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Abstract

The exploration of possible diffusion paths of technological innovations requires knowledge about the potential of the technologies concerned. The technical potential of energy hubs (EH) aimed at coupling the electricity and district heating (DH) network depends strongly 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 linking the development of the building stock with the spatial and capacitive low- and high-temperature DH potential through the aid of a geographic information system-based analysis for the Swiss canton of Zurich. The approach allows to identify suitable DH areas, primarily supplied by non-renewable energy carriers, and to convert these by assigning them to renewable heat sources. In order to explore the possible bandwidth and key factors of the potential until 2050, the method presented considers future scenarios related to developments of DH technology and policy efforts regarding buildings directives. The results show that the potential of high-temperature (HT) DH could be doubled in one of the scenarios. Furthermore, the EH potential is quantified in the same scenario to 3.75 TWh\textsubscript{th}/a for today (five times the current existing HT-DH network) and 3.25 TWh\textsubscript{th}/a for 2050.

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

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1.1 Introduction

Over the past two decades, the political aims of reducing greenhouse gas emissions and exploiting more environment-friendly, renewable and sustainable energy sources have been developed in most of the industrialized countries, often triggered by the signing and ratification of the Kyoto Protocol in 1997 (United Nations Framework Convention on Climate Change (UNFCCC), 1997). Switzerland is also aiming for a substantial reduction in greenhouse gas (GHG) emissions. The federal government announced at the end of August 2019 to target a reduction of net carbon emissions to zero by 2050 (Der Bundesrat, 2019). This aim fulfills the climate deal of the Paris Agreement, which targets to limit global warming to 1.5°C by 2100 compared with the pre-industrial era (United Nations Framework Convention on Climate Change (UNFCCC), 2016).

Buildings in Switzerland consumed in total 92 TWh; this represents more than 40% of final energy consumption and greenhouse gas (GHG) emissions in 2017 (Bundesamt für Energie, 2018a). To reach the goals of the Energy Strategy 2050 (ES2050), the Swiss federal government is increasing efforts in implementing energy-saving measures regarding space heating and domestic hot water preparation. Overarching goals of the ES2050 are ambitious carbon emission mitigation targets and the phaseout of nuclear power. Two main policy measures are targeted at achieving these goals: First, to raise energy efficiency, especially in buildings, and, second, to increase the use of renewable energies (Bundesamt für Energie, 2018b). This means that besides retrofitting of the existing building stock, also an increased share of renewables is required on the supply side of the heating sector.

However, the increasing share of volatile and intermittent renewable energies increases the necessity to balance generation and consumption at all times. Providing the necessary flexibility and facilitating the integration of renewable energies could both be ensured by “distributed multi-energy systems”. Grosspietsch, Saenger, & Girod, (2019) showed that there is a lack of common
terminology in the literature on these systems. Therefore, in this paper, the terminology Energy Hub (EH) is used synonymously to terms such as decentralized energy systems, multi-energy systems, distributed energy systems, or hybrid renewable energy systems.

EH are defined as multi-carrier energy systems, consisting of distributed energy technologies and energy networks. Through energy conversion elements, EH could link different energy infrastructures and allow the balancing or optimizing of the integrated energy system.

A rapidly growing body of literature exists on the EH concept and different modeling concepts associated with it (e.g. Favre-Perrod 2005; Grosspietsch et al. 2018; Pierluigi Mancarella 2014; Wasilewski 2015). In addition, Grosspietsch et al. (2019), Mohammadi et al. (2017) and Balakrishnan et al. (2016) reviewed the different concepts, terminologies, and models used. Furthermore, many studies address how to design, optimize, and plan or schedule EH, for example with mixed-integer linear programming or game-theoretical approaches (e.g. Geidl & Andersson, 2007; Mavromatidis et al. 2018; Orehounig et al. 2015; Rayati et al. 2015; Sharafi & ELMekkawy, 2014; Sheikhi et al.2015; Sobhani et al. 2020).

All of these studies have in common that at least two different energy networks are interconnected, which results in synergy effects. In particular, several studies show that an integrated view of the energy system by merging the electricity infrastructure with the heat infrastructure, creates synergetic advantages from a system-level perspective, and increases the benefits in terms of energy and cost savings compared to uncoupled network infrastructures (e.g. Bloess et al. 2018; H Lund et al. 2010; B. V Mathiesen et al., 2015; Pensini et al. 2014; Thellufsen & Lund, 2015). 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.

Following Lund et al., (2014), the following categorization is made between four generations of DH networks: High-temperature (HT), mostly unidirectional, DH systems of the first (1880-1930), second (1930-1980), and third (1980-2020) generation are centralized, by pressurized hot water or steam distributed, and fossil-fueled systems. The high temperature (> 70°C) in these DH networks entails significant transport losses.

DH networks of the fourth generation are concepts of possibly bidirectional low-temperature (LT) (< 70 °C) smart thermal networks, where grid losses are less than in previous generations, and where also cooling demands could be supplied. While older DH generations with relatively high grid losses are primarily linked to buildings with high heat demands and high flow temperatures, the connection of newly constructed, or comprehensively renovated low energy
buildings requiring low flow temperatures, is also possible with DH systems of the fourth generation. 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” (Henrik Lund et al., 2014 p. 3). The possibility to use distributed heat of lower temperatures comes along especially with absorption or compression heat pumps, which deploy for example geothermal or surface water heat sources. EH are associated in this paper exclusively with DH networks of the fourth generation.

