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Modeling the Technical Potential of Energy Hubs: A Spatio-Temporal Analysis for the Swiss Canton of Zurich

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ABSTRACT

By coupling electricity and district heating (DH) networks, so-called energy hubs (EH) are generated. Those have the potential to include more renewable energy sources, depending on local conditions regarding supply and demand. This paper presents a novel approach by matching the heat demand of residential and commercial buildings with local renewable heat sources and by considering the development of the building stock with the spatial and capacitive DH potential through the aid of a geographic information system-based analysis for the Swiss Canton of Zurich. By identifying suitable DH areas, primarily supplied by non-renewable energy carriers, are assigned to renewable heat sources. This method allows to explore the possible bandwidth and key factors of the potential for future scenarios until 2050, related to developments of DH technology and policy efforts regarding buildings directives. The results show that high-temperature (HT) DH could be doubled, and that the EH potential is quantified at 3.75 TWh_{th}/a for 2020 (five times the current value) and 3.25 TWh_{th}/a for 2050, in the same scenario.

Keywords: Energy hubs, District heating, Distributed multi-energy systems, Bottom-up modeling, Geographic information system, Spatial analysis

NOMENCLATURE

Abbreviations	
a	Annum
A	Area
AWEL	Office of Waste, Water, Energy, and Air of the Swiss Canton of Zurich
BAU	Business as Usual
EH	Energy Hub
ERA	Energy reference area
ES2050	Energy Strategy 2050
GHG	Greenhouse gas
GIS	Geographical Information System
HT(-DH)	High-temperature (district heating)
LT(-DH)	Low-temperature (district heating)
MFH	Multi-family house
MuKEn	Mustervorschriften der Kantone im Energiebereich
NEP	New Energy Policy
ÖREB	Cadaster of public restrictions on land ownership
th	Thermal

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1. INTRODUCTION

Like many other industrialized countries, Switzerland is aiming at a substantial reduction in greenhouse gas (GHG) emissions to net zero by 2050 [1]. Triggered by signing the Kyoto Protocol 1997, this should help to fulfill the goal of the Paris Agreement of 2016, i.e. to limit the global warming to 1.5 °C by 2100 compared to the preindustrial era.

The building sector of Switzerland is responsible for more than 40% of final energy consumption and about the same amount of GHG emissions. By fostering energy efficiency, the use of renewable energies [2], and energy-saving measures regarding space heating and domestic hot water preparation, the Swiss federal government is making efforts to reach the goals of the Energy Strategy 2050 (ES2050).

One way to improve the energy efficiency and emission intensity of buildings is deploying Energy Hubs (EH). In general, an EH is a multi-carrier energy system that can be achieved through local system planning and the integration of renewable energies. Using energy conversion and storage technologies, the generation and consumption of variable renewable energies (VRES) can be balanced. Furthermore, EH could link different energy infrastructure to balance and optimize integrated energy systems.

Coupling at least two different energy networks can result in synergy effects. In particular, merging the electricity with the heat infrastructure could result in energy and cost savings in comparison to uncoupled networks. Therefore, this study focuses on linking the electricity network with the district heating (DH) network by EH that harness low-temperature renewable heat sources with centralized or decentralized heat pumps. To narrow down the broad spectrum of possible DH networks, the focus is on DH networks of the fourth generation [3]. Those are possibly bidirectional low-temperature (LT) (<70 °C) smart thermal networks, where grid losses are low and cooling demand can also be supplied. Additionally, the fourth generation is characterized by the "ability to recycle heat from low-temperature sources and integrate renewable heat sources such as solar and geothermal heat" [3]. The possibility of using lower temperatures comes along with heat pumps, which deploy e.g., geothermal or surface water heat sources.

By complementing with short- or long-term thermal energy storage systems, DH networks would also enable high fuel efficiency and low-cost energy systems [4].

Other advantages of EHs are maximizing the harvesting of renewable energies from building-integrated systems and the possibility to share energy between different consumers and producers within the network. It results in balancing load profiles of different users in the same network and helps to raise energy efficiency (e.g. [5]). The investment costs per unit of installed capacity decline due to economies of scale [6].

