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National spatio-technical potential for PTES in Sweden: A first-order assessment by criteria screening

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ABSTRACT

For Sweden, a country with one of the most developed district heating sectors in the world, the continued decarbonisation of central heat supplies and the contemporary development towards lower heat distribution temperatures is generating increased interest in large-scale seasonal thermal energy storage technologies. By virtue, not only of energy storage, but also of load shifting and peak shaving capabilities, seasonal storages are recognised today as key components in highly integrated and smart energy systems but have so far seen very limited application in Sweden. Given that Denmark, neighbour to Sweden and with a district heating development on par, is a world-leader in the application of pit thermal energy storages (PTES), this paper aims to initiate investigations into the possibilities for a similar application in Sweden. A spatial analysis sequence, akin to indicator modelling, identifies suitable areas for the construction of PTES by elimination of non-suitable areas based on a set of input data parameters and associated selection criteria, all within cost-effective heat transmission distances of aggregated district heating areas. The national potential in terms of available suitable land, expressed and discussed here by two model extremes scenarios, is generally high, but with local variations and with a characteristic latitudinal difference.

Keywords

District heating;
Pit thermal energy storage;
Criteria screening;
Spatial analysis;
National potential

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1. Introduction

Large-scale seasonal thermal energy storages are recognised today as essential and cost-effective system components in district heating systems (DHS) aiming to integrate higher shares of renewable and low-enthalpy energy sources [1-6]. Pit thermal energy storages (PTES) in particular [7, 8], often in combination with solar thermal heat production, have found vivid and remarkable Danish application over the last decades [9-11], but very limited use in Sweden. Although Sweden, in parallel, has been able to significantly decarbonise central heat supplies, mainly by using bioenergy, waste, and industrial heat recovery [12], expected sharper competition over biomass in the foreseeable future may very well alter current availabilities. In view of this and given the great developments in neighbouring Denmark, it is not unreasonable to wonder if a similar application would be possible also in Sweden?

This was the outset for the project "Solar district heating with pit storage for Swedish conditions", which ended in February 2025 after 26 months of operation and whose progress has been documented in two previous papers [13, 14] and one final project report [15]. For this paper, the final account, exclusive attention is focused on the pit storage aspect, which consists of a geographical study with spatial analysis and criteria screening, akin to indicator modelling. In this sense, this work relates to sustainable energy planning and management in particular [16,

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17], by method developments within the area of so-called continental mapping using publicly available data, as well as to the progression of smart energy systems in general [18, 19], by new findings concerning Swedish opportunities for large-scale PTES.

Given this focus and the current void of similar studies, the entire area of investigation represents something of a research gap, at least concerning the Swedish context. One recent report, Sköldberg et al. [20], investigated possible seasonal storage solutions for six Swedish district heating (DH) type systems. The study aimed at determining at what storage size, relative to annual district heat loads, the cost-benefit would be the greatest (suggesting 10% as most prevalent). The Swedish Energy Agency published a study on the Swedish solar thermal potential in 2021 [21], precursive to the project, confirming the sensitive interdependency with biomass prices and stating potentials up to 6.0 TWh/a depending on assumptions. However, none of these works took the spatial domain into consideration. While not limited to Sweden, a 2018 IEA SHC Task 52 report [22] did use a kindred spatial screening approach but with focus on land availabilities for solar collector fields, not for pit storages.

Thus, ploughing into new territory, the aim of this study is to evaluate the viability of a preliminary geographical investigation (first-order assessment) of suitable locations for large-scale PTES in vicinity of Swedish DHS and, if so, to answers the following research questions:

1. Is it possible to perform a first-order assessment of suitable land available for large-scale PTES in Sweden based on publicly available data?
2. What is the spatio-technical potential in terms of available suitable land for PTES within cost-effective heat transmission distances from Swedish DHS?
3. Are there any characteristic differences across the national territory concerning these potentials?

Considering this aim, the study results can be of generic nature only and should not replace dedicated local feasibility studies (Concerning study limitations, see further section 5.3 below). The value of interest here is overall orientation and initial understanding, much like starting from a blank paper and finding its margins and edges.

2. Background and study preparations

Study preparations included an updated database on Swedish DHS, described further in [13]. The update produced two main outputs: (1) a tabular list of all known DHS currently in operation (the database), and (2) a geographical representation of district heating areas (DHA), depicting the anticipated spatial distribution of these systems. In addition, a heat transmission transfer distance, used for the lineation of analytical boundaries, was defined during these preparations.

