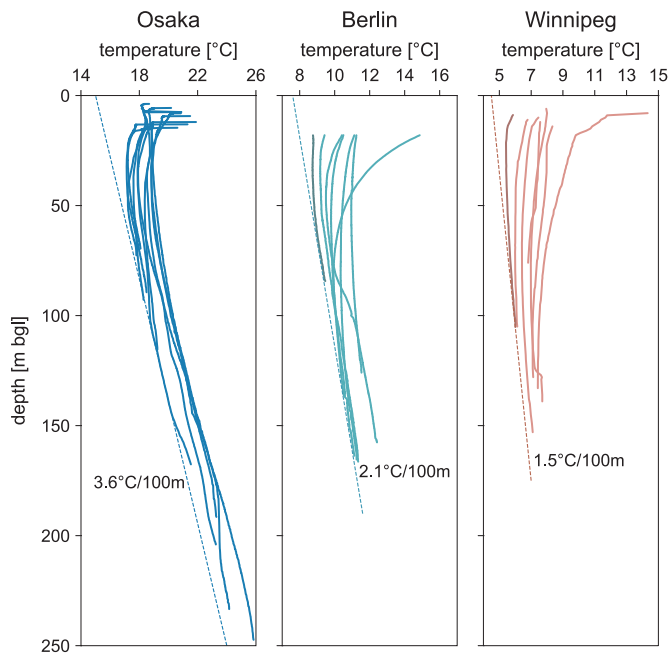
f) Aquifer thermal energy storage (ATES)

Storage

Fig. 1. Technological variants of shallow geothermal use in urban aquifers.

Fig. 2. Exemplary borehole temperature profiles recorded at different locations in the cities of Osaka, Japan [41], Berlin, Germany and Winnipeg, Canada [53]. The undisturbed geothermal gradient estimated based on the deep temperature measurements is indicated by the dashed lines. The darker bold lines represent temperature profiles from rural areas that reflect temperature increase due to climate change (not available in Osaka).

2.2. Thermal regime beneath cities

The temperature of shallow ground is closely linked to the conditions in the atmosphere [37,38]. With a much higher heat capacity and lower diffusivity, the ground conserves temporal trends in atmospheric temperature. Seasonal temperature variations at the ground surface follow those in the air and are measurable as dampened signals down to around 20–30 m (Fig. 2). Deep borehole temperature profiles follow roughly the ambient geothermal gradient of around 3 °C/100 m, but in the top 100 m typically flatten out due to the recently augmented conductive heat flux from above (Fig. 2). Towards the ground surface, groundwater dynamics and seasonal influences are typically reflected in bumpy temperature profiles with distinctive vertical trends [14,39–41].

When temperature measurements are taken close to settlements or in urban environments, the thermal conditions in the ground are often significantly modified. Human encroachment and land use change in cities induce large-scale thermal anomalies in the ground, which are called subsurface urban heat islands (SUHIs). Borehole temperature profiles delineate the accumulated energy by characteristic trends, where the urban heating induces a growing temperature towards the surface (Fig. 2).

During recent years, city-wide soil and groundwater temperature monitoring programs and measurement campaigns in urban soil and groundwater revealed that subsurface warming is common beneath built-up areas. Extensive SUHIs were mapped beneath big metropolitan agglomerations such as Tokyo [39], Berlin [42], London [43], Moscow [44], Barcelona [45], as well as in smaller cities such as Karlsruhe, Cologne [25], Oberhausen [46], Lyon [29], Basel [47], Turin [48,49], Zaragoza [50,51] and Winnipeg [52,53]. Regional surveys in Asia (e.g. [27,39,54,55]), Europe (e.g. [23,42,56–58]) and North America (e.g. [40]) have documented large-scale urban subsurface temperatures between 2 and 6 K higher than in the less affected countryside (Fig. 3). Local anomalies are even more pronounced, for instance, beneath car parks or close to buried district heating systems [42].

Available studies that investigate factors and mechanisms of urban
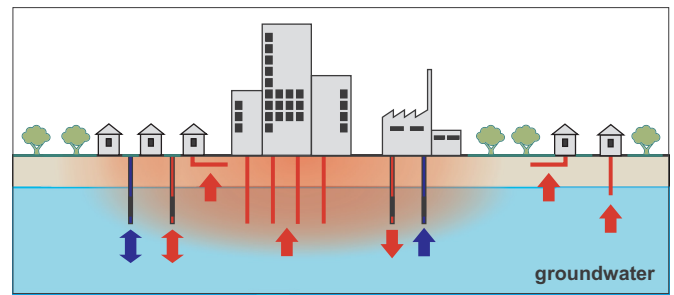
Fig. 3. Schematic representation of a subsurface urban heat island (SUHI) with different geothermal systems in operation.

subsurface warming can be roughly differentiated into those that focus on local or site-specific phenomena, and those that examine SUHI driving forces on a city scale. Among these are thermal pollution by wastewater [59], ground heating effects from asphalt [60,61], heat release from basements of buildings [29,62], thermal effects from tunnels [63], geothermal energy exchange [64,65], and case-specific impacts from brickworks [56]. For investigating causes of large-scale manifestations of SUHIs, comprehensive monitoring programs have been conducted for example in several German cities [25,66,67], which revealed the dominant heat flux from paved ground and buildings on the city scale. This is supported by estimations from Ferguson and Woodbury [52] based on their survey in Winnipeg and Attard et al. [29] in Lyon. The studies by Taniguchi et al. [68,69] in Osaka, Tokyo, Seoul and Bangkok and Headon et al. [43] in London highlighted the role of groundwater abstraction and the induced changes in the flow regime.

A variety of modelling concepts have been presented to simulate the disturbed thermal conditions in urban ground. A common choice are one-dimensional (1-D) analytical and numerical models for scrutinizing the role of land surface effects on temperature-depth profiles (e.g. [66,69,70]). Ferguson and Woodbury [52] inspected the heat release from basements of buildings via vertical two-dimensional (2-D) numerical models. Rivera et al. [71] and Bayer et al. [60] demonstrated the use of superimposed analytical models for transient simulation of the thermal impact from asphalted streets and buildings. Numerical models are attractive for complex conditions that cannot be reliably simulated by analytical models, and when sufficient data is available for robust calibration. For example, Epting and Huggenberger [47] used a three-dimensional (3-D) numerical flow and heat transport model for Basel, Switzerland.

A major challenge is the transferability of findings from one city to another one, which is difficult and sometimes impossible due to the characteristics of past urban development, land use and subsurface management, as well as the climatic, geographical, geological and hydrological conditions unique for each case. However, generally valid results and a profound physical understanding of the mechanisms are needed to estimate ground thermal development also in cities that are not studied in similar detail. Recently, correlations between satellite-derived land surface temperatures and soil [72] or groundwater temperatures [24,73] could be identified. Such easily accessible remotely sensed data could serve as a basis for the first-tier estimation of any city´s subsurface thermal regime.

The thermal footprint of cities has a wide range of impacts, changing not only the engineering properties of urban soils [74], but the rising temperatures are also critical for in-situ ecosystems [5,75], contaminant transport in groundwater [51,76,77] and they compromise the use of ground-based heat sinks for the mitigation of atmospheric urban heat islands. Last but not least, it determines the efficiency of shallow geothermal energy use: on the one hand, SUHIs provide the opportunity for exploiting geothermal resources for heating, and on the other hand, warming of the urban subsurface is liable to deteriorate the performance of geothermal systems operating in cooling mode.

