Geothermal energy in urban planning

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Abstract. Geothermal energy is a collective term referring to Earth heat extraction and use of the ground capacity to absorb and store thermal energy to supply heat or cold. Thermal ground exchange or shallow geothermal energy has been increasingly used in the housing sector to sustain comfortable room temperature. Increasing utilization of geothermal energy, particularly in urban areas, requires integration into urban planning processes. The question of subsurface planning, or underground space integration into land-use planning, or three-dimensional planning has been an emerging research theme in this decade. This paper will focus on specific issues that pertain to geothermal energy use in land use planning in urban areas. These issues include (1) holistic vision of underground space as a resource, (2) geothermal energy technologies in terms of using space, (3) multiple users and installations of heat pumps and their interaction, (4) possible conflicts and interference with other subsurface users and functions, (5) demand and suitability of geothermal use in housing, (6) urban densities and geothermal energy feasible use, (7) and general principles of urban geothermal land use planning. A feasibility case study of using heat pumps to provide heating for a typical historic multifamily building in the Petrogradsky district of the city of St. Petersburg, Russia is given.

1. Introduction
Contemporary global challenges, as reflected by the United Nations Sustainable Development Goals [1] include a reduction in greenhouse gases emissions and the use of fossil fuels, which requires increased energy efficiency as well as the share of renewable energy. Geothermal energy has ample potential to address the issues of lowering energy consumption by allowing energy storage in the ground and supplying energy systems with Earth heat. Geothermal energy is of a particular interest to the housing sector, where it can be used as a local source. However, to ensure geothermal energy renewability and sustainability, research, innovations, planning, and management advancements are required [2]. Geothermal energy is high on the urban underground space development agenda; the use of urban underground space has been growing globally [3] and high densities of underground space use are expected in advanced cities in the near future [4].

This paper focuses on exploring different aspects of geothermal energy development, primarily in urban areas. Apart from technical geothermal potential, about which a brief literature review is given, we focus on planning, environmental, and stakeholder issues using a pilot research area of Petrogradsky District area in Saint Petersburg, Russia.
Petrogradsky District area represents a typical downtown area, densely built-up with very little green space available, historic buildings are 100-200 years old. Underground space has been predominantly used for linear communal infrastructure; there are 3 metro lines built in deep tunnels. There are singular pedestrian underpasses and car garages under recently built or reconstructed buildings, but underground space remains largely undeveloped, which gives a potential opportunity for shallow geothermal heat exchange installations.

Zhang et al. [5] has been studying the city of Westminster district, London, UK, their theoretical modeling study has demonstrated that the technical potential could fully supply the heat demand of up to 70% of the buildings. Similar studies have been conducted in Karlsruhe, Cologne, and Osaka, revealing that there is indeed ample potential to supply urban buildings using geothermal energy. The urban geothermal potential is a complex notion [6, 7], researchers identify different (sometimes overlapping) further components of this term. There is theoretical potential (total physically available energy); technical potential (energy that can be harnessed by available technologies); economic potential (energy that would be profitable to extract under particular regulatory and market conditions), sustainable potential (long-term use of geothermal resources ensuring their renewability); developable potential (a share that would comply with regulations and environmental restrictions); acceptable potential (energy that is feasible to use under regulatory and environmental conditions, incorporation aspirations for urban sustainability, but somewhat leaving behind current market conditions and economic profitability). The synthesis of different types of geothermal energy potentials is illustrated on Figure 1.

The acceptable potential of geothermal energy exploitation should incorporate social and stakeholder considerations as well. The introduction of new technologies is a complex process requiring societal and professional mobilization to develop appropriate technical, legal, and regulatory frameworks; as well as government programs and incentives to facilitate pilot projects. Our study has been focused on this particular array of issues that would accompany geothermal energy development. Several legal and institutional barriers were identified, which if removed would allow developers an easier introduction of geothermal energy. Removing procedural approval barriers would still not be sufficient for the full realization of the geothermal potential of the area and in the city and region at large, governmental incentives and roadmap programs would be required to facilitate geothermal energy use.

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**Figure 1.** Categories of geothermal potential beneath cities [7].