All four generations of DH systems are commonly viewed as promising technologies for raising the energy efficiency and decreasing GHG emissions of space- and domestic hot water heating in buildings (Connolly et al., 2012; International Energy Agency, 2014; Mathiesen, Lund, & Karlsson, 2011; Rezaie & Rosen, 2012). Moreover, from an integrated system perspective, with increasingly volatile and intermittent solar or wind power shares, DH networks would also enable high fuel efficiency and low-cost energy systems by complementing them with short- or long-term thermal energy storage systems (David, Mathiesen, Averfalk, Werner, & Lund, 2017). Electric storage units can also achieve this but are more expensive and less efficient due to the small number of charging cycles (Henrik Lund et al., 2014; Mathiesen et al., 2015).

Several advantages are coming along with the EH approach of coupling the electricity network with the district heating network. One of them is to maximize the harvesting of renewable energies from building-integrated systems. Another advantage is the possibility to share energy between different consumers and producers within the network. Besides, the load complementarity of different users on the same network fosters the balancing of load profiles and helps to raise energy efficiency (e.g. Zhang et al., 2018). Furthermore, the investment costs per installed capacity unit of the energy system components are reduced due to economies of scale (Zach, Erker, & Stoeglehner, 2019). Thus, from a policy perspective, an EH is a complementary technology to facilitate and integrate more renewable energies, to match locally production with consumption, to raise the security of the supply, and to reduce greenhouse gas emissions (Grosspietsch et al., 2018; Mancarella, 2014).

1.2 Research scope

This paper aims to evaluate the technical diffusion potential of EH and to provide a preliminary feasibility study for project developers, municipalities, and policy-makers evaluating whether and when public interventions seem appropriate to catalyze the process in order to reach the optimal
speed of diffusion (e.g. from a social welfare perspective). The focus here is particularly on the evaluation of potential fourth generation DH areas in the Swiss canton of Zurich.

However, the technical potential – i.e. the potential which can be used under technical and geobiophysical restrictions – of DH depends strongly on local conditions regarding supply and demand. Especially, local renewable energy sources are characterized by spatial availability, which could limit their compatibility with the prevailing demand (Schneider et al., 2016).

For local renewable energy- and network-planning spatial information technologies, particularly Geographical Information System (GIS)-based analyses are more commonly used. Brewer et al. (2015); Hong et al. (2014); Janke (2010); Sun et al. (2013) and Wang et al. (2016) applied this method to analyze the potential of solar PV generation on a regional scale. There is also a range of studies evaluating the wind energy potential with this approach (e.g. Baban & Parry, 2001; Sliz-Szkliniarz & Vogt, 2011; Voivontas et al., 1998). Furthermore, the approach was used for assessing the potential of biomass exploitation for energy production (e.g. Beccali et al., 2009; Messineo et al., 2012; Singh et al., 2008).

More recent studies have also used the GIS-based approach to determine the DH potential (e.g. Chambers et al., 2020; Chambers et al. 2019; Dochev et al. 2018; Gils et al. 2013; Leurent 2019; Maria Jebamalai et al. 2019; Nielsen and Möller 2013). Gils et al. (2013) applied the GIS-based approach to the continental US and determined a technical DH supply potential of up to 43% of the total heat demand in residential and commercial buildings. Leurent (2019) analyzed the DH potential for France, and the potential if the heat demand is uniformly reduced by 50% in 2050. Nielsen and Möller (2013) showed how the heat atlas of Denmark combined with a GIS model of DH costs could be used to assess the potential of DH for different scenarios regarding reduced heat demands. They revealed that in one of their scenarios, the technical DH potential is 63% of the Danish built-up area. Dochev et al. (2018) enhanced the use of heat atlases or heat cadasters for DH potential analyses by combining these with street networks for the city of Hamburg. They developed a method to estimate the linear heat density and explore areas potentially suited for a new heat distribution grid. Maria Jebamalai et al. (2019) developed a plug-in for GIS software that enables the automation of the planning and designing of DH systems with given network constraints, demonstrating its usefulness by a case study of a neighborhood in the Dutch city of Nijmegen. Chambers et al., 2020 performed a spatiotemporal analysis of the potential for supplying DH networks with industrial excess heat in Switzerland. They found that 17.4% of the Swiss heat demand could be supplied by industrial excess heat when using LT DH networks with seasonal storage.
Chambers et al. (2019) investigated, with a heat atlas approach, the technical DH potential for high- and low-temperature networks in Switzerland under different scenarios. They demonstrated that DH systems could supply 53% of the total Swiss heat demand by considering high- and low-temperature networks. Furthermore, they developed a method to estimate the linear demand density with a logarithmic relation between the number of buildings and the minimum pipe length of the DH network.

However, the DH potential analysis of Chambers et al. (2019) for Switzerland shows some limitations. New constructions and the retrofitting of buildings were not modeled. Thus, the overall demand accounts for neither the added demand of new buildings nor the annual heat demand decrease of renovated buildings. Moreover, the DH network potential is not shown over time; i.e., the development of the building stock is not considered. Hence growing or declining areas are not identified, but the authors merely assessed a scenario for 2050 by uniformly decreasing the heat demand by 50%. Besides, they focused exclusively on the demand side and did not consider the availability of heat sources. However, attractiveness of DH relies heavily on the accessibility to local and in particular renewable heat sources. This limitation reduces the DH potential identified and ignores a fundamental determining factor for DH network development.