Thus, EH is a technology that enables to facilitate and integrate more renewable energies, to match locally production with consumption, to raise the security of the supply, and to reduce GHG emissions [7,8].

This paper aims to evaluate the technical diffusion potential of EHs and provide a general feasibility study to reach an optimal speed of diffusion, in terms of social and technical restrictions. The specific focus is evaluating potential fourth generation DH areas in the Swiss canton of Zurich.

This study aims at evaluating the technical diffusion potential of (i) HT DH networks and (ii) EH coupling the electricity network with the low-temperature DH network in the Swiss canton of Zurich over time with consideration of the building stock evolution? More precisely, the technical potential of HT DH networks and of EH with low-temperature district heating networks by considering local renewable heat sources and the building stock development. The technical potential is thereby measured in two ways: as a spatial technical potential in hectares and as a heat energy potential in GWh_{th}/a. Scenarios with different heat density thresholds are analyzed, economic feasibility is implied but not specifically calculated, the technical potential represents the maximum adoption potential. A GIS-based spatial analysis for the case of the Swiss canton of Zurich is conducted to identify suitable areas and link them to nearby renewable heat sources.

The case of the Swiss Canton of Zurich was selected for three reasons. First, the federal constitution of Switzerland is aiming for 2.2 tons (t) of CO_2 per capita and year by 2050 [9], which means that the emissions for space heating and domestic hot water should not exceed 0.5 t/(cap*a); current values are around 2 t/(cap*a) [10]. The second reason is the size and diversity of the canton. Different regional areas like urban, suburban, and rural areas, with different population densities can be transferred to other similar areas. Various renewable heat sources can be divided into directly used (e.g. biomass, waste and industry) and such utilized by heat pumps (different water resorts and geothermal). A more detailed specification can be found in [11] (esp. Table 1). The last reason is the availability of data, which is more detailed than on the national scale.

2. DATA AND METHODOLOGY

2.1 Data

To determine the LT- and HT-DH potential at the hectare level requires geo- and time-dependent information about heat supply and demand. The dataset used is based on three nation- or canton-wide sources.

First, the Swiss heat energy atlas [12]. It contains spatially disaggregated and projected annual heat demands at the hectare level for residential, commercial, and industrial buildings. This dataset distinguishes between the energy carrier share of the projected heat from oil or gas, and renewable heat from heat pumps or district heat supplied by a DH network. According to this dataset, the existing HT-DH network of the Canton of Zurich has an area of 1912 ha and a capacity of 749.98 GWh_{th}/a. The average energy carrier share of DH is 43%, i.e. less than half of all buildings within the area are connected to the network. The energy carrier shares of industrial buildings are not provided, so that these are not considered in the analysis (they account for only 11% of the total heat demand of the Swiss Canton of Zurich, cf. Table 1, so ignoring them here seems justifiable). The demand for process heat (~1000 °C), which is around ten times higher than the domestic heat demand, would also expand the DH potential.

Table 1. Heat demand statistics, by building category

	Total [GWh_{th}/a]	Mean/Median/Max. [MWh_{th}/ha/a]	Area [ha]
Resid.	8049	274 / 220 / 3643	28,250
Comm.	5723	195 / 38 / 70,488	29,344
Industr.	1775	1759 / 720 / 47,640	1009

The projected heat demand is based on the Federal Statistical Office's 2014 Buildings and Dwellings register [13], which is the second dataset used, aggregated to the hectare level. It contains building information on classification, construction year, dwelling surface area, and geographical coordinates. More specifically, twenty different building types are distinguished according to the Eurostat nomenclature [14]. The average dwelling size is used to determine buildings that need to be renovated. By dividing the respective heat demand with the respective cumulative residential area of dwellings, the average specific heat demand within each grid cell is calculated (for residential buildings 113 $kWh_{th}/m^2/a$). By comparing each cell with heating standards and thresholds, grid cells are determined on which renovation is to be carried out in the model.