## 2. Data and Methods

### 2.1. Thermal regime beneath cities

Anthropogenic activities and changes in land-use in cities cause large-scale thermal anomalies in the earth, which are called subsurface urban heat islands (SUHIs). The temperature profiles of the good outline of the accumulated energy by characteristic indicators where urban heating causes a temperature increase closer to the surface (Figure 2).
Figure 2. Schematic representation of a subsurface urban heat island (SUHI) with different geothermal systems in operation [7].

The temperature of the shallow ground is closely related to atmospheric conditions [8, 9]. Having a much higher heat capacity and less diffusion, the ground retains temporary air temperature indicators. Seasonal variations in surface temperature follow fluctuations in the air and can be measured as attenuated signals down to 20-30 m (Figure 2). The temperature profiles in the well-depth roughly correspond to the geothermal gradient of around 3°C/100 m, but in the top 100 m are usually flatten out due to the recently increased conductive heat flow from above (Figure 2).

Regional studies in North America (e.g., [10]), Europe (e.g., [11, 12, 13-15]) and Asia (e.g., [16, 17, 18, 19]) have confirmed the presence of large-scale underground temperatures in urban settings compared to less affected rural areas. Local anomalies are even more pronounced, for example, under parking lots or near buried district heating systems [12].

The heating footprint of cities has a wide range of impacts: it changes the technical properties of urban grounds [20], increases the temperature, which is crucial for the in-situ ecosystem [21]. SUHIs make it possible to use geothermal resources for heating.

2.2. Study area

This research is focused on a set of issues that would accompany the development of geothermal energy. A hypothetical geothermal energy project in the center of the Petrogradsky district of the city of St. Petersburg, Russia was taken as a case study. The research issues and objectives include: (1) identify the most promising types of grounds as a geothermal source; (2) consider the geological conditions of the Petrogradsky district; (3) determine the necessary depth and number of wells of geothermal plants; (4) consider the needs of thermal energy; (5) identify areas suitable for drilling; (6) define promising directions of development of geothermal energy in the region.

Analysis of geological conditions of the surface layer of the Petrogradsky district in St. Petersburg showed that most of the territory is represented by loose sandy rocks with coarse and medium-grained sands (Figure 3). Peat and clay soils have the greatest heat capacity [22]. For loose rocks like sand, the specific heat is relatively lower. The most optimal in terms of the heat capacity of the soil for use in geothermal purposes are lands characterized by medium-compacted clays and sandy loams.

Geological conditions. Analysis of the geological profile of the territory under consideration by depth showed that the Petrogradsky district is characterized by undifferentiated deposits at a depth of down to 30 meters. However, clay soils, which have a high potential for heat transfer, predominate at depths from 30 to 100 m (Figure 4). At such depths, the potential of geothermal resources will be higher than on the sandy surface, and for this reason, the Petrogradsky district is relevant for the development of geothermal resources.
Figure 3. Engineering-geological map of the day Surface in Saint Petersburg city centre [23].

Figure 4. Geological Map of Pre-Quaternary Deposits, Saint Petersburg city center [23].
The depth of wells for geothermal installations depends on several reasons. If there are no restrictions on the area, it is better to make several wells of medium depth. Modern geothermal technology allows to drill wells at a depth of 300 meters and more. However, it is easier to carry out technical support of wells and monitor their condition at shallow depths.

The Aptekarsky island municipality, which is part of the Petrogradsky district, was chosen as a pilot territory. The map of functional zones shows that residential buildings prevail in the center, while social and business buildings prevail closer to the periphery (Figure 5).

![Figure 5. Map of functional zones of Petrogradsky district, Aptekarsky Island, Saint Petersburg](image)

The type of building use (residential/commercial/mixed) was determined, as well as the average height, most buildings in the area are 4-5 story structures (Figure 6).

![Figure 6. Map of building’s levels of Petrogradsky district, Aptekarsky Island, Saint Petersburg](image)
3. Results
A five-story residential building has been identified as a sample building (Figure 7). The sample building is a typical 5-storey building in the Petrogradsky district. Underground liner infrastructure like metro lines and conduits was not taken into account during this analysis for simplification purposes. However, we estimate that presence of liner underground infrastructure could hamper geotechnical installations on about half of the territory of densely build Petrogradsky district. Geological conditions are summarized as clays with thin layers of sandstones, the thickness and depth stratification was taken as 50 – 100 meters.