The objective of this paper is to close the identified research gap by answering the following research questions: What is the technical diffusion potential of HT DH networks and of 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?

The aim of this paper is to evaluate 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 GWhth/a. Note that by considering scenarios with different heat density thresholds, economic feasibility is implied but not specifically calculated (e.g. by means of a discounted cash flow analysis). 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.

1.3 Research Case

The rationale for choosing a cantonal scope and case is threefold. First, it is derived directly from the federal constitution of Switzerland by assigning the responsibility for achieving climate
targets in the building sector to the cantons (Swiss Confederation Article 89 paragraph 4, 1999). The Swiss canton of Zurich is aiming for 2.2 tons (t) CO₂ per capita and year by 2050 (Regierungsrat Kanton Zürich, 1983), which means that the emissions for space heating and domestic hot water should not exceed 0.5 t/(cap*a). The emissions for space heating and hot water are presently at around 2 t/(cap*a) (AWEL, 2018).

The second rationale for choosing the Swiss canton of Zurich for this case study is its size and diversity. With urban, suburban and rural areas, and in particular with the two high population density areas (the cities of Zurich and Winterthur), the case study is sufficiently heterogeneous in order to transfer the findings of this study to similar other regions. From a supply perspective, the Swiss canton of Zurich is chosen because it has various renewable heat sources that could supply the EH or LT-DH. Renewable heat sources are divided into two groups, sources that are utilized directly and sources that are utilized by heat pumps (see Table 1). Depending on the renewable heat source, the temperature level of the DH network is defined in this study. For low-temperature DH networks, centralized or decentralized heat pump substations near the end-user are needed to lift the flow temperature to 60 °C and decrease the risk of Legionella bacteria growth (Bundesamt für Gesundheit, 2009).

The third rationale is the availability of data. On a cantonal scale, more detailed data is available for this study than on a national scale.

Table 1: Classification of low-temperature (LT) and high-temperature (HT) district heating networks based on renewable energy sources

<table>
<thead>
<tr>
<th>Utilization Type of heat Source</th>
<th>Fuel Direct</th>
<th>Residual</th>
<th>Heat Pump</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>HT</td>
<td>HT</td>
<td>HT</td>
<td>LT/LT</td>
</tr>
<tr>
<td>Wood</td>
<td>HT/LT</td>
<td>LT/LT</td>
<td>LT</td>
<td>LT</td>
</tr>
<tr>
<td>Waste</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
</tr>
<tr>
<td>Industry</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
</tr>
<tr>
<td>Wastewater</td>
<td>HT/LT</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
</tr>
<tr>
<td>Lake</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
</tr>
<tr>
<td>River</td>
<td>LT/LT</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
</tr>
<tr>
<td>Groundwater</td>
<td>LT/LT</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
</tr>
<tr>
<td>Geothermal</td>
<td>LT/LT</td>
<td>LT</td>
<td>LT</td>
<td>LT</td>
</tr>
</tbody>
</table>

2 Data and Methodology

2.1 Data

The determination of the LT- and HT-DH potential at the hectare level requires geo- and time-dependent information about heat supply and demand. The georeferenced datasets used in this study are mainly based on three nation- or canton-wide available open sources.

The first source is the Swiss heat atlas, which was published end of July 2019 and is used as a basis for this study. The heat atlas is provided by the Swiss Federal Office of Energy (Bundesamt für Energie BFE, 2019) and contains spatially disaggregated and projected annual heat demands at the hectare level of residential, commercial, and industrial buildings. Figure 1 shows an example
of the heat demand for the city of Zurich. Residential and commercial demands are displayed in
different shades of red and industrial demands in various shades of blue reflecting the heat demand
values of the individual hectares.

Furthermore, this dataset distinguishes between energy carrier share of the projected heat
demand for residential and commercial buildings, i.e., non-renewable heat from oil or gas, and
renewable heat from heat pumps or district heat supplied by a DH network. According to this data,
the Swiss canton of Zurich has an existing HT-DH network with an area of 1912 hectares and a
capacity of 749.98 GWhth/a. The average energy carrier share of DH in these areas is 43%, i.e. less
than half of all buildings within the existing HT-DH network area are connected to the network.

![Figure 1: Heat demand raster of the city of Zurich](image)
*Source: Own illustration, based on data from BFE (2019) and Google*

Although the information on industrial heat demand exists in the Swiss heat atlas, the energy
carrier shares are not given for industrial buildings. Therefore, the heat demand of industrial
buildings is not taken into account in this study for assessing the technical DH potential. Another
reason for not considering industrial buildings is that they demand process heat. Process heat may
require much higher flow temperatures (~1000 °C), compared to residential and commercial
buildings, and is directly used for manufacturing goods or the treatment of materials. Residential
and commercial buildings, in contrast, are characterized by seasonal room heating demand and
constant domestic hot water demand throughout the year. The DH network temperature does not
need to be higher than 100 °C for this requirement.
However, neglecting industrial heat demand is a small limitation, since industrial buildings account for only 11% of the total heat demand in the Swiss canton of Zurich (cf. Table 2). Approximately 52% of the total heat demand in the canton of Zurich is from residential and 37% from commercial buildings. The highest heat consumers in the canton are the university hospital (70.49 GWhth/a) in the city of Zurich and the international Zurich Airport (66.65 GWhth/a).