2.1 Updated database on Swedish DHS

Swedish data in the original Halmstad University District Heating and Cooling database, version 5 (HUDHC_v5) [23], listed 386 unique Swedish DHS, 372 with heat data, summing up a total annual district heat delivery volume (Q_s) of 47.1 TWh/a, see Table 1. The data was mainly based on 2015 records published by former Svensk Fjärrvärme, now managed by Swedenergy [24], and complemented with technical data from the Swedish Energy Market Inspectorate [25]. For the update, two new datasets were used, one public [26] and one internal [27], the latter used as reference only.

The tabular list output counts 547 DHS believed to be in operation, with an additional 17 systems identified but omitted since no recent operational data could be found. The annual sum of 2016 to 2021 average heat deliveries from all systems was found at 52.7 TWh/a, and, as such, the list consists of 27 fields mainly referring to various ID-numbers, names, coordinates, populations, and delivered heat.

Table 1. Datasets for an updated database on Swedish DHS.

Dataset	Nr [n]	Match to original reference	Q_s [TWh/a]	Heat deliveries time reference	Ref.
Original ref. (HUDHC_v5)	386	-	47.1	2015	[23]
Public dataset (EMI)	486	379	51	Avg. 2016–2021	[26]
Internal dataset (Swedenergy)	520	386	51.5	Avg. 1996–2021	[27]
Updated database (Tabular list)	547	386	52.7	Avg. 2016-2021	[13]

2.2 Geographical representation of district heating areas

A first geographical dataset with modelled Swedish DHA was developed in the sEEnergies project [28] and published in February 2020 under the name "D5.1 District Heating Areas" [29]. This dataset was rendered for all EU27 member states plus the United Kingdom based on point source location data in the original HUDHC_v5 database [23]. By access to the updated tabular list, the current project provided the occasion, on a Swedish case-study-basis one might say, to update (and improve) also the principal rendering methodology from the sEEnergies project, documented in [30], which itself was established in part on approaches and data developed in the preceding Heat Roadmap Europe project [31-33].

The motive for modelling of DHA was, firstly, to have an understanding of network distributions and sizes, especially since the character of storage connections (central/decentral) typically depends on available pipe diameters and distances to distribution network pressurization installations. While DHS operators naturally keep maps of their networks, these are seldom publicly available which makes modelling a requirement for generic studies. Secondly, geographical representations were needed also for the lineation of analytical boundaries.

The rendering process utilised and combined satellite imagery (share of built-up area per hectare from the European Settlement Map (ESM) [34, 35]), energy statistics (heat demand for residential and service sector buildings), and the tabular list (locations of DHS), see Figure 1. As an intermediate output, "urban areas", were derived by subjecting ESM raster-grid cells to requirements, for example, removal of parts smaller than four hectares and a coherency requirement of nine hectares. For Sweden, a total of 11,240 urban areas were rendered and attributed location names through the GeoNames dataset [36].

As reference, a national heat demand for space heating and domestic hot water preparation was found at 78.9 TWh/a, based on energy statistics for 2015 [37] and generic conversion efficiencies, including electricity shares, according to the Stratego approach [38]. This