3. Urban geothermal potential

The term "geothermal potential" is often used, but with dissimilar meanings. Mostly, it is determined by spatial mapping of geothermal resources [78,79], and quantified by energy, energy per area, volume or time, or assessed by ranking schemes [80,81]. For introducing the definition of the urban geothermal potential, we refer to Rybach [82], who suggested hierarchical categories of geothermal potential in general, which are oriented at common taxonomies used for other renewables [83–85]. The total physically available energy determines the all-embracing "theoretical potential". The next sub-category, the "technical potential", is the portion of the theoretical potential that can be harnessed by available technologies. As only part of the technically extractable energy is economically reasonable, this fraction is defined as "economic potential".

There are different additional sub-classifications available, and Rybach [82] suggests to distinguish further the "sustainable potential" and finally, as part of this, the "developable potential". The sustainable potential is introduced to highlight that long-term use of geothermal resources often means depletion, while lower production rates than economically reasonable can alleviate or avoid depletion. The developable potential accounts for regulations and environmental restrictions and represents the smallest fraction embedded in all other potentials. We slightly update the available classification in order to reflect that a hierarchical structure is not always suitable (Fig. 4). In particular, there is a fraction of energy that does not offer direct economic benefits, but still, its development may be reasonable by specific regulations and/or offer environmental benefits. This is defined as "acceptable potential".

In the following, the meanings of the different potential categories are described separately, and previous works dedicated to each potential of shallow geothermal energy utilization are reviewed. Table 1 lists the most relevant studies and their scopes. This table and the subsequent description also includes studies on regional geothermal potential and areas involving rural regions. These are added for including and comparing related concepts for geothermal potential assessment, which may be suitable also for estimation of the urban geothermal potential.

3.1. Theoretical potential

The theoretical potential is defined in most cases as the total energy E (kJ) stored in a reservoir [81,82]. This heat in place can be calculated for a given reservoir volume, V, based on the caloric equation of state:

$$E = [nc_w + (1 - n)c_s]V\Delta T \tag{1}$$

where n is the porosity, c_w and c_s (kJ m^{-3} K^{-1}) are the volumetric heat capacities of groundwater and solid, and ΔT (K) is the induced temperature change or increment. In further detail, $\Delta T = T_0 - T_1$, where T_0 is the undisturbed ground temperature and T_1 the target temperature.
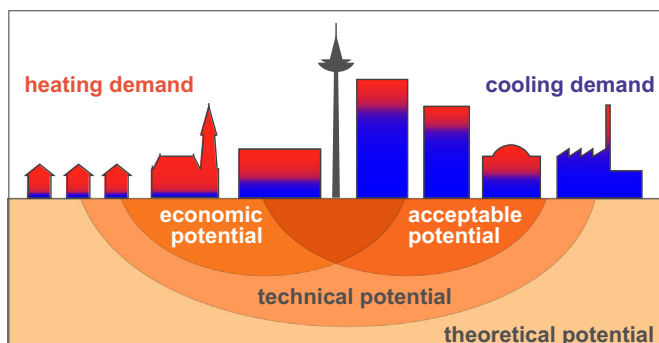

Fig. 4. Illustration of the order of categories of geothermal potential beneath cities.

The theoretical potential of other renewables is much more fluctuating than the geothermal potential, which makes it an appealing complementary choice for the provision of baseload energy. However, while the thermal regime in the ground might be tardy, it is not static. As a hypothetical volume V of the ground is not an enclosed system, but open to lateral fluxes, a refined definition of the theoretical potential is the theoretically available energy from a reservoir over a timespan, including heat storage and recharge.

The heat recharge through the base of a given ground volume can be determined from the geothermal gradient, but this gain is typically compensated by a similar release of heat to the atmosphere. For undisturbed ground, annual heat gains and losses are balanced. In the case of direct anthropogenic disturbance, such as accelerated urban subsurface heating in SUHIs or active groundwater use, the shallow ground represents a complex transient thermal regime. Finally, the available energy over time will also depend on the geothermal technology operated: As continued energy extraction causes accelerated heat flux towards the reservoir, strictly speaking, this increases the heat recharge for a given time and thus also the theoretical potential [71,86].

The natural heterogeneity of rocks, and the uncertainty in the description of the relevant physical ground properties are crucial factors that only allow an approximation of the theoretical potential. The short-term and long-term thermal changes, especially beneath cities, complicate an accurate estimation of the recharge component. Thus, most previous studies on the theoretical geothermal potential are based on simplifying assumptions to facilitate large-scale energy potential (J) or potential density (J/m^2) mapping. For example, Kastner et al. [101] computed the heat in place deep beneath the region of Berlin, Germany. Detailed 3-D geological maps were used to characterize the geological structure and physical properties of several sedimentary formations down to 4–5 km. This delivered projected maps of energy density for each formation. The study by Zhu et al. [88] was focused on the additional heat in place caused by SUHIs in aquifers of Cologne in Germany, Winnipeg in Canada, and other cities. Their work reveals that the theoretical potential of the accumulated "urban" heat in comparison to the colder rural surrounding would be sufficient to meet the cities' heating demand for years. For the cities London and Beijing, Zhang et al. [90] calculated the heat in place within the first 150 m below the ground surface by a given temperature change of $\Delta T = 4$ K and 6 K.

The heat in place is considered as a basis for calculation of technical potential [102–104], but more detailed quantifications of theoretical potential under transient conditions are rare. Benz et al. [66] built upon the work of Zhu et al. [88] and compared estimated annual urban groundwater heat gains for the German cities of Cologne and Karlsruhe with the accumulated heat in place (assuming a $\Delta T = 4$ K). The heat gain was computed based on 1-D vertical heat flux models that account for the various sources of SUHIs at the ground surface but neglect transient effects [25]. Thus, the estimated heat gain appeared relatively high, with a median anthropogenic heat gain of 2.1 PJ for Karlsruhe and 1.0 PJ in Cologne. For the city of Osaka, Benz et al. [41] derived the vertical heat input into the shallow groundwater from borehole temperature profiles and compared it with changes in the thermal regime observed from 2003 to 2011. Also here, a significant fraction of the computed mean heat gain of 500–750 W/m^2 was not stored at the measured well sites. More insight into transient heat transport effects, simultaneous heat losses, expansion of the prevailing SUHI and lateral transport by groundwater are needed for a closed heat balance calculation.

Instead of the heat in place, Epting et al. [86] chose the volumetric Darcy flow rate Q_D of the shallow groundwater beneath Basel, Switzerland, computed by a numerical model. By simulating the spatial temperature distribution of the SUHI, Q_D and ΔT could be spatially resolved and the theoretical potential E_{GW} provided by the groundwater could be mapped:

$$E_{GW}(t) = Q_D c_W \Delta T t \tag{2}$$

Table 1
Scope of selected available studies on the geothermal potential of (mostly) urban subsurface.