Table 2: Heat demand statistics according to building categories

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>8,049</td>
<td>274</td>
<td>220</td>
<td>3643</td>
<td>28,250</td>
</tr>
<tr>
<td>Commercial</td>
<td>5,723</td>
<td>195</td>
<td>38</td>
<td>70,488</td>
<td>29,344</td>
</tr>
<tr>
<td>Industry</td>
<td>1,775</td>
<td>1759</td>
<td>720</td>
<td>47,640</td>
<td>1009</td>
</tr>
</tbody>
</table>

The projected heat demands, in turn, are based on the Federal Statistical Office's 2014 Buildings and Dwellings register (Bundesamt für Statistik, 2014). This is the second dataset implemented in the present model but again aggregated to the hectare level. Building information on classification, construction year, dwelling surface area, and geographical coordinates are included in this dataset, which is explained in more detail next.

Twenty different building types (residential and non-residential) according to the Eurostat nomenclature (Eurostat, 1998) are implemented in the model. Additionally, for residential buildings the net dwelling areas are given. The average dwelling size in the Swiss canton of Zurich is 97 m². The information on the surface area of dwellings is crucial in order to determine buildings in the model that need to be renovated. The average specific heat demand within each grid cell is calculated by dividing the respective residential heat demand with the respective cumulative residential area of dwellings. The average specific heat demand of residential buildings is 113 kWhth/m²/a. By comparing the specific heat demand of each grid cell with heating standards and thresholds, the grid cells on which a renovation is to be carried out in the model are determined.

The third dataset contains the georeferenced renewable heat sources in the Swiss canton of Zurich, which is obtained from the cantonal GIS-database “GeoLion”(Amt für Raumentwicklung des Kantons Zürich (Baudirektion), 2019). Implemented renewable energy sources and their heat potential are listed in Table 3. Some of the potential sources in this dataset have restrictions that have been taken into account in the model.
Table 3: Renewable Energy Sources

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Potential [TWhth/a]</th>
<th>Temperature level of the district heating network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste incineration plants</td>
<td>1.524</td>
<td>High-Temperature</td>
</tr>
<tr>
<td>Wastewater treatment plants</td>
<td>0.67</td>
<td>High-/Low-Temperature</td>
</tr>
<tr>
<td>Waste wood and sewage sludge-CHP</td>
<td>0.293</td>
<td>High-Temperature</td>
</tr>
<tr>
<td>Wood-fired power plants</td>
<td>0.2 (actually used)</td>
<td>High-Temperature</td>
</tr>
<tr>
<td>Fermentation plants</td>
<td>0.08 (actually used)</td>
<td>High-Temperature</td>
</tr>
<tr>
<td>Heat from surface waters (lake or river)</td>
<td>1.75</td>
<td>Low-Temperature</td>
</tr>
<tr>
<td>Geothermal heat</td>
<td>n/a</td>
<td>Low-Temperature</td>
</tr>
</tbody>
</table>

For example, the waste incineration power plant at Josefstrasse in the city of Zurich, with a heat potential of 0.33 TWhth/a, is expected to be decommissioned in 2022 (Stadt Zürich Tiefbau- und Entsorgungsdepartment, 2017). Therefore, the potential of that plant is already excluded in the model. For wood-fired power- and fermentation plants, the actually generated heat is specified in the dataset and not the potential. In addition, only larger wood-fired power-plants with an installed power capacity of 1 MW or more are included. Besides, the utilization of surface water sources (river or lake) is considered only for areas with a maximum distance of 500 meters (m) from the shore. Similarly, the geothermal potential cannot be harnessed everywhere through ground sourced heat pumps. It is prohibited to harness heat with ground sourced heat pumps in order to avoid the pollution of drinking water reservoirs near groundwater resources (AWEL, 2010).

2.2 Method

By means of a joint evaluation of the described datasets combined with the bottom-up simulation of the building stock development, the results of the present study are obtained. The model overview in Figure 2 illustrates the conceptual framework. The simulation is run from 2017 to 2050 with a temporal resolution of one year. The spatial resolution of a GIS-based urban energy system assessment is a central factor determining the resulting potentials (Jalil-Vega & Hawkes, 2018; Pfenninger et al., 2014). Hence, the spatial resolution of the presented model is 100 m × 100 m, allowing an extremely high spatial analysis of areas with a technical DH potential (i.e. exceeding the minimum energy density threshold reported further below). This represents over 170,000 grid cells (hectares) for the Swiss canton of Zurich. There is no need to use an even more detailed building-scale resolution, as the aim of the present study is not to determine the optimal allocation of heat supply but merely to identify the technical potential.

Mainly two open-source software tools were used to perform the analysis. QGIS (QGIS Development Team, 2019) is a free geographic information system that supports analyzing and processing georeferenced data. The data sets presented above are imported into QGIS using the
Swiss coordinate system “CH1903+” and the swissBOUNDARIES3D map, which encompasses the municipal boundaries (Bundesamt für Landestopografie, 2019). In this study, QGIS is also 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 the other tool. The second tool is NetLogo (Wilensky, 1999), a tool mainly used for agent-based modeling. 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\(^1\) from QGIS and implement a raster of 100 m × 100 m.