![Figure 7. Petrogradsky district case study. Location of a typical residential building](image)

The selected residential building was built in 1955 and has a total area of 7006.50 m². The material of load-bearing walls – brick; area of residential premises: 4040.5 m²; free courtyard area: 647.9 m².

According to the [24], for houses built in 1931-1956, the consumption standard is 0.0197 Gcal per 1 square meter of the total area of residential premises per month.

The area of residential premises in the building under consideration is 4040.5 m². Therefore, the consumption of heating services for this house according to the standards is 79.6 Gcal (4040.5*0.0197) per month or 0.11 Gcal/hour, which is 127,929 W ≈ 128 kW. To cover the needs of the 5-storey building under consideration in Saint Petersburg, it is necessary to install heat pumps with a total capacity of 128 kW.

In a reference case of installing a heat pump in the Swedish city of Laholm [25], pumps with a capacity of 14 kW and 20 kW were installed to heat a building of 1200 m². This amount of heat can provide 7 heat pumps with a capacity of 20 kW.

The calculation of the number of wells depends on several factors. It is important to take into account the type of soil prevailing in the drilling area and the technical characteristics of the equipment itself. Soil with high moisture content, such as clay, will be more effective. If drilling operations are carried out on clay soils, the heat transfer rate will be about 50 W per 1 laid meter [48].

Then the total capacity of the heat pump is calculated. For a house with a total living area of 4040.5 m² and 7 heat pumps with a total capacity of 128,000 W, the length of drilling wells is 2560 m (128,000 W / 50 W/m = 2560 m). To reduce the drilling length wells can be clustered and amount bore halls can be increased using geothermal probes [47]. The geothermal probe is a heat exchanger that exchanges heat between a heat carrier and the ground. There are several types of probes, typically, geothermal probes are made mostly as U-shaped pipes [45, 47], in which the heat carrier flows through one pipe from the surface to the base of the well for the geothermal probe, i.e., from top to bottom. And the other pipe, the heated heat carrier flows from the bottom to the top. During the ascent,
the heat carrier constantly gives part of the accumulated heat energy to the colder ground. As a result, the efficiency of the U-shaped tube probe is quite modest [45].

To increase the efficiency are used of a coaxial geothermal probe [45]. The structure consists of an external plastic PE-HD pipe [46], plugged on one side and inserted into it a second pipe with poor thermal conductivity for the supply of cold coolant. The principle of operation and layout of wells are shown in Figure 8.

The cold heat carrier is supplied through the inner pipe, and the heat carrier heated in the lower layers is returned through the outer pipe. The area around the well in this case is as warm as possible. The heat removal rate for a probe of this design is 64 W/m at a delta of 3°C between the ground and the coolant. The practice of using it in the Moscow region shows, that a coaxial probe is quite sufficient for soils with an average of 30 W/m [45]. Drilling is carried out at an angle of 45-60° to the horizon. When the specified depth is reached, the probe is installed and the casing pipes are removed. With this scheme, up to 15-20 probes can be located in one well, which practically do not affect each other. The cluster location of the probes in a single well reduces construction works area disruption to a minimum.

The proposed scheme has the following advantages: (1) the probes are arranged in a fan at a depth of up to 50 m; (2) the probes are also laid under existing buildings; (3) the small effort and capacity required for drilling weak soils allow you to work with a light portable drilling rig that is easily fixed to the surface and does not violate the soil and vegetation cover. Drilling mud and washing liquid remain in the well and do not clog the area.

Zhang et al, 2014 [5] studied particularities of placing wells around the buildings. Suggested distance between any two wells is 6 m. Wells are installed in the buffer zone, which is located within 3 m from the edge of the building, both from it and under it. Using this reference case it is feasible to place 7 heat pumps around the perimeter of the case study building and within the courtyard area of 647.9 m² (Figure 8).

![Figure 8. Petrogradsky district case study. a) example of a drilling wells placement area; b) scheme of operation of a coaxial geothermal probe.](image-url)
4. Discussion

4.1. Capacity to meet the demand for thermal energy

Following the quantification of various types of geothermal potential, the next step in implementing a utilization strategy is to link it to the existing, measured, or estimated thermal energy demand. Existing studies that compare some type of geothermal potential and its capacity to meet demand can be divided into 2 categories: (1) studies that assess the geothermal potential based on actual or estimated energy needs (the heating needs of typical residential buildings in different geographical and climatic conditions can be met by a specific technical project); (2) studies that calculate a specific type of geothermal potential, such as theoretical or technical, for a given situation, and then compare the energy extracted with the value of energy demand [7, 16]. The estimated capacity to meet demand is significantly reduced if focus is on the heat flow either in the subsurface [26] or in the aquifer [27] which is replenished annually by natural and anthropogenic heat resources.