Authors	Potential	Location	Spatial scale	Use mode	Technology	Interference
Doyle [87]	theoretical	St. Antonio (USA)	urban	heating	not defined	n/a
Zhu et al. [88]	theoretical	Cologne/Winnipeg, etc.	urban	heating	not defined	n/a
Mueller et al. [89]	theoretical	Basel, Switzerland	urban, districts	heating	not defined	yes
Epting et al. [86]	theoretical	Basel, Switzerland	urban	heating	not defined	yes
Zhang et al. [90]	theoretical	London/Beijing	urban	heating	not defined	n/a
Zhang et al. [90]	technical	London	district, plots	heating (cooling)	BHE	yes
Alcaraz et al. [91]	technical	Azul city (Argentina)	district, plots	heating	BHE	yes
Miglani et al. [36]	technical	Zurich, Switzerland	district, plots	heating	BHE	yes
Casasso and Sethi [92]	technical	Province of Cuneo, Italy	rural, urban	heating, cooling	BHE	no
Alcaraz et al. [93]	technical	Barcelona, Spain	district	heating, cooling	BHE	no
Garcia-Gil et al. [45]	technical	Barcelona, Spain	urban	cooling	BHE	no
Ondreka et al. [79]	technical	SW-Germany	rural	heating	BHE	no
Munoz et al. [94]	technical	Santiago Basin, Chile	rural, urban	heating	BHE	no
Galgaro et al. [95]	technical	Southern Italy	rural, urban	heating, cooling	BHE	no
Santilano et al. [96]	technical	Western Sicily, Italy	rural, urban	heating, cooling	BHE	no
Buday et al. [97]	technical	Debrecen, Hungary	rural, urban	heating, cooling	horizontal collectors	n/a
Garcia-Gil et al. [45]	technical	Barcelona, Spain	urban	cooling	GWHP	no
Pujol et al. [98]	technical	Perth Basin, Australia	urban	heating	GWHP	no
Munoz et al. [94]	technical	Santiago Basin, Chile	rural, urban	heating	GWHP	no
Allen et al. [99]	technical, economical	Ireland	rural, urban	heating, cooling	GWHP	no
Rivera et al. [65]	technical, acceptable	Zurich, Switzerland	urban	heating	BHE	yes
Schiel et al. [35]	technical, acceptable	Ludwigsburg, Germany	urban	heating	BHE	no
Arola and Korkka-Niemi [23]	technical, acceptable	Turku/Lohja/Lahti, Finland	rural, urban	heating, cooling	GWHP	no
Arola et al. [100]	technical, acceptable	Finland	rural, urban	heating	GWHP	no

This groundwater heat potential is a local potential, representative of the energy stored and replenished in the groundwater recharge area. Additional steps are required in the modelling setup to account for hydraulic interference among neighbouring wells and thus include potential feedback of existing and newly added groundwater heat exploitation in sequential periods of t (years) on ΔT. Similarly, in a related study on the SUHI in Basel, Mueller et al. [89] numerically simulated heat fluxes in and out of the ground (aquifer) volumes beneath districts accounting for current thermal groundwater use. In such an approach, horizontal heat flow between neighbouring districts has to be carefully considered, as new installations in "up-gradient" districts will impact thermal groundwater use in "down-gradient" districts. Thus, the theoretical potential of the entire city would no longer be equal the sum of the potentials for all districts.

Aside from the standard definition of the heat in place, and the consideration of transient heat gain, there also exist alternative interpretations of the theoretical potential. For example, the geothermal potential maps by Bertermann et al. [105] for Europe show a spatial resolution of the thermal conductivity $(W\,m^{-1}\,K^{-1})$. This is motivated by the focus on very shallow geothermal systems such as horizontal loops of ground heat exchangers (GHEs), since their performance is strongly influenced by this parameter. A completely different perspective is presented by Doyle et al. [106] and Doyle [87], who assessed the concurrent potential of different ground use options beneath cities such as the San Antonio Metropolitan Area, USA. Here, ranked potentials of space, geomaterials, groundwater and geothermal energy are contrasted and presented on a dimensionless scale from 0 to 100. It is disputable, however, whether use of the term "geothermal potential" is suitable in these studies, since it is not expressed based on energy units.

3.2. Technical potential

The technical potential refers to the fraction of the theoretical potential that can be used with a certain technology. Most of the published work on shallow, low-temperature geothermal potential is focused on the technical potential, referring to either closed, vertical heat exchangers (BHEs) or open-loop circulation by groundwater wells (GWHPs). These studies are separately discussed below.

The technical potential is mainly computed adhering to limitations and boundaries [15,45,82], such as maximum drawdown caused by

wells, induced temperature change in the subsurface, or drilling depth of boreholes. This reflects that a technological application window is customarily constrained by regulations and standard design practice. Often the role of (further) regulations, public interests and concerns is inspected after the technical potential is computed at full technical freedom. Thus, these additional limiting criteria are discussed when introducing the acceptable potential as a subclass of the technical potential in Section 3.4.

Generally, we can distinguish (i) the general technological potential defined by hypothetical application of a technology for full exploitation within given physical or regulatory limits, and (ii) the specific technological potential for a given installation or use scheme. Referring to the potential of a city, we are especially interested in (i) and this is, therefore, the focus of the subsequent paragraphs. Category (ii) in principle covers any individual design study based on a specific use scheme with a given demand. In the context of the specific technical potential, numerous studies investigated the technical performance and/or feasibility of given ground-sourced energy applications. In some related regional studies, there is less focus on the potential but interest in the question, how regulations should be formulated to facilitate efficient and sustainable use, especially for adjusting existing and planning further installations. For example, Herbert et al. [107] set up a numerical model to simulate the thermal effect of GWHP systems in central London, and Epting et al. [108] and Epting et al. [50] examined in detail the thermal groundwater management in Basel and Zaragoza.

The study by Fujii et al. [109] is dedicated to a numerical model-based comparison of BHE performance in the Chikushi Plain, as similarly done by Shrestha et al. [110] in the Tsugaru Plain (both in Japan). Again, both studies do not quantify a geothermal potential, but present the basis for planning geothermal use schemes, e.g. by determination of preference areas for using the ground as source for space heating. Similarly, Tinti et al. [111] provided a qualitative suitability index for Europe specifically for coaxial BHE of 50 m depth and dual source heat pumps. Using a GIS approach, the spatial variation in (hydro)geological, thermal and mechanical subsurface parameters, land cover and energy use are accounted for in a hierarchical modelling process, which is designed as the basis of a Multi-Criteria Decision Analysis.

3.2.1. Open systems

The most straightforward estimation of the technical potential E_{tec}

(kJ) is by defining a recovery factor, δ (-), that states the extractable heat as a fraction of the heat in place (Eq. (1)):

$$E_{tec} = \delta E \tag{3}$$

The recovery factor is commonly considered for deep geothermal reservoirs and aquifers. It depends on the technology considered, temperature range, petro-physical properties and aquifer type, and it is derived based on different concepts. Often empirical or arbitrary values are suggested such as δ = 0.05–0.5 [112,113], 0.15 [114], 0.25 [115], 0.3 [116] or 0.5 [81]. In a well doublet with extraction and injection well, the recovery factor is given by [102,103,117,118]

$$\delta = \frac{1}{3} \frac{T_{top} - T_{inj}}{T_{surf} - T_{inj}} \tag{4}$$

where T_{top} is the top aquifer (water table) temperature, T_{surf} is the ground surface temperature [73], and T_{inj} is the temperature of the water injected. Calcagno et al. [103] calculated for well doublets operated in a deep, low-permeable aquifer in France a value of δ = 0.05. For single wells, in this context, a value of δ = 0.1 is recommended. Among the studies on urban shallow geothermal energy potential, there appears to be none dedicated to a spatial analysis of technical potential with this concept. This may be due to the neglect of interference among neighbouring wells, which can be a crucial factor for the performance of adjacent systems operated densely beneath cities. This may also be due to the fact that shallow geothermal resources beneath cities do not represent closed reservoirs, where the heat in place can serve as a proper reference.