To answer the elaborated research questions, the implemented model in NetLogo follows a six-step modular approach, which is explained in more detail in the following sections.

**Module 1: Clustering of the existing DH grid**

A spatially based clustering algorithm is developed to cluster grid cells with existing HT district heating. Adjacent grid cells, with a distance of less than 500 m to each other, and district heating shares are combined to form a connected DH network. The threshold value of 500 m is calibrated by comparing different threshold values and the resulting clusters with maps of existing DH networks in the Swiss canton of Zurich. 500 meters is the most suitable threshold to reproduce the existing network.

**Module 2: Assignment of clusters to renewable heat sources**

After clustering the existing DH grid cells, the clusters are assigned to nearby heat sources with a distance of less than 500 m. Some clusters could be supplied by different nearby heat sources. In

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\(^1\) The shapefile format is a geospatial vector data format for GIS software.
order to obtain an unambiguous assignment, heat sources with a higher value of heat are first considered. The priority of the assignment is adopted from the “White Book District Heating Switzerland”, as shown in Table 3 (Eicher+Pauli i.A. Verband Fernwärme Schweiz (VFS), 2014). To update the remaining potential of a source, the aggregated heat demand of a cluster is subtracted from the capacity of the heat source to which it is assigned. The nearest other sources are also taken into account if one source is insufficient.

Module 3: Technical feasibility of grid cells

Offering low-cost energy presupposes economic viability. Spatially high concentrated heat demand is, besides the distance from the heat source to heat consumers, an indicator of the economic viability of a heat network. The higher the heat density, the more heat can be supplied with the DH network, and the higher is the expected economic efficiency. Therefore, heat density thresholds are often used to explore suitable areas (Gils et al., 2013). According to “Planungshandbuch Fernwärme” (EnergieSchweiz Bundesamt für Energie BFE, 2017, p. 108), the stated value of the suitability criterion for Switzerland is 700 MWhb/ha/a. Areas with a heat density of 500-700 MWhb/ha/a are only conditionally suitable and areas below 500 MWhb/ha/a are not considered as suitable for DH at all. These heat density feasibility-thresholds apply, above all, to older generation HT-DH networks with flow temperature levels above 70 °C. Significantly lower values are also given in other sources (Chambers et al., 2019). Especially for LT-DH networks, heat density threshold values may be significantly lower. In order to take account of the DH technology development, and as a robustness check of the results, this study considers several heat density threshold values.

The technical feasibility of a grid cell is defined by the values of the heat density and energy carrier share. Grid cells are classified as technically feasible for DH if the following two conditions are met: First, the grid cell has a higher heat density than the exogenously specified heat density threshold. Second, the energy carrier share of non-renewable energy sources (e.g., oil and gas) is higher than renewable energy sources (such as heat from heat pumps and district heat from renewables). The reason for the second condition is twofold: Replacing renewable heat supply with DH would be inefficient in achieving the ES2050 targets, and buildings already supplied by renewable heat would likely not want to bear the costs of connecting to the DH network.

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. Two expansion procedures, internal and external, are
defined to identify all possible options for the ratio of spatial expansion to capacitive expansion of the future HT-DH network. Internal expansion means that non-connected buildings within the existing DH areas are converted, thus increasing the energy carrier share of DH in the already existing DH areas to 100%. This represents an exclusive capacitive expansion without a spatial expansion. External expansion of the DH systems converts adjacent areas to the existing DH network and thus represents the spatial and capacitive expansion of the DH network. The external expansion of existing DH networks is identified in grid cells that meet the following three conditions: First, the technical feasibility criterion is fulfilled. Second, the grid cell is less than 300 m away from an existing network. This assumption is made to minimize grid losses. Third, the heat source of the existing DH network has some remaining potential to supply the specific cell. If more than one adjacent grid cell meets all of these conditions, a grid cell is selected randomly. The external expansion procedure further assumes that all residential and commercial buildings on a grid cell are connected to the DH network if the grid cell meets the three conditions mentioned. This simplifying assumption may be flawed, but since the objective of this study is to assess the technical potential and not the market potential, it is justifiable.

**Module 5: Creation of new DH grids**

This module initiates the construction of completely new DH networks on grid cells that meet the technical feasibility criterion, are close (less than 500 m) to an unharnessed heat source and not connected to the existing DH network. This initialized network is then again expanded until the potential is fully exploited.

**Module 6: Construction and renovation of buildings**

The economic viability of traditional HT-DH networks is reduced by the decreasing heat demand of the existing building stock due to an energy-efficient refurbishment. This effect may not apply in the same way for LT-DH networks, but in the technology emergence stage, economic feasibility is questionable anyway (Prando et al., 2015).

The last module realizes the time dependence of the model by constructing new buildings (increasing the total heat demand) and renovating the existing building stock (decreasing the total heat demand) with a bottom-up approach. Both of these processes are explained in more detail below.