The cantonal GIS-database "GeoLion" [15] is used for georeferenced renewable heat sources in the Canton of Zurich. The renewable energy sources considered and their heat potentials are reported in Table 2. Data restrictions, such as expected decommissioning of power plants, are taken into account. For wood-fired power- and fermentation plants, the actually generated heat is specified in the dataset instead of the potential. In addition, only larger wood-fired power plants with an installed capacity of 1 MW_e or more are included. Utilization of surface water sources (river or lake) is only considered for a maximum distance of 500 meters (m) from the shore; similarly, geothermal potential cannot be harnessed everywhere through heat pumps. To protect drinking water reservoirs, it is prohibited to harness heat with ground sourced heat pumps near groundwater resources [16].

Table 2. Renewable energy sources and heat potentials

Energy source	Potential [TWh_{th}/a]	T level of DH network
Waste incineration plants	1.524	HT
Wastewater treatment plants	0.67	HT / LT
Waste wood, sewage sludge-CHP	0.293	HT
Wood-fired power plants	0.2 (used)	HT
Fermentation plants	0.08 (used)	HT
Heat from surface waters (lake, river)	1.75	LT
Geothermal heat	n/a	LT

2.2 Method

A simulation model is run from 2017 to 2050, with an annual time resolution, and combined with a bottom-up simulation of the building stock development (for further methodical details see [11]). A spatial resolution of 100 x 100 m (determined by a geographical information system / GIS-based urban energy system assessment [17,18]) results in over 170,000 examined grid cells for the Canton of Zurich. To identify the potential of heat supply, a higher resolution is not needed. QGIS and NetLogo, two open-source software tools, were mainly used to perform the analysis. The first is a free GIS that supports analyzing and processing georeferenced data, the second is a tool mainly used for agent-based modeling [19]. The above-presented data sets are imported into QGIS using the Swiss coordinate system CH1903+ and the swissBOUNDARIES3D map, which encompasses the municipal boundaries [20]. Further, it is used to check the *plausibility* of the data by comparing it with other sources (e.g. Google Maps), sort and aggregate it to the hectare level, visualize it, and process it in the right format for NetLogo. NetLogo's GIS extension enables geographic referencing through projections that correlate grid cells with positions in space. For this study, the GIS extension is exploited to import the processed shapefiles from QGIS and implement a raster of 100 × 100 m. To answer the elaborated research question, the implemented model in NetLogo follows a 6-step modular approach (Fig. 1).

Module 1: Clustering of the existing DH grid. To cluster grid cells with the existing HT district heating, a spatially based algorithm is developed. It forms connected DH networks, with grid cells of a distance of less than 500 m, which is the most suitable threshold to reproduce the existing network.

Module 2: Assignment of clusters to renewable heat sources. The clustered grid cells are assigned to nearby heat sources less than 500 m away. Heat sources with a higher value of heat are preferred to get a unambiguous assignment. Remaining potentials of a source are updated by subtracting the heat demand of the cluster. Nearest other sources are taken into account if one source is insufficient.

Module 3: Technical feasibility of grid cells. Areas with higher heat densities can be supplied by more heat within the DH network, resulting in a higher expected economic efficiency, which is important for offering low-cost energy presupposes economic viability. Therefore, heat density thresholds are often used to explore suitable areas [21]. According to "Planungshandbuch Fernwärme" [22], the stated value of the suitability criterion for Switzerland is 700 MWh_{th}/ha/a. Areas between 500 and 700 MWh_{th}/ha/a are only conditionally suitable, whereas areas below 500 MWh_{th}/ha/a are not considered. These heat density feasibility-thresholds apply, above all, to older generation HT-DH networks with flow temperature levels above 70 °C. Several heat density threshold values were considered in this study in order to take the DH technology development into account, especially for LT-DH. A grid cell is defined as technical feasible, if the grid cell has a higher heat density than the exogenously specified heat density threshold, and if the energy carrier share of non-renewable energy sources is higher than renewable energy sources. The reasons for the latter are twofold, first replacing renewable heat supply with DH would be contradictory to the ES2050 targets, and second with renewable heat supplied buildings would likely not want to bear the costs of connecting to the DH network.