The extractable heat (Eq. (4)) does not give any insight into the time-dependent availability of ground energy. This can be accounted for by expressing the potential as power or energy per operation time, e.g. in W or MWh/a. This temporal technical potential of open systems, $P_{tec} = E_{tec}/t$, is calculated by introducing an extractable groundwater volume per time t, equivalent to the feasible pumping rate or well yield, Q (m³ s⁻¹):

$$P_{tec} = Q c_W (T_0 - T_{inj}) \tag{5}$$

where T_0 is the undisturbed ground(water) temperature and T_{inj} is the reinjection temperature. The extractable volume accounts for groundwater recharge and thus transient sustainable use. This formulation is equivalent to the approach by Epting et al. [108] for calculating the momentary theoretical potential of a given groundwater flux (Eq. (2)). In contrast, the pumping rate Q here refers to the application of a technology. Its values are determined based on water permits, existing groundwater extraction from delineated aquifer bodies, well hydraulics or expert judgement. In a recent study, Casasso and Sethi [119] adapted the original approach by estimating the feasible pump rate based on the transmissivity of the aquifer and the well radius. The original approach was applied to urban and rural regions in Ireland [99,120] and Finland [23,100]. By including the efficiency of heat pumps, the final energy provision was computed. By referring to an increase or decrease of ground(water) temperatures, both heating and cooling potentials can be quantified. A shortcoming of this approach is that a fixed undisturbed temperature T_0 is assumed. Due to infiltration of thermally altered water, T_0 is not undisturbed anymore, and for unbalanced heating and cooling, it changes towards T_{inj}. This feedback is especially important for dense GWHP applications as in cities. For an overview on the mathematical concepts behind this thermal feedback interested readers are referred to the studies by Banks [121] and Milnes and Perrochet [122].

A comparable approach was presented by Munoz et al. [94] for the Santiago basin in Chile, but here feasible extraction rates Q were estimated based on simple well hydraulics from aquifer thickness and transmissivity, considering the saturated aquifer thickness as the maximum feasible drawdown for an approximation. By defining a fixed induced temperature change of T_0-T_{inj} = 5 K, required well depths (5–400 m) were mapped. In contrast to the full exploitation of an aquifer in Munoz et al. [94], the case study of the Metropolitan area of Barcelona by Garcia-Gil et al. [45] set a maximum drawdown constraint s_{max}, and calculated feasible Q by Thiem's analytical equation for pumping test analysis:

$$Q = s_{max}(r) \cdot 2\pi Z \cdot ln^{-1}\left(\frac{R}{r}\right) \tag{6}$$

where R is the radius of influence, $s_{max}(r)$ denotes the maximum drawdown at distance r around the well, and Z is the transmissivity. As demonstrated for the study case in Barcelona, different aquifer layers can be considered by summing up the extraction of all layers. Geological and hydrogeological data was taken from a 3-D model, and the surface air temperature was chosen as T_{inj}. This facilitated an analysis that accounts indirectly for the demand by the specific value of T_{inj}. As result, the technical potential P_{tec} (kW), based on the demand, was mapped in GIS. A crucial point here is that this approach only considers the point-wise (and thus the specific) potential, and neglects any lateral hydraulic and therefore thermal interaction and competition of neighbouring GWHP systems.

For concerted management of open-loop systems exploiting the Yarragadee aquifer beneath Perth, Australia, a related method developed by Ungemach et al. [123] for the Paris basin was utilized [98]:

$$P_{tec} = \eta Q c_W (T_0 - T_{inj}) \tag{7}$$

where η represents the efficiency of the heat exchange. While the extraction rate Q is pre-defined such as in Eq. (5), here additionally the efficiency of producing the heat (or cold) for end users is accounted for (e.g. η = 0.95, [98]). For the example of Perth, the supplied heat from the open systems operated in the city was estimated to be more than 110×10^3 GJ per year.

3.2.2. Closed systems

For BHEs, several guidelines offer default extraction rates (i.e. thermal efficiencies), γ, for different lithologies and ranges of water content [14,124–126] (Fig. 5). If a geological model is available, geothermal potential maps of power, P_{tec} (W), can be built:

$$P_{tec} = \sum_i b_i \gamma_i \tag{8}$$

where the BHE is drilled through different formations i with different thickness b_i (m) and specific heat extraction rates γ_i (W/m). This was presented, for instance, for the Upper Rhine Valley and the Black Forest in Baden-Württemberg, SW-Germany [79] based on specific heat extraction rates provided by the guideline VDI [124] (Fig. 5). This was also demonstrated for the Marche region [127] and for the Salento peninsula (Italy) [128], and here named "equivalent thermal performance". For the city of Ludwigsburg, Germany, Schiel et al. [35] implemented this approach to support the GIS-based spatial management of heating with shallow geothermal energy. Based on a 3-D geological model and rock-specific heat extraction rates in the range of γ_i = 40–70 W/m, they computed the spatial geothermal potential. Here the individual BHE borehole lengths, B, were set to the given maximum allowed borehole depths.

Another related family of studies on spatial potential trends focuses on the calculation of the required total borehole lengths, B_{tot}. For regional-scale estimation of low-enthalpy geothermal resources for district heating in the Santiago basin, Chile, Munoz et al. [94] adopted the approach by Ondreka et al. [79] to compute the required (total) borehole length to supply a given heating demand of 2.7 kW per installation, which is assumed to be typical for a standard Chilean one-story house.

As an alternative to the convenient pre-definition of expected BHE heat extraction rates, methods were proposed that also account for the use mode and physical heat transport processes in the ground at the specific site. For four regions of southern Italy, Campania, Apulia, Calabria and Sicily, Galgaro et al. [95] presented a GIS-based mapping
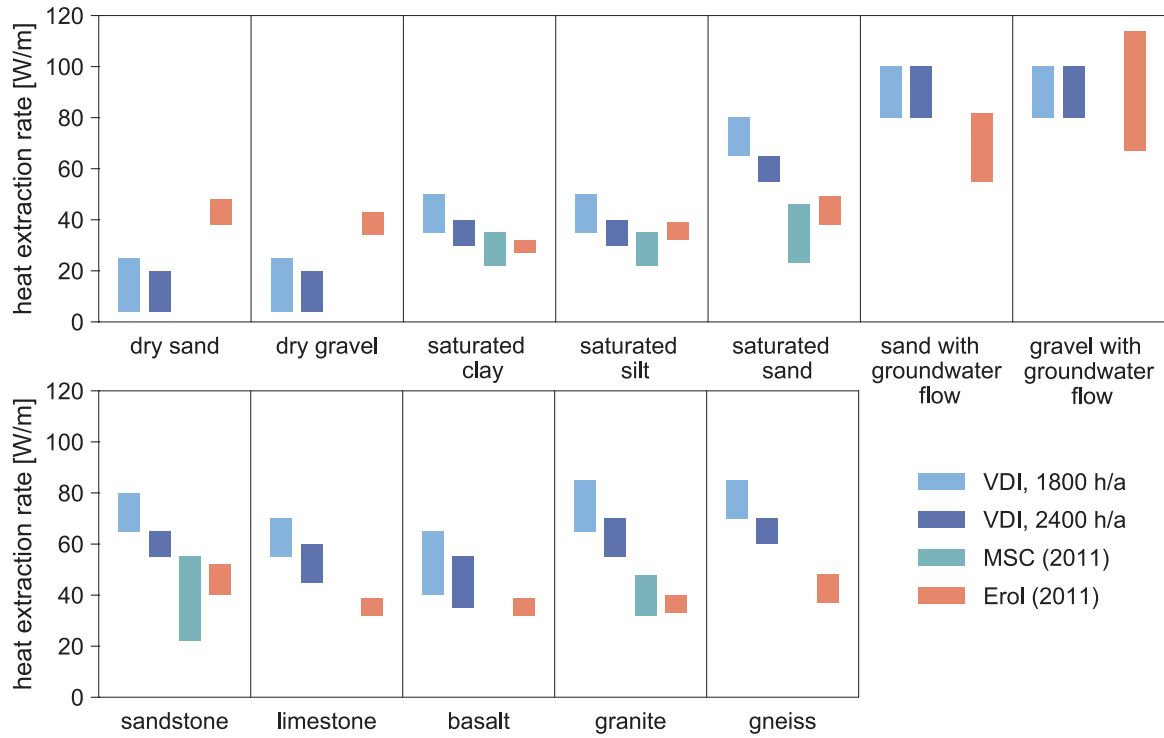
Fig. 5. Specific heat extraction rates, γ (W/m), for single closed GSHP systems of 40–100 m length (only heating) for a given annual operation times of different rock types given by VDI (1800 h/a, 2400 h/a) [124], MCS (2400 h/a) [126], Erol (2400 h/a) [14,125].