Newly constructed buildings are divided into single-family houses (SFH) and multi-family houses (MFH). The number of annually newly constructed buildings is according to the five-year average (2013–2017) of the “statistics for newly built buildings with dwellings per municipality”
A normal distribution with a coefficient of variation of 10% is applied to these numbers. In addition, the values are reduced by 20% because an above-average number of buildings has been constructed in recent years (Statistical Office of the canton Zurich, 2017). The value of 20% was derived from the modeling of population development, population forecasts, and the assumption that the number of new buildings correlates with the population development. According to the Statistical Office of the canton of Zurich (2019b), the population in the canton of Zurich will be 2 million in 2050. Therefore, the population figures and the number of new buildings are reduced to the level of this projected value.

Besides, new buildings must meet the efficiency requirements by the MuKEn regulation (Konferenz Kantonaler Energiedirektoren, 2015). The MuKEn (Mustervorschriften der Kantone im Energiebereich) is a building code to implement the aims of the ES2050. The currently valid MuKEn 2008 requires for all new residential buildings a specific heat demand of 48 kWth/m²/a. This threshold is considered in the model. The area of the specific heat demand threshold refers to the energy reference area (ERA) and is defined in the SIA Standard 416/1 (Schweizer Ingenieur- und Architektenverein, 2007).

This study assumes that the ERA of a dwelling is equal to the size of the dwelling, as indicated in the buildings and dwellings register. In order to maintain the currently existing average dwelling size of 97 m² in the canton of Zurich, the model further assumes that new dwellings will also have a size of 97 m² on average. A normal distribution is modeled on the dwelling size with a coefficient of variation of 20%.

To determine grid cells or hectares in which new buildings could be constructed, the ÖREB cadaster – i.e. the cadaster of public legal restrictions on land ownership – is implemented (Office for Spatial Development of the canton Zurich, 2019). This dataset divides the whole canton into different zones, e.g. residential-, agricultural-, protection-, and historical core-zones. For the construction of new buildings and dwellings, only residential zones are considered during the entire simulation. Historical core zones of cities, which are also residential zones, are excluded. The decision in which grid cell exactly a building is to be constructed is made randomly in the set of areas described. In order to avoid unrealistically high numbers of buildings on a grid cell, the threshold value for the maximum number of buildings is set to 10.

Concerning renovations, the building code MuKEn 2008 requires that the specific heat demand is reduced to 90 kWth/m²/a (Konferenz Kantonaler Energiedirektoren, 2015). In the present model, it is assumed that buildings with a significantly higher heat demand than the construction standards for new buildings, according to MuKEn 2008, are more in need of renovation. Therefore,
buildings or dwellings with a specific heat demand of at least twice as high as the permissible specific heat demand standard of new buildings are renovated first, followed by buildings with a higher specific heat demand. A truncated normal distribution with the upper bound of 90 kWhth/m²/a is modeled with a coefficient of variation of 20%. The number of annual renovations is exogenously given according to the renovation rates of the conducted scenarios.

The methodology outlined in this section prioritizes HT-DH 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

Based on a system analysis according to Vester, (2002), Zach et al. (2019) identified temperature level, available heat sources, full-load hours and energy consumption density as decisive indicators for DH systems. Thus, when assessing the future technical potential of DH technologies, scenarios for different building refurbishment rates had to be taken into account, which influences both the heat demand and the temperature level of the network. This study considers three of the four indicators. The scenario parameters are divided into demand- and supply-side parameters. In particular, the annual renovation rate represents the demand parameter, and the heat density threshold the supply side parameter. The nearby available heat sources determine the temperature level of the DH network. 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 derived from ES2050, which again are similar to the scenarios in the World Energy Outlook 2018 of the International Energy Agency (IEA, 2018). 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% per year (Prognos AG i.A. Bundesamt für Energie, 2012). Various scenarios are also executed to consider future improvements in DH technology that would increase the calculated potential. Specifically, areas with low heat density could show technical potential through ongoing innovations in LT-DH technologies. The heat density threshold values considered in this study are 400, 500, 600 and 700 MWhth/ha/a. The reference scenario is defined as the BAU scenario with a heat density threshold of 700 MWhth/ha/a.
3 Results and Discussion

EH have great diffusion potential in the canton of Zurich. By using the described methodology, the expansion of the currently existing HT-DH network is examined and areas for EH were identified. The results from the reference scenario show that the HT-DH capacity could be doubled with an exclusively external expansion and even tripled with an internal and external expansion, compared to the current existing capacity in the canton of Zurich. The EH potential or LT-DH potential is quantified in the reference scenario at 3.75 TWhth/a, which is five times more than the currently existing HT-DH network.

3.1 High-Temperature District Heating Network

Figure 3A depicts the resulting clusters of the existing HT-DH network. In total, 261 different clusters are created, which is indicated by different colors. The spatial sizes of the clusters range from 1 hectare (ha) to 693 ha. The largest cluster in terms of area and capacity is in and around the city of Zurich with 419 GWhth/a, followed by the cluster in Winterthur with 128 ha and 71 GWhth/a, respectively.