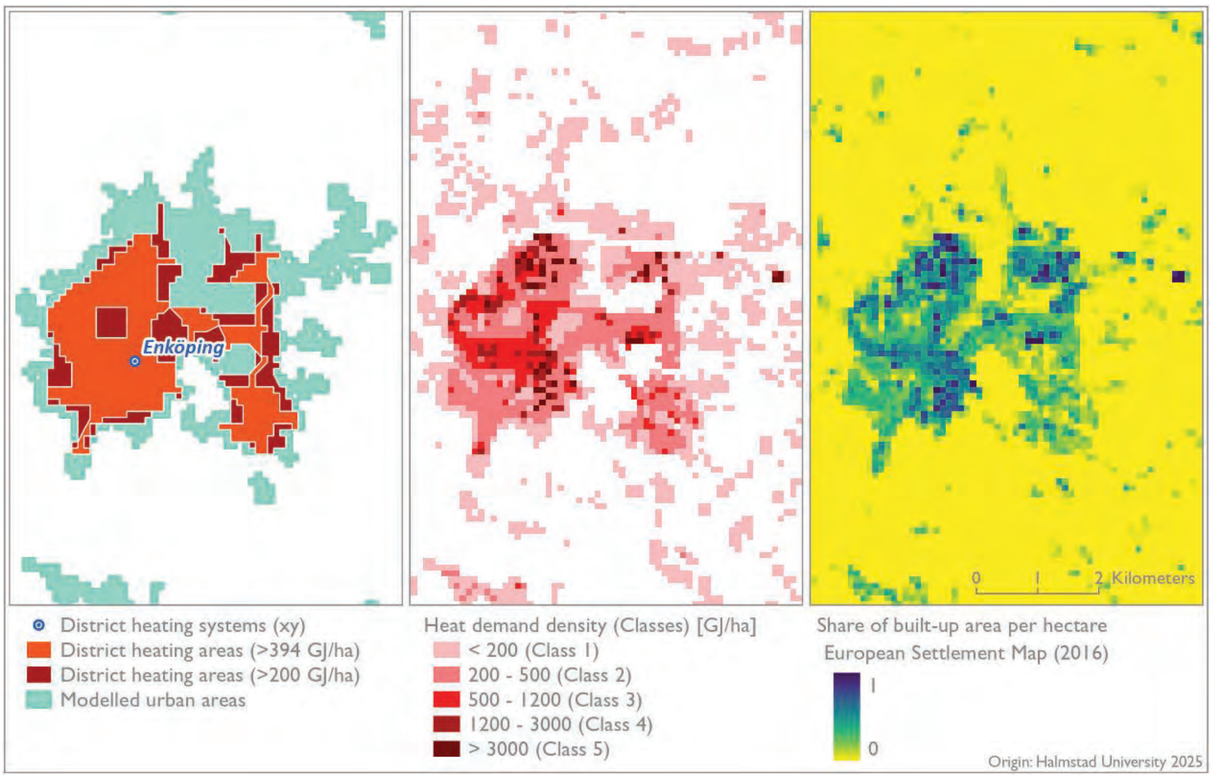

Figure 1. Rendering process of DHA (left) based on residential and service sector heat demand densities (centre), in turn based partly on underlying satellite imagery quantifying the relative share of built-up areas (right), exemplified for the district heating system point-source location (xy) in the city of Enköping (named thereafter in the database).

reference was compared to the original 2015 Heat Roadmap Europe raster dataset (81.1 TWh/a) [32, 33, 39] and the corresponding 2015 baseline raster dataset from the sEEnergies project (78.1 TWh/a) [40], both of which were associated with certain imperfections (further described in [13]). On this basis, a new Swedish heat demand density raster was calculated as the arithmetic average of each grid cell from the above two datasets, totaling at 79.7 TWh/a.

To render DHA, the annual heat delivery volume ($Q_s = 52.7\ TWh/a$), see Table 1, was distributed consecutively over all raster cells, starting at the cell with the highest value (23,590 GJ/ha), down to the point where the accumulated distribution sum matched this total volume. Unelaborated, this occurred at 394 GJ/ha. However, given that this density level was higher than that of several rural DHA candidates, an elaborated threshold level at 200 GJ/ha was used to incorporate as many as possible of these smaller systems. The idea behind this mode of distribution was that DHS have been built where economic feasibility is at its highest, which not necessarily is the case in a country like Sweden where additional preferences, other than pure economic viability, may have influenced system investment decisions.

2.3 Boundary layer by heat transmission threshold distance

The final preparatory step involved the creation of a boundary layer, i.e. delineation of analytical boundaries since only locations within cost-effective heat transmission distances from DHA needed to be investigated. For this purpose, DHA borders were used as origin from which so-called “dynamic boundary buffers” were extended according to a derived expression which relates such a desired heat transmission threshold distance, $L_{threshold}$ [m], to a unit cost of heat transmission, C_{unit} (50 SEK/MWh in this case), as presented in Eq. (1):

$$L_{threshold} = C_{unit} \cdot \frac{P_{\max} \cdot \tau}{\lambda + \sigma \cdot z \cdot P_{\max}^{w} + \phi \cdot Z^{\delta} \cdot P_{\max}^{3+w\cdot\delta}} \quad (1)$$

Where $P_{\max}$ is the maximal heat capacity for transmission [MW], τ is the hours of operation [h] (8760 for seasonal storage), λ is the intercept of an associated heat cost function [SEK/m], σ the corresponding slope of this function [SEK/m^2], and where *z and w* are coefficient and exponent respectively for an associated expression for optimum diameter, D, and where ϕ *and* δ are coefficients in an associated expression for total heat transmission cost. A detailed description of this derivation is provided as supplementary material.

By application of Eq. (1), where the product $P_{\max} \cdot \tau$ was set to correspond to the annual heat delivery volume (Q_s) of each DHS, at an anticipated solar fraction of 80%, a dynamic boundary layer covering approximately 39.7 thousand sqkm was created (8.8% of the total Swedish land are), see Figure 2.

3. Datasets for spatial analysis

This section describes the input data and the associated screening process. A complementary account may also be found in [14].