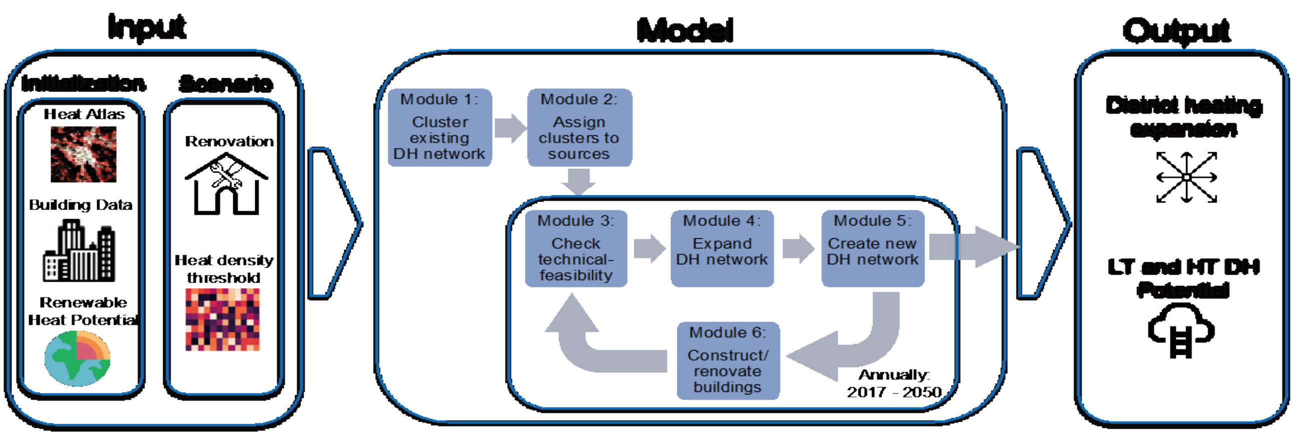

Fig. 1. Model overview

Module 4: Expansion of the existing DH network. This module addresses the potential for expanding the existing DH network into areas mainly supplied by non-renewable energy carriers. Internal and external expansion is distinguished. Internal expansion means that non-connected buildings are connected within the existing DH areas, to increase the energy carrier share to 100%; external expansion, in contrast, represents the spatial and capacitive expansion of the DH network to adjacent areas. External expansion is only possible if the technical feasibility criterion is fulfilled, the grid cell is less than 300 m away from an existing network (minimizing grid losses), and the heat source of the existing DH network has some remaining potential to supply the specific cell. If more than one adjacent grid cell fulfills all three conditions, a grid cell is selected randomly. Further it is assumed that all residential and commercial buildings on a grid cell are connected to the DH network, if a grid cell meets all three conditions. Since this study assesses the technical potential and not the market potential, this assumption is justifiable.

Module 5: Creation of new DH grids. If a technically feasible grid cell is close (< 500 m) to an unharnessed heat source and not connected to the existing DH network, a completely new DH network is constructed and, again, expanded until the potential is fully exploited.

Module 6: Construction and renovation of buildings. Due to energy-efficient refurbishment of the existing building stock, the economic viability of traditional HT-DH networks is reduced. Therefore, the last module realizes the time dependence of renovating the existing building stock to reduce the total heat demand and, on the other side, constructing new buildings which increases the total heat demand. New buildings are divided into single- and multi-family houses (SFH/MFH). A 5-year average number of annually newly constructed buildings is taken from [23] and provided with a variation of 10% of a normal distribution, and a reduction of 20% because an above-average number of new buildings has been constructed in recent years [24]. The latter was derived from modeling of population development, population forecast, and the assumption that the number of new buildings correlates with the population development of 2 million people in 2050 in the Canton of Zurich [25].

The building code MuKEn (Mustervorschriften der Kantone im Energiebereich), implemented for the aims of ES2050, was considered in the model as well. The relevant threshold value for new residential buildings is 48 $kWh_{th}/m^2/a$. The related area for the specific heat demand threshold refers to the energy reference area (ERA), as defined in SIA Standard 416/1 [26]. By the ÖREB cadaster, a cadaster of public legal restrictions on land ownership, grid cells are determined where new buildings may be constructed. Apart from other given zones, only residential zones (excl. historical core zones) were considered. A maximum value of 10 new buildings per grid cell was implemented in order to avoid unrealistically high numbers.