![Figure 3 A: Resulting clusters for the existing high-temperature district heating network; B: Expansion areas of high-temperature district heating](image-url)
The external expansion module is applied according to the methodology outlined for module 4, and after the existing HT-DH network has been clustered and assigned to nearby sources. In order to show the possible areas of expansion more clearly, the existing network is omitted in Figure 3B. For the initial simulation year and an exclusive external expansion, the spatial increase for the entire canton is 520 ha, and the capacitive increase 733 GWh\textsubscript{th}/a. This also means that the grid cells considered for the network expansion have an average heat demand that is twice as high as the threshold value of 700 MWh\textsubscript{th}/ha\textsubscript{a}/a for the reference scenario. Especially the municipalities of the cities of Winterthur, Dietikon, Horgen, and the northwestern part of the city of Zurich, have great potential for expansion. Table 4 shows the capacitive and spatial expansion potentials for these municipalities. In Winterthur, the HT-DH network capacity could be expanded by over 350% and in Dietikon by over 280%.

<table>
<thead>
<tr>
<th>Municipalities</th>
<th>Spatial expansion [ha]</th>
<th>Spatial increase [%]</th>
<th>Capacitive expansion [GWh\textsubscript{th}/a\textsubscript{a}]</th>
<th>Capacitive increase [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winterthur</td>
<td>180</td>
<td>115</td>
<td>268.4</td>
<td>357</td>
</tr>
<tr>
<td>Zurich</td>
<td>151</td>
<td>19</td>
<td>232.2</td>
<td>48</td>
</tr>
<tr>
<td>Dietikon</td>
<td>33</td>
<td>206</td>
<td>46.1</td>
<td>285</td>
</tr>
<tr>
<td>Horgen</td>
<td>28</td>
<td>33</td>
<td>36.9</td>
<td>153</td>
</tr>
</tbody>
</table>

Figure 4 shows the high-temperature district heating share in the total residential and commercial heat demand for the biggest municipalities in the canton of Zurich, again for the reference scenario and an exclusive external expansion. For the whole canton, the potential could be doubled from a 5% to a 10% share in the total heat demand. In addition, the large expansion potential for the aforementioned communities can again be seen.
Figure 4: High-temperature district heating share in the total residential and commercial heat demand for an exclusive external expansion and the reference scenario

The hatched area in Figure 5 represents all possible options for the ratio of spatial expansion to capacitive expansion of the future HT-DH network in the canton of Zurich for the reference scenario. The maximal spatial expansion is for the case of an exclusive external expansion represented with the blue marker. Over 2400 ha are developed with HT-DH, with a total heat demand of 1483 GWhth/a. The yellow marker represents the relatively small potential of creating completely new HT-DH networks after an exclusive external expansion. The green marker represents an exclusive internal expansion. The graph also clearly shows that less than half of all buildings in the existing HT-DH areas are connected to the network. Thus 1556 GWhth/a are already accessible with only an internal expansion. The orange marker represents an external expansion after an internal expansion and the purple marker the potential to create completely new HT-DH networks for this case. Almost all cells that have been connected with an exclusive external expansion can also be considered in this case. From this, it can be deduced that the limiting factor for even greater expansion in the case of an exclusively external expansion is the availability of technically feasible grid cells in the vicinity of the existing HT-DH network. Conversely, this also means that the limiting factor for the external expansion after an internal expansion (orange marker) is the potential of the available heat sources supplying the existing HT-DH network.
Figure 5: Internal and external high-temperature district heating network expansion

The potential to create completely new HT-DH networks is virtually zero for the entire canton of Zurich. A total of 35 ha is identified as feasible, with a total capacity of 56 GWhth/a. However, these areas are spread over the entire canton, making the realization of new HT-DH network deployment even more difficult. This indicates that already existing HT-DH networks are well localized, and their expansion is sufficient.

Before the expansion potential of HT-DH network is presented over time and under consideration of various scenarios, the building stock development is shown. Table 5 displays that by 2050 more than 33% of all buildings or dwellings for the reference scenario had been renovated (assuming a renovation rate of 1% p.a.). In addition, over 40,000 new buildings and 240,000 new dwellings were constructed by 2050. This means that most of the modeled new buildings in the canton of Zurich are MFH. These figures vary slightly from simulation to simulation due to the above-mentioned stochastics in the model.

| Table 5: Development of the building stock until 2050 for the reference scenario |
|---------------------------------|----------------|----------------|----------------|
| Number                          | New buildings | New dwellings  | Renovated dwellings |
| Number                          | 41,100        | 243,220        | 254,785          |
| Share relative to initial stock | 12.57%        | 32.24%         | 33.78%           |

The specific heat demand decreases with the development of the existing building stock. Figure 6 reveals the evolution of the average specific heat demand of residential buildings over time. In
the initial simulation year 2017, the average is around 113 kWhth/m²/a and decreases or converges to approximately 70 kWhth/m²/a until the end of the simulation in 2050. The blue curve indicates the BAU scenario and the green curve the NEP scenario for the energy-efficient refurbishment rates of residential buildings. The yellow line at 48 kWhth/m²/a, shown as a reference, is the building standard for new constructions according to MuKen 2008.

As explained in the methodology, buildings with a much higher heat demand are considered first to be renovated. That is the reason for the slight convexity of the curves. In addition, as shown in Figure 6, the specific heat demand limit of 90 kWhth/m²/a for renovated buildings is not sufficiently strict to reach an average specific heat demand of less than 70 kWhth/m²/a for the canton of Zurich by 2050.