4.2. Multifunctionality of underground resources

The multi-functionality of the subsurface creates opportunities, but also creates conflicts between competing uses, for instance between geothermal installations and underground structures [2, 3, 29, 30]. Von der Tann emphasizes that conflicts arise due to the incompatibility of views of various interested groups on the subsurface and its functions [32], while [33] gives a detailed account of ecosystem services, including geothermal to be included in the planning process. At the same time, a common problem of growing concern around the globe is that subsurface resource is usually used in accordance with the “first-come, first-served” principle [34-36], which hinders: (i) structured prioritization and optimization of competing subsurface uses, (ii) fair inter- and intra-generational distribution of limited natural resources, and, consequently, (iii) sustainable urban development.

The Netherlands is currently developing rules for subsurface planning. The upcoming law about environment and planning aims to promote urban development by focusing on subsurface use, as well as combining 15 separate environmental laws into one act [37]. The ambitions for sustainable use of subsurface in territorial planning processes were formulated in a covenant of 2016 between the Dutch government, municipalities, provinces, and water authorities. The covenant addresses various functions and uses of subsurface resources, such as pipes and cables, geothermal energy, and natural resources.

Some fairly recent initiatives to collect subsurface data have been launched in the United Kingdom and the Netherlands to assist in spatial planning processes. In 2012, the British Geological Survey, in collaboration with Glasgow City Council developed the “Assessing Subsurface Knowledge” (ASK) network to collect and provide accessible environmental and engineering geo-scientific data [38, 34]. Glasgow’s planning policy, based on voluntary agreements, partnerships, and collaboration, explicitly recognizes the environmental and economic value of the subsurface and "reflects the importance of the subsurface environment for the health, wealth, and growth of the city” [40]. Subsurface data is voluntarily shared by industry and national stakeholders in the UK, a practice that needs to be replicated and stepped up to allow a comprehensive sustainability project appraisal. A framework for such appraisal was developed by [41]. Following innovative legislation, the Netherlands established the Basisregistratie ondergrond (BRO) underground register in 2015 “to consolidate geological and exploration data, as well as data on mining activities and related structural assets” [39, 42].

The General trend in Europe and the world is that subsurface resources have not been taken into account in spatial planning processes for a long time until the implementation phase of the plan is reached [39, 43, 44]. This inevitably leads to missed opportunities, since most of the benefits are achieved through an integrated consideration of the subsurface at the early phases of the spatial planning process [40, 43]. A recent study in Germany [45] of municipal landscape plans reveals very limited consideration of subsurface, but, on the other hand, it has been acknowledged that strategic spatial planning of European urban regions [46] needs to make ample consideration of renewable energy sources, including geothermal use potential opportunities and near future deployment.

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perspectives.

5. Conclusions
A consistent concept for assessing geothermal potential has been under development. We have identified that the theoretical potential can be a valid indicator. Since heat flows are highly dependent on heat transfer, it can be difficult to distinguish between theoretical and technical potential. However, existing concepts for assessing the economic potential of geothermal energy in cities has not yet been fully developed for specific needs, e.g. Saint Petersburg central districts dense build stock.

The paper presents an example of the development of geothermal energy for a typical residential building in the Petrogradsky district in the city of Saint Petersburg. The required capacity for heating the building and possible options for placing drilling wells has been studied.

A promising direction for further research is the development of multi-scale approaches, in which local assessment and planning of the use of geothermal resources are integrated into a district or even citywide integrated energy management plan. To achieve these aspirations future work can be focused on:

1. Evaluation of the combined use of various geothermal technologies (including storage), and ideally consider their coordinated application in the context of integrated urban metro management;
2. Development of transparent and critical strategies for evaluating data and conceptual uncertainties, data gaps, and critical modeling assumptions.
3. Integration of the spatial variable of geothermal resource use into urban planning tools.

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