For renovations, MuKEn 2008 requires that the specific heat demand is reduced to 90 $kWh_{th}/m^2/a$ [26]. First, buildings with a specific heat demand of at least twice as high as the permissible specific heat demand standard of new buildings are renovated, later buildings with a higher specific heat demand. The number of annual renovations is exogenously given according to the renovation rates of the conducted scenarios.

In total, this methodology prioritizes HT-DT over LT-DH, because HT-DH is an established technology, and the sources of HT-DH networks provide a higher value of heat. All grid cells that meet the technical feasibility criterion and could not be assigned to an HT-DH network after performing modules 4 and 5, are potential areas for LT-DH networks.

2.3 Scenarios

Assessing the future technical potential of DH technologies, scenarios for different building refurbishment rates need to be considered, influencing both the heat demand and the temperature level of the network. Parameters of the scenario are divided into the demand- and supply-side. The annual renovation rate represents the demand parameter, the heat density threshold the supply side parameter. Nearby available heat sources determine the temperature level of the DH network. All three parameters are decisive indicators defined in [6]. The fourth parameter by Zach, the change in energy consumption density is modeled with scenarios for the energy refurbishment rate of the existing building stock and the construction of new residential buildings.

The scenarios are based on the ES2050. The "Business as Usual" (BAU) scenario corresponds to an average retrofit rate of 1% per year. The "New Energy Policy" (NEP) scenario would raise the retrofit rate to 2% p.a. [28]. Various scenarios are also executed to consider future improvements in DH technology that would increase the calculated potential. Through innovations in LT-DH technologies, low heat density areas could show technical potential. 400, 500, 600 and 700 $MWh_{th}/ha/a$ are the heat density threshold values used, the BAU scenario is used as reference with a heat density threshold of 700 $MWh_{th}/ha/a$.

3. RESULTS AND DISCUSSION

EH have large diffusion potential in the canton of Zurich. By expanding the current HT-DH network and identifying areas for EH, the capacity of EH-DH could be doubled with exclusively external, and even tripled with internal and external expansion. The EH potential of LT-DH could be increased five times and was about 3.75 TWh_{th}/a in the reference scenario.

3.1 High-Temperature District Heating Network

In total, 261 different clusters, in spatial sizes from 1 hectare (ha) to 693 ha, are created around the Canton of Zurich (for a graphical representation see [11], Fig. 3A). The largest cluster belongs to the area around the city of Zurich with 419 GWh_{th}/a, followed by the second-largest cluster of Winterthur with 128 ha and 71 GWh_{th}/a.

After clustering and assigning to nearby sources, external expansion is applied, as outlined in module 4 (for visualization cf. [11], Fig. 3B). For the initial simulation year and exclusive external expansion, the spatial increase for the canton is 520 ha, and the capacity increase 733 GWh_{th}/a, which is on average a doubled heat demand relative to the threshold value of 700 MWh_{th}/ha/a for the reference scenario. Especially the municipalities of the cities of Winterthur, Dietikon, Horgen and the northwestern part of the city for Zurich have large potential for expansion. Table 4 shows the capacitive and spatial expansion potential for these municipalities.

Table 3. Expansion potential of HT-DH for selected municipalities in the reference scenario (external expansion only)

	Spatial exp. [ha]	Spatial increase [%]	Cap. exp. [GWh_{th}/a]	Cap. increase [%]
Winterthur	180	115	268.4	357
Zurich	151	19	232.2	48
Dietikon	33	206	46.1	285
Horgen	28	33	36.9	153

Figure 4 shows the share of high-temperature district heating in total residential and commercial heat demand for the four largest municipalities in 2019. For the whole canton, the potential could be doubled from a 5% to a 10% share. In addition, the large expansion potential for the aforementioned communities can again be seen.