procedure that utilizes geological, climatic and geothermal data to derive governing parameters for model-based BHE performance assessment. For modelling of BHEs under different ground conditions, established BHE planning software was applied to a broad range of scenarios. The results were utilized to derive an expedient and computationally fast mathematical regression function as a substitute for the planning software. Similar to Zhang et al. [90], the total required length of B_{tot} was computed for potential heating/cooling demands. However, instead of referring to given BHE layouts, Galgaro et al. [95] translated the total borehole length requirement in land use demand, based on another moderately well fitted exponential regression function:

$$p_{tec} = \frac{P_{tec}}{A} = \alpha e^{-\beta B_{tot}}$$

(9)

with $\alpha = 136\,\text{kWh year}^{-1}\,\text{m}^{-2}$ and $\beta = 0{,}0037\,\text{m}^{-1}$, and where p_{tec} represents the annually extractable energy (kWh/year) per area (m²), i.e. the power density. They defined a fixed requirement of 49 m² for a BHE of $B = 100$ m, assuming that, by a mutual borehole distance of 7 m in a lattice arrangement, significant thermal interference can be avoided. The general technical potential of closed systems was then addressed by mapping p_{tec} on a 100 m × 100 m grid. The approach was applied at higher resolution also to regions of western Sicily [96].

The "G.POT" method [92] is based on the infinite line source and borehole resistance model [13] and explores the maximally extractable heat and cold for realistic ranges of physical ground and borehole properties, such as thermal conductivity, initial ground temperature, borehole length and thermal resistance. Similar to the regression approach presented by Galgaro et al. [95], Eq. (9), the G.POT method also relies on an empirical regression. A smart feature is that time-dependent annual heat (or cold) extraction is considered by a semi-sinusoidal function of specific heat extraction rates. Ground heterogeneity can be accounted for by weighting the physical values of the formations described by a geological model. The method was applied in the province of Cuneo (Italy), on a total area of 6900 km², and is also suitable for urban areas.

Zhang et al. [90] used the BHE design method by Kavanaugh [129] to compute B_{tot} for given heating demands in mapped plots of Westminster, a borough of London. They inspected areas with a given drilling depth (i.e. individual borehole length $B = B_{max}$) and a fixed distance between boreholes of 6 m. For a given demand, the obtained B_{tot} was compared with the feasible one for given BHE field schemes. In their study, they accounted for SUHI effects, assuming a ground temperature of 13 °C and a constant fluid inlet temperature at the heat pump of 5.2 °C. However, they also mention the limitations of assuming a constant ground temperature, and that an improved temperature map would greatly improve the accuracy of their model. The obtained energy provision was compared to heating requirements estimated for each building to determine a map of capacity (i.e. technical potential) to demand ratio.

The thermal interaction between adjacent installations is critical, especially in densely populated cities with high utilization of the technical potential. Hence, methods that penalize [90], or assess and therefore avoid interference were suggested. Miglani et al. [36] followed a similar approach as Zhang et al. [90] to calculate B_{tot} and distribute BHEs in property plots of the Altstetten area of Zurich, Switzerland at a minimum distance of 7.5 m. In order to investigate the role of long-term ground cooling and thermal interference, the infinite line source (ILS) solution was spatially and temporally superimposed. This provided insights into the specific technical potential by comparing available ground energy with the mapped demand.

Rivera et al. [130] also referred to the conditions in Zurich in their study on the general technical potential of BHE grids distributed over the entire city. Their objective was to compare the extractable energy for undisturbed thermal conditions to those in the presence of a SUHI. In order to account for transient effects, long-term SUHI evolution and accelerated heat flux from active ground cooling, spatially and temporally superimposed finite line source (FLS) models with elevated ground heat flux were employed. It was demonstrated in different scenarios with ground temperatures of up to 5 K higher than outside of the city, that the SUHI raised the technical potential of geothermal heating by up to more than 40%. As the ground surface effects diminish

with depth and onset time of the heat sources, this benefit is influenced by the installation depth (B_{max}) and thus lower for long BHEs. For a moderate B_{max} = 100 m, and groundwater heated by the SUHI by 3 K, the technical potential of the heated ground of the city, however, still is 22% higher than under pristine conditions.

Alcaraz et al. [91] adopted the moving infinite line source solution (MILS) for spatial arrangement of BHEs in Azul city, Argentina. By delineating the thermal plume evolving for certain heat extraction rates, groundwater flow velocity and physical aquifer properties, BHE positions were arranged within given plots. Design criteria were the steady-state or time-dependent plume fringe defined based on a given thermal alteration of the subsurface compared to ambient undisturbed conditions (e.g. a temperature increment of 0.5 K). A similar, yet pixel-based mapping of maximum (specific) extraction rates using also the MILS was generated for a sector of the city of Barcelona [93]. Here, instead of referring to plot or property boundaries, point-wise technical potential rasterized on a map was presented. Specific temperature increments were pre-defined (10 K at a radial distance of 0.25 m from the BHE axis) after 6 months of operation considering alternating heating and cooling modes. Neglecting interference with neighbouring systems, the obtained heat extraction rates ranged between 50 and 118 W/m (B = 100 m), strongly controlled by the groundwater flow velocity. In their case-study on the Metropolitan area of Barcelona, Garcia-Gil et al. [45] similarly applied the ILS and MILS for saturated and saturated ground conditions, respectively. Steady-state conditions and cooling application at constant heat injection was assumed.

A unique fuzzy-type classification of the technical potential was presented by Buday et al. [97] for the region of Debrecen, Hungary. Based on geological and depth-dependent criteria, "installability maps" were developed in GIS, which evaluate the potential of technological application in five classes: prohibited, not suggested, unfavourable, neutral, favourable, and very favourable. The classes in the presented maps are thus distinguished based on case-specific conditions and expectations, but no quantitative geothermal potential was derived.

3.2.3. Studies with both open and closed systems

There exist few published studies dedicated to the comparison of open and closed systems, or which compare the potential of different technological variants. Nam and Ooka [131] discuss a general protocol based on GIS-supported pre-selection of possible locations for BHEs or GWHPs, numerical model-based analysis of performance and economic analysis. In contrast, Garcia-Gil et al. [45] presented technological potential calculations for both open and closed systems. However, the derived characteristic units for the potentials were different, which hampers a meaningful comparison. While GSHPs were assessed by spatial maps of power per affected area by the thermal plumes (W/m²), for GWHPs the potential was given in locally feasible power (kW). The study by Munoz et al. [94] on the Santiago Basin in Chile compared the depth for wells to the depth of boreholes for supplying a default energy demand of 2.7 kW, finding a range of 5–400 m for the wells, and 35–105 m for closed boreholes. The higher range for the depths of wells was strongly influenced by groundwater availability.