![Figure 6: Average residential specific heat demand over time](image)

After explaining the building stock development, the HT-DH potential can be presented over time. Figure 7 depicts the expansion potential of HT-DH networks as a function of time and heat demand densities over time for the BAU scenario (annual renovation rate of 1%). The columns, representing the capacitive expansion, belong to the primary vertical axis on the left, and the lines, representing the spatial expansion, to the secondary vertical axis on the right. The capacitive potential decreases for all thresholds by approximately 8% to 9% (from the beginning of the simulation to the end). Moreover, the capacitive potential for HT-DH is 10% higher for the heat density threshold value of 400 MWhth/ha/a than for the reference threshold value of 700 MWhth/ha/a over the entire simulation period. However, the spatial potential is 22% higher for the 400 MWhth/ha/a threshold value than for the reference threshold value. 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.

Figure 7: High-temperature district heating potential as a function of time and heat demand densities for the BAU scenario

The consequences of an annual renovation rate of 1% in the BAU scenario show, on the one hand, that the spatial potential decreases by 5.33%, and for the NEP scenario by 7.95%, at the end of the simulation. On the other hand, the capacitive potential decreases by 8.16% for the BAU scenario and 14.38% for the NEP scenario. Consequently, the renovation rate correlates more positively with the HT-DH capacity potential than with the spatial LT-DH potential.

3.2 Low-Temperature District Heating Network

This section presents the spatial and capacitive LT-DH potential that is associated with EH for the canton of Zurich. First, the potential is depicted over time without restrictions from available low-temperature heat sources. Second, the resulting cluster sizes of LT-DH networks are presented and discussed. This is followed by the LT-DH potential as a function of time and renovation rates. Finally, the potential is matched with available LT heat sources.

Figure 8 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 for the reference scenario (yellow columns) is 5 TWh/a. Taking into account the reduction of the heat demand over time through the renovation of buildings, the potential in terms of heat energy is
reduced to 4.5 TWhth/a at the end of the simulation for the reference scenario. Assuming feasibility for LT-DH networks with a significantly lower heat density threshold of 400 MWhth/ha/a (blue columns) increases the potential to 8 TWhth/a.

In addition, Figure 8 also shows the spatial LT-DH potential. For the reference scenario, the spatial potential is over 3100 ha at the beginning of the simulation and over 2500 ha at the end. For a heat density threshold of 400 MWhth/ha/a the spatial potential is over 8400 ha and is reduced to 6700 ha at the end. This means that the spatial decrease in both cases is around 20%. However, the reduction in the heat energy potential in the reference case is only 11% and for a heat density threshold of 400 MWhth/ha/a 14%.

Figure 8: Low-temperature district heating potential as a function of time and heat demand densities for the BAU scenario without heat source limitations

Figure 9 illustrates the LT-DH potential as a function of time and renovation rates for a heat density threshold of 700 MWhth/ha/a (showing the potential reduction from the beginning of the simulation to the end). Although the decrease in terms of heat energy is 11% for the BAU scenario or 20% for the NEP scenario, the spatial decrease in both scenarios is 9% higher than the decrease in heat energy. Hence, almost one third of all possible areas that would be feasible for a DH network today are no longer feasible in 2050 for the NEP scenario. As DH networks are designed to be operated for at least 25 years, project planners must take these results into account and avoid areas where the demand is reduced due to retrofitting.
Finally, the LT-DH potential is assessed by assigning it to available heat sources. Figure 10 shows that the technically usable potential for LT-DH is lower, as many networks are located outside geothermally favorable areas. More than 1.25 TWh_{th}/a and 800 grid cells could not be assigned to a source in the reference scenario. This means that the LT-DH potential which could be sourced by renewable heat sources is 3.75 TWh_{th}/a. Furthermore, the great potential of the lakes “Greifensee” and “Pfäffikersee” could be hardly harnessed, as there are no areas with high heat density in the vicinity. In contrast, the potential of Lake Zurich can be utilized completely. However, a large area in the city of Zurich cannot be supplied with LT heat sources, as there are groundwater resources underneath and it is therefore not permitted to use ground source heat pumps (cf. Figure 10 with the enlarged picture of the city of Zurich).
4 Conclusion

Reducing greenhouse gas emissions and exploiting more renewable and sustainable energy sources is currently one of the biggest challenges. Energy hubs and district heating systems could do both, facilitate the integration of renewable energy systems and reduce GHG emissions. Therefore, the present study aims to serve as a preliminary technical feasibility analysis for HT DH networks and EH with LT-DH networks. Through the GIS-based methodology developed in this study, the enormous spatial and capacitive potential of LT and HT-DH was demonstrated. The main results of this study are that the HT-DH potential could be doubled in the reference scenario and the LT-DH potential is quantified in the same scenario to 3.75 TWhth/a for the situation today (a fivefold increase relative to the current existing HT-DH network) and is projected to be 3.25 TWhth/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 has some limitations, most of which could be removed with future research. The model assumes in case of an expansion that all buildings in an area are connected to a DH network, which is very unlikely. Other limitations are due to the lack of data or data quality. Similar to the Heat Atlas, a “Cooling Atlas” should be considered, as LT-DH networks could also supply cooling demands. This could affect both the technical and economic feasibility of LT-DH networks.

The following topics for future research result from this study and its limitations. The model could be expanded to incorporate time-dependent heat demands of commercial and industrial buildings as well. Besides, cooling demands, which can affect the feasibility and therefore
potential of DH, could also be considered. Finally, future research could also include load profiles for the different building types, 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 even more.

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