Different options for the ratio of spatial expansion to capacitive expansion of the future HT-DH network in the Canton of Zurich and for the reference scenario are possible. An exclusively external expansion has the maximal spatial expansion, with over 2400 ha developed HT-DH and a total heat demand of 1483 GWh_{th}/a. Creating completely new HT-DH networks has relatively small potential after exclusive external expansion. Exclusive internal expansion has a potential of 1556 GWh_{th}/a by connecting all buildings to the existing HT-DH network. Internal, followed by external expansion has a potential of around 2200 GWh_{th}/a (for a visualization see [11], Fig. 5). Note that almost all cells that have been connected with an exclusive external expansion can also be considered in this case. The limiting factor for a greater expansion of exclusively external expansion is the availability of technically feasible grid cells in the vicinity of the existing HT-DH network. The limiting factor is the potential of the available heat sources supplying the existing HT-DH network.

Creating completely new HT-DH networks, the potential for the entire Canton of Zurich is virtually zero. In total 35 ha with a capacity of 56 GWh_{th}/a. However, because the areas are spread over the whole canton the realization of new HT-DH networks is even more difficult but indicates that the existing HT-DH networks are well localized, and that their expansion is sufficient.

For the HT-DH network expansion potential in the future, the building stock development is needed. Assuming a renovation rate of 1% p.a., 254,785 or 33.78% of the initial stock will be renovated and 41,100 new buildings and 243,220 dwellings (12.57% and 32.24% of the initial stock) are constructed by 2050. That means, most of the modeled new buildings are MFH.

The specific heat demand decreases with the development of the existing building stock. The evolution of the average specific heat demand of residential buildings over time starts at around an average of 113 $kWh_{th}/m^2/a$ in 2017, and decreases or converges to approximately 70 $kWh_{th}/m^2/a$ until the end of the simulation in 2050.

Together with the building stock development and heat demand densities, the HT-DH potential for the BAU scenario (annual renovation rate of 1%) is presented over time in Figure 2.

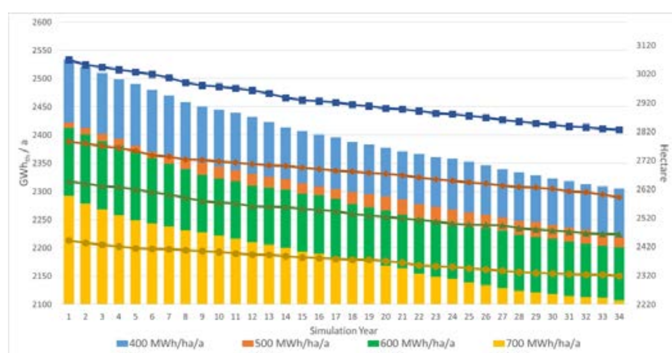

Figure 1. HT-DH potential as a function of time and heat demand densitites, BAU scenario. The y-axis on the left shows the capacity expansion in GWh_{th}/a (stacked bars), the y-axis on the right shows the spatial expansion in ha (lines).

The capacitive potential decreases for all heat density thresholds by approximately 8–9% (from the beginning of the simulation to the end). For a threshold of 400 MWh_{th}/ha/a, the capacitive potential for HT-DH is 10% higher and the spatial potential is 22% higher than for the reference value of 700 MWh_{th}/ha/a over the entire simulation period. This means that the relative increase in capacity does not correspond with the relative spatial increase, which illustrates the importance of the threshold for the results.

3.2 Low-Temperature District Heating Network

This section presents the spatial and capacitive potential of EH in the Canton of Zurich. Figure 3 shows the LT-DH potential as a function of time and heat demand densities for the BAU scenario (assuming again an annual renovation rate of 1%) without considering the limitations of available heat sources. The capacitive potential at the start of the simulation is 5 TWh_{th}/a for the reference scenario. Taking the reduction of heat demand through renovating buildings, it is reduced to 4.5 TWh_{th}/a at the end of the simulation. Taking a significantly lower heat density threshold of 400 MWh_{th}/ha/a, the potential increases to 8 TWh_{th}/a.