3.2.4. Further technical criteria

A common technical criterion is the available space. For example, as a technical constraint in the work by Schiel et al. [35], the space available for BHE installation was limited by a land-use map, defining parcels where BHEs can be installed and built-up space where installations are not feasible. This space limitation was also integrated into the approach by Alcaraz et al. [91] presented with the example of Azul city, Argentina. Zhang et al. [90] compared BHE installation around buildings and under buildings for the Westminster district of London. BHE allocation maps were derived in GIS, and it was demonstrated that the technical potential could fully supply the heat demand of up to 70% of the buildings. A similar concept was adopted by Miglani et al. [36], but with a transient computation of extracted fluid

temperatures. For their study case, under most conditions, the BHEs could fulfil the required demand with power densities of 0–220 W/m² (mean of 90 W/m²), with some BHEs being influenced by adjacent installations.

3.3. Economic potential

The fraction of the technical potential that can cost-effectively be harnessed is the economic potential. Due to the variable technical and economic boundary conditions at each site and in each city, the economic potential is highly case-specific. A premise is good technical performance, i.e. energy efficiency, achievable with geothermal installations. This justifies the economic potential being a subclass of the technical potential (Fig. 4).

The economic boundary conditions are governed by capital and operating costs such as expenditures for planning, equipment, installation, maintenance and decommissioning; all these factors are influenced by the maturity of the corresponding market. Economic factors are also subject to promotion programs, subsidies, write-offs and levels of taxation [15,82,132]. Shallow geothermal heating and cooling are profitable when competing technological alternatives are more expensive. Thus, for instance, an increase in oil and gas prices promotes higher economic potential.

Mapping of the economic potential is needed for interpreting the commercial viability of the technical potential. It can be utilized to judge current and future conditions, and thus the stage of development of urban geothermal energy use. Such insight can support further investigation and mitigation of market barriers. The focus on plots, districts or entire cities facilitates concerted management of installations, as economic potential at different scales may be different: ideally, it improves through integrated management at larger scale [65,90].

The full economic potential of the geothermal energy beneath a city has not been studied in a comprehensive manner yet. One issue is that the superordinate technical potential has barely been exhaustively explored. Moreover, even based on a solid estimation of the technical potential, an economic assessment can hardly resolve the highly site-specific diversity of those factors in a city that are relevant for comparative cost assessment. A suitable first-order measure of the economic potential would be the relative or absolute discounted cost savings in comparison to existing or competing heating/cooling practice. For this, reliable long-term performance prediction of GSHPs and/or GWHPs is necessary and this is difficult considering the long system lifetime of several decades. Aside from this, also indirect economic benefits from the replacement of fossil fuels and the associated environmental burden would ideally be included.

In the following, some closely related work on the economic potential is discussed in detail. For instance, in their study on the anthropogenic heating of the aquifers underlying cities and towns in southern Ireland, Allen et al. [99] presented a back-of-the-envelope calculation of cost savings from applying individual GWHP systems instead of fossil-fuel boilers. Economic advantages were identified especially in case of dual-mode use for heating and cooling, and for installations of a large capacity. However, neither was the role of the specific urban or SUHI conditions quantitatively linked to the economic potential, nor a detailed cost estimation presented. Hence, it is not clear what the implications of the observed possible advantages for individual GWHPs would be for the up-scaled economic potential of an urban region.

Similarly, Lu et al. [133] inspected the economic feasibility of an individual vertical GSHP for a residential property in Melbourne, Australia. Their study showed that the GSHP system is economically favourable to an air-source heat pump (ASHP), if the considered life time is longer than 20 years, due to the comparably high initial costs. The same effect was observed by Nguyen et al. [134], who also revealed significant impacts of the long-term evolution of natural gas and electricity prices. Payback times between 8 and 20 years were found by

Rivoire et al. [135], depending on building type, insulation level and climatic conditions for several European locations.

Gemelli et al. [127] mapped the economic potential of BHEs for the Italian Marche region using GIS. As a basis, the standard space-heating power demand (in kW) for domestic environments was computed by referring to the local heating degree days, average living space and common operation time of 2400 h/a. This data was used to obtain the required power supply of the BHEs, and, by subdivision through the locally estimated specific heat extraction rate, to calculate the required borehole length. For mapping the regional economic potential, different indicators were presented: the BHE drilling cost, the payback time in comparison to gas-fired boilers, the costs per CO_2-equivalent saved, and the market chances. Finally, a market attractiveness indicator for a specific installation was given by the ratio of individual income and installation costs. Significant differences were detected between different communities, with a major role being attributed to the ground thermal properties.

The shallow geothermal energy potential of Iran was subject of the work by Yousefi et al. [136], who distinguished large-scale regions of cold, moderate and hot temperature, and three regions of different humidity, to derive nine regional classes. By definition of a reference standard building in a city of each region, the heating and cooling demands were determined and the costs for geothermal systems were compared associated with this type of building but in a different city. The coldest regions showed the highest potential for cost saving in comparison to fossil fuel-based supply. In the same manner, Sivasakthivel et al. [137]compared the application of GSHPs in different Himalayan cities, and there exist several similar studies in different countries.

Yan and Qin [138] presented a cost-benefit analysis of so far barely used shallow geothermal resources for partial winter-time heating in Xi'an, China. They, however, do not scrutinize or map the spatial technical potential, but anticipate a certain coefficient of performance for the heat pumps and specific operational costs. The purpose was to develop an integrated heating system that incorporates the geothermal energy in place, yet for simplification, additional expenditures for construction and maintenance of the heat supply network were not considered. This aggravates a full assessment of the economic potential on the urban scale. For comparison with coal-fired heating, Yan and Qin [138] also included (savings of) fees for governmental pollutant charges of sulphur dioxide and nitrogen oxides release. Here, apparently, macroeconomic savings from local environmental benefits are accounted for by administrative charges.

3.4. Acceptable potential

Even if a substantial technical potential exists, city-wide application of shallow geothermal systems is mostly restrained. Aside from crucial cost factors that limit the economic potential, there may be further regulations, lack of experience and expertise, environmental criteria, public concerns and interests, or even simply no need for low-enthalpy geothermal energy. These criteria delineate the acceptable potential as a fraction of the technical potential (Fig. 4). A fundamental issue of integrating geothermal energy in urban systems is often not the availability of the ground, but the energy distribution system that needs to be built and/or adjusted. Thus, at most places, insulated installations for local supply of neighbourhoods are developing first, and their concerted management is the initial priority. This means that a major task is managing ground thermal interference among individually operated adjacent installations, which was addressed in some but not all studies listed in Table 1.

In most countries, there exists no regulation or recommendation on temperature constraints for the thermal use of groundwater and the shallow subsurface [10,15]. Also, a minimum distance between two adjacent systems is not always given. If provided, this minimum distance is often arbitrarily defined rather than scientifically derived.

Regulative frameworks thus often are not able to prevent negative consequences of the geothermal use of shallow urban aquifers and cumulative thermal impacts. Furthermore, available regulations or guidelines are inconsistent [15]. However, due to hydrogeological differences and natural variability in physical ground properties, it is not desirable to follow static regulations, such as fixed temperature thresholds.

As an example, Epting et al. [50] dealt with managing geothermal potential in urban aquifers of Basel (Switzerland) and Zaragoza (Spain) based on the so-called thermal stress of an urban aquifer rather than through the direct quantification of its geothermal potential. For this, variants of a "relaxation factor" [139] were introduced that relate the induced to an acceptable temperature change. If an aquifer is under significant stress, then remedial solutions should be considered, such as winter cold-water injection from a river in case of immoderate ground heating. By spatial mapping of the thermal stress in a city's subsurface, recommendations on the concerted management of geothermal installations can be derived.

As visualized in Fig. 4, acceptable conditions do not have to be embedded within an economically favourable range, as in some cases it may be interesting to gain other benefits, such as improved environmental performance, at the expense of increased costs for urban heating and cooling [6,138,140]. For example, in case of the city of Ludwigsburg, Germany, special interest was on the savings of greenhouse gas emissions. It was emphasized that around 30% of the CO_2 emissions could be saved by supplying the entire current space heating and hot water requirements by geothermal energy [35]. Economic constraints, however, were not addressed.

In contrast to the four categories suggested in Fig. 4, Rybach [82] subdivided the economic potential into a sustainable potential and this further into a fraction that is developable. Economically attractive solutions, however, may not always be sustainable. Vice versa, sustainable solutions that focus on natural regeneration may not be the most cost-efficient. For example, Rivera et al. [65] calculated the technical potential of the city of Zürich, Switzerland, based on the Swiss guideline for BHE design, which foresees a guaranteed lifetime of 50 years, where the temperature at the borehole is not allowed to undercut a threshold. In Rivera et al. [65] an optimal sustainable use mode was computed, where the deficits from heat extraction were balanced by natural replenishment and SUHI accelerated heat flux so that the threshold was never violated (i.e., also not after the period of 50 years). The resultant sustainable fraction of the geothermal potential was smaller than technically feasible.

Finally, at early development stages, economic risks often represent market barriers that only can be overcome by learning through early installations. Thus, the economic potential in such cases would need to be calculated more exhaustively than summing up expected operational and capital costs of the first systems in place. In fact, uncertainty in urban ground conditions and long-term performance of geothermal installations is high even in well-developed cities. The economic risk of failure, due to predictive uncertainty and unclear long-term performance, thus can be a crucial issue of technologies operated for decades.

3.5. Capacity to meet the thermal energy demand

Following the quantification of different types of geothermal potential, the next step towards implementation of a utilization strategy is linking it to an existing, either measured or estimated, thermal energy demand. Available studies that contrast some type of geothermal potential and its capacity to meet the demand can be broadly divided into two categories. The first type are studies that evaluate the geothermal potential based on an actual or estimated energy demand, i.e. most often they aim to identify the system design required to meet the demand. These studies show that the average annual heating demand of typical residential buildings under different geographical, as well as climatic settings can be met by a certain technical design, as described
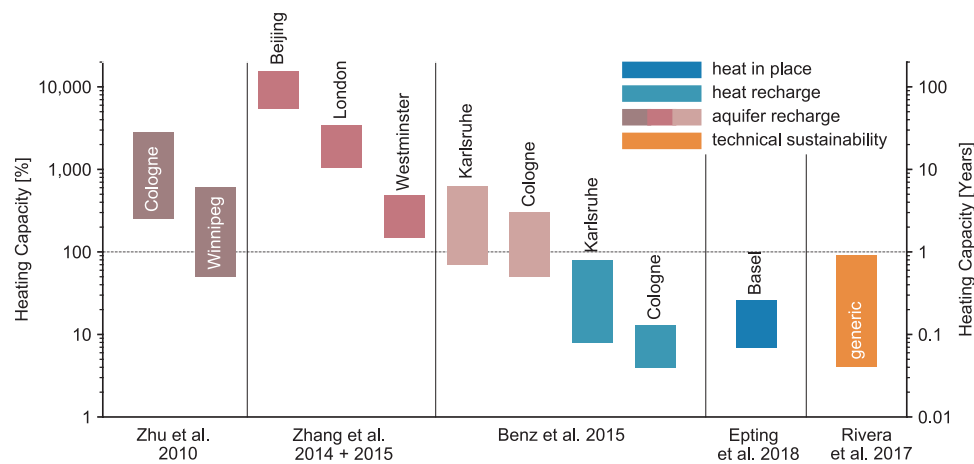
Fig. 6. Heating capacity, i.e. ratio of geothermal potential to annual residential heating demand for several cities based on the findings from previous studies, in percent and years [65,66,86,88,90,141].

above [92,94,95,127].

The second type are studies that calculate a specific type of geothermal potential, such as theoretical or technical, for a given (hydro-) geological situation and in some cases using a pre-defined system design, and then compare the extractable energy to an energy demand value. Early studies compared the theoretical potential, i.e. the heat in place, to city-wide heat demand data, estimated based on energy use statistics, to obtain the city-specific heating capacity for a period of time [66,88,90,141]. Depending on the case studies and underlying assumptions the annual demand could be satisfied between 0.5 and 101.3 times (Fig. 6). Yet, these values are also highly susceptible to the quantification of the demand, as a comparison between the different studies in the city of Cologne reveals [66,88]. Schiel et al. [35] employ a spatial approach by parcel-wise comparison of the measured heat demand and extractable energy by BHEs. They find that the demand of 40% of the parcels could be fully met, yet no detailed values are given for the entire case study site.

The estimated capacity to cover the demand decreases significantly, if one focuses on the heat, either in the subsurface [66] or in an aquifer [86], that is annually replenished by natural and anthropogenic heat inputs. Thus, the maximum heat coverage in the cities of Karlsruhe and Cologne is reduced from 550% to 71%, and from 250% to 9%, respectively, in accordance with the magnitude of the heat recharge (Fig. 6). Assuming long-term sustainability under various system design options, Rivera et al. [65] reflected a broad range of different demand values and varying assumptions on the surface thermal conditions. While their results indicate that a large portion of the residential heat demand can be met sustainably on a large scale, further issues, such as the spatio-temporal variation of the heat demand and peak demands [86], need to be considered for an in-depth assessment of the capacity of the geothermal potential.

4. Discussion and implications for future geothermal management in cities

The presented overview of previous work on the shallow geothermal potential of cities shows a great diversity with variable definitions of potential classes and different quantification and calculation techniques. We find applications in many different cities and regions from many continents of the world. Most frequently results from European cities are reported, and relatively small insight published on conditions in cities from countries such as China and USA, which dominate the direct use market of geothermal energy.

4.1. Differentiation between the defined potential classes

There is no consistent picture on approaches used for the technical potential, which often makes it impossible to contrast the figures published for different cities. There are several issues: (i) the constraints for calculating the technical potential are assigned based on the specific objective of each study, including or ignoring regulative thresholds, land use restrictions, etc., (ii) there co-exist different measures of technical potential, (iii) there co-exist different procedures for geothermal system design and performance evaluation, (iv) there is no clear distinction or attuned approach accounting for both heating and cooling, (v) there are limited efforts so far to consider and compare opportunities with both open and closed as well as other renewable energy systems.

4.2. Quantification of the geothermal potential

It is demonstrated that the heat in place, computed for a given ground volume beneath a city, is an easily calculable measure of the theoretical potential. Even within common geological parameter uncertainty, thermal properties such as the heat capacity are much less variable than for example hydraulic properties, so that a major determinant is the area of the city and the considered depth of boreholes or wells. Additionally, subsurface heating may yield a much higher theoretical potential for those cities with pronounced SUHIs, when comparing two places with the same target temperatures T_1 of heat extraction. In contrast to heat extraction to supply heating systems, interestingly, we found no study that is dedicated to a theoretical potential with respect to cooling with exclusively heat injection. In that case, Eq. (1) could be applied considering $\Delta T = T_1 - T_0$. Target temperatures could be oriented at regulative thresholds for groundwater temperatures.