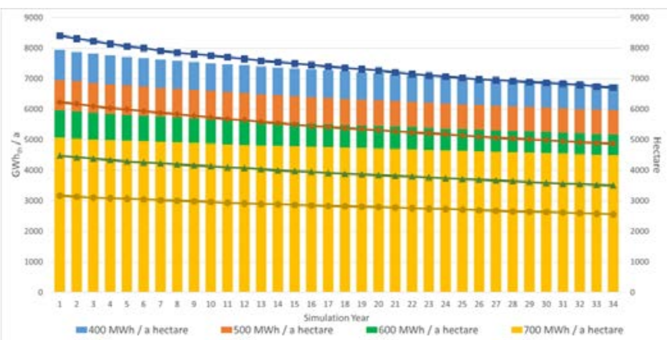

Figure 2. LT-DH potential as a function of time and heat demand densities, BAU scenario, w/o heat source information. See Fig. 2 for what the y-axes show.

The spatial LT-DH potential of the reference scenario is quantified to over 3100 ha to 2500 ha, from start to end of the simulation. Again with a lower density threshold of 400 MWh_{th}/ha/a, the spatial potential is 8400 ha and reduced to 6700 ha. The spatial decrease in both cases is around 20%, while for the reduction in the heat energy potential it is 11% for the reference scenario and 14% for a threshold of 400 MWh_{th}/ha/a.

Figure 4 illustrates the LT-DH potential as a function of time and renovation rates for a heat density threshold of 700 MWh_{th}/ha/a (showing the potential reduction from start to end of the simulation). Although the decrease of heat energy is 11%/20% for the BAU/NEP scenario, the spatial decrease in both is 9% higher than the decrease in heat energy. Hence, almost one third of today's feasible areas are no longer feasible in 2050 for the NEP scenario, and because DH networks are designed to operate at least 25 years, project planners must take these results into account.

Finally, the LT-DH potential is assessed by assigning it to available heat sources. As many networks are located outside geothermally favorable areas, the technically usable potential for LT-DH is lower. More than 1.25 TWh_{th}/a and 800 grid cells could not be assigned to a source in the reference scenario, so 3.75 TWh_{th}/a could be sourced by renewable heat sources. Furthermore, the great potential of the two lakes "Greifensee" and "Pfäffikersee" could be hardly harnessed. In contrast, the potential of Lake Zurich could be mostly utilized (Fig. 4).

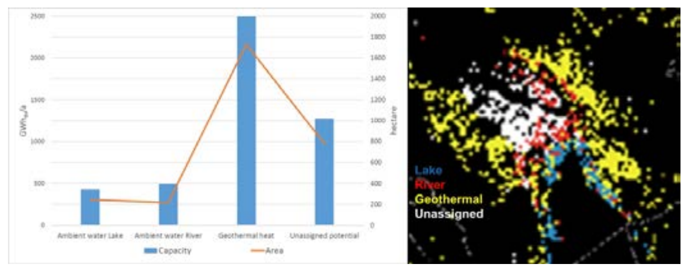

Figure 3. LT-DH potential assigned to sources for the reference scenario and enlarged picture of the city of Zurich

4. CONCLUSION

Using energy hubs and district heating could facilitate the integration of renewable energy systems and therefore reduce greenhouse gas emissions. This study aims to provide a technical feasibility analysis for HT-DH and EH with LT-DT networks. A GIS-based methodology was developed and the large spatial and capacitive potential of LT and HT-DH was demonstrated. The HT-DH potential could be doubled compared to the currently existing ones in the reference scenario and the LT-DH potential is quantified at 3.75 TWh_{th}/a for today (a 5-fold increase relative to current existing HT-DH network) and projected at 3.25 TWh/a for 2050. Based on these findings, it is recommended for policy-makers to create a White Book for LT-DH networks, where thresholds are specified that will indicate the economic feasibility and encourage the planning of LT-DH projects.

However, this study also has its limitations. In the case of an expansion, all buildings in an area are connected to a DH network, which is very unlikely.

Others are due to the lack of data or data quality that could be refined in future research.

Furthermore, the model could be expanded to incorporate time-dependent heat demands of commercial and industrial buildings and by also considering cooling demands. Future research could also include load profiles for different building types, enabling to estimate areas with full-load hours. Such areas would enhance the attractiveness, as investments into the grid infrastructure pay off earlier and increase the feasibility of DH systems.

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