A shortcoming of the heat in place calculation (Eq. (1)) is that an adiabatic system is assumed. However, when considering technologies that operate for decades, transient heat flow and replenishment through the boundaries of the considered ground volume offer access to a much higher theoretical potential. In fact, the shallow subsurface of a few hundreds of meters beneath a kilometres wide city represents a body with high surface/volume ratio and thus high lateral thermal exchange capacity. As an illustrative example, let us consider a subsurface body with an edge length of 100 m, consistent with the typical depth of 100 m for installation of a BHE, and a surface area of 7 m × 7 m, the typical space requirement assigned to a single BHE (Fig. 7). Assuming a bulk heat capacity of 2.5 MJ m^{-3} K^{-1} (e.g. water-saturated sandstone), and an arbitrary temperature change of $\Delta T = 5$ K, the heat in place would be $E = 61.25$ GJ. When a BHE offers a moderate heat extraction
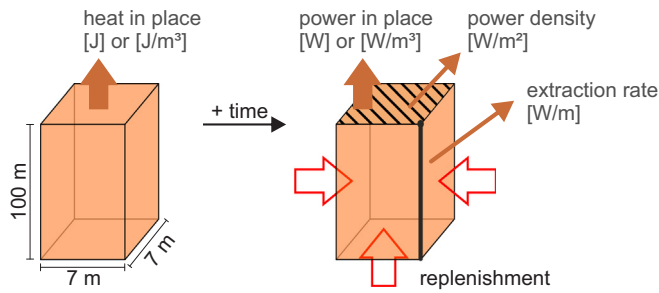
Fig. 7. Overview on four typical concepts for the quantification of the geothermal potential, applying different temporal and spatial dimensions, and obtaining results in different physical units.

rate of 50 W/m (Fig. 5), or indeed any type of geothermal system with a power density of about $102 \, W/m^2$, the heat continuously extracted by the system reaches the available theoretical potential after 142 days. The feasible power density by an intermittently operated system may be higher, but even then, there is a point in time, when the theoretically available heat is exploited, yet the system is still working. While many studies characterise the geothermal potential in terms of heat extraction (or exchange) rates [W/m], power density $[W/m^2]$ appears to be a useful measure for contrasting the technical geothermal potential of different technologies, as it allows to relate the extractable, or required, amount of energy per time unit [W] to the critical factor of available space in urban areas $[m^2]$.

The results from some of the previous studies can be converted into power density, by assuming a specific BHE setup, i.e. depth of 100 m and spacing of 7 m, and a common number of operating hours per year (2400 h/a). The large range of power density values in Fig. 8 reflects the diverse underlying assumptions, from large-scale, renewable utilization within strict temperature bounds [65], to local, short-term evaluation under strong influence of groundwater flow [93]. The comparably low demand-driven power density values from Santilano et al. [96] and Galgaro et al. [95], which are calculated based on the required heating demand of example buildings, indicate the overall feasibility of shallow geothermal energy supply. However, in case of low and equally balanced thermal energy demands, derived net power densities become high, and this has to be reflected when comparing the conditions in different cities.

4.3. Assessment of thermal conditions beneath cities

According to the varying definitions of potential classes and due to the different procedures for system design, the demand for parameters needed for a district- or city-wide potential assessment varies a lot. This is complicated by the special thermal conditions beneath cities, where often a huge amount of heat is artificially stored in SUHIs. There are several cities with subsurface thermal monitoring, and some, where regional geological flow and transport models were developed (e.g. [86,93]). Resolving the role of relevant local effects on individual installations with urban models is challenging, whereas local models cannot represent city-wide trends. Analytical models, such as line source models for closed systems and single or doublet well models can be used for local and regional assessment, and they may offer interesting opportunities for assessing combined closed and open system application. However, these analytical models have been developed with strongly simplifying assumptions, such as homogeneous ground properties and mostly stationary boundary conditions, which limit their applicability to prior assessments. In contrast, studies with numerical models show a formidable field of application and flexibility and facilitate a refined understanding of the role played by anthropogenic heat sources on the thermal regime of urban aquifers. However, such urban numerical models require several hundred thousand nodes by square kilometres and are difficult to implement at an urban scale. In addition, there is limited published work that critically discusses the reliability of data-hungry urban numerical flow and heat transport models, especially when the available amount of data is limited.

5. Conclusions and outlook

This review paper highlights a global consensus on the capacity of shallow geothermal energy to be a strong technical solution for urban heating and cooling. However, there is currently no consistent concept available for assessing the geothermal potential. As demonstrated, the theoretical potential is only a good indicator, if it considers the heat in place as well as acknowledges heat fluxes (especially in SUHIs). As these fluxes strongly depend, among others, on the applied heat extraction (or injection), it can be difficult to distinguish between the theoretical potential and the technical potential.

The available procedures for estimation of the technical potential are manifold. As most rely on tabulated or modelled feasible heat extraction rates, the differences are smaller at second sight. Mostly standard guidelines, planning tools or modelling approaches are employed, so the broad ranges of the results are mainly caused by their different capabilities and limitations. Together with case-specific geological, climatic and regulative boundary conditions, they generate a wide span of different outcomes. This is revealed when considering the power density as reference indicator for the technical geothermal potential. For further insight into the specific differences, ideally a well-defined benchmark city with given conditions would be needed, where different procedures could be applied and their outcomes compared. This could also be the basis not only to identify a favourable procedure, but to
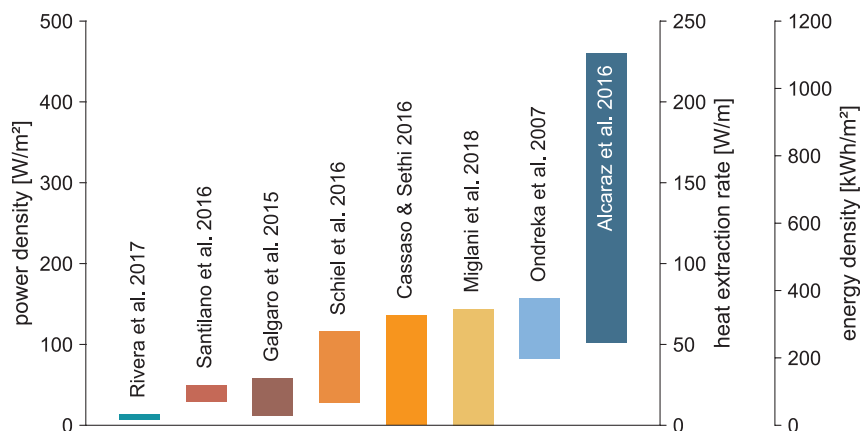

Fig. 8. Power density values obtained by different case studies [35,36,65,79,92,93,95,96], normalized for a BHE depth of 100 m, 7 m spacing between individual BHE and 2400 h/a annual operation hours. The corresponding values for the heat extraction rates and energy densities are shown for better comparability.

develop a robust recipe for geothermal potential assessment. A promising direction is the development of multi-scale approaches, where local assessment and planning of geothermal utilization is embedded in a district or even city-wide integrated energy management plan. For this, future work should in particular:

- assess the combined use of different geothermal technologies (incl. storage), and ideally address their concerted application in the context of integrated urban underground management;
- define more clearly the geothermal potential for cases with both heating and cooling, and discuss meaningful power densities when active replenishment of thermal deficits is considered;
- develop transparent and critical assessment strategies for data and conceptual uncertainty, data gaps and of crucial modelling assumptions;
- validate geothermal potential estimations by field data and tailored monitoring schemes;
- provide a more realistic assessment of coverage and the spatially and temporally fluctuating heat /cold demand of a parcel, district or city;
- integrate spatially variable geothermal utilization in urban energy planning tools.

Clarification of the technical potential, and demonstration of successful geothermal use concepts for cities, is crucial to promote acceptance. Social aspects as part of acceptance potential are however rarely discussed. The growing technological experience in running open and closed systems enhances robustness, reliability and thus cost efficiency. Available concepts to assess the economic potential of shallow geothermal energy in cities, however, are still not mature. This is due to the need to account for a variety of technological, geo-environmental as well as economic aspects.

Acknowledgements

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