3.1 Input datasets

Early project activities involved discussions and consultancy to determine what input data to include. Several decisive geological parameters were considered, such as soil depth and soil type, given that PTES are constructed by the excavation of soil where a substantial part of the storage volume (the pit) is located below the soil surface. Additionally, the slope of the land and the character of available land areas were recognised as important factors. Several additional parameters were also considered, for example ballast production sites (where existing excavations potentially could be used), central heat production sources (additional heat to perhaps be stored), as well as ground water levels (a critical factor for PTES construction). Eventually, four input datasets, see Table 2, were selected and prepared for further analysis.

3.1.1 Elevation

The original elevation data (input dataset 1 in Table 2) from Lantmäteriet, the mapping, cadastral and land registration authority in Sweden [41], was initially accessed as 76 separate raster files (tiles covering parts of the country), which were merged into one consistent national elevation raster catalogue and subsequently delineated by means of the boundary layer (as were all input datasets). See also [42].

3.1.2 Soil depth

The second input dataset, soil depth, was accessed as part of the “soil depth model” (“Jorddjupsmodell”), developed by the Swedish Geological Survey (SGU) [44]. The soil depth input dataset is an interpolation

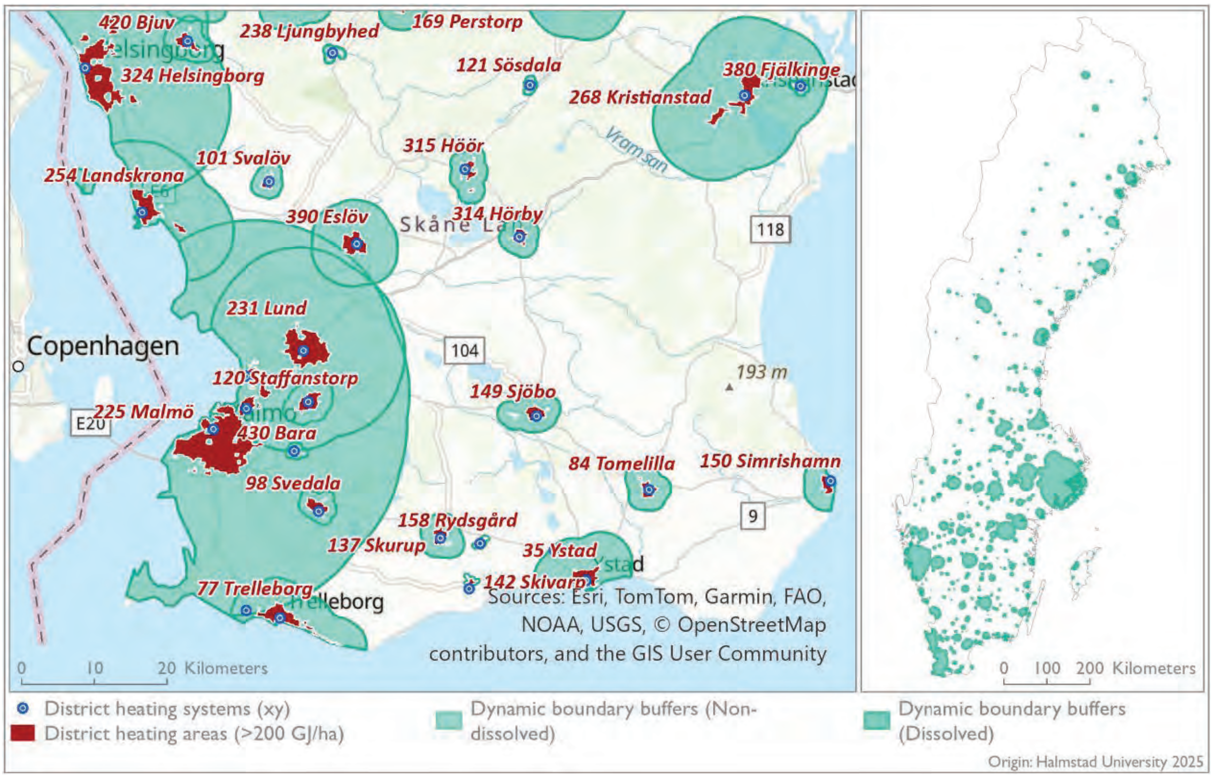

Figure 2. Dynamic boundary buffers drawn around modelled DHA and DHS point-source locations (xy) in the South-Western Skåne region, at left, and for the nation at right.

based among other on the analysis of soil depth information from well drilling, exploration drilling, mapping observations, and seismic surveys etc. See also [43].

3.1.3 Soil type

The ground layer JG2 from the SGU soil type dataset [46], provides a comprehensive picture of the distribution of soil types in or near the soil surface. The layer refers to the type of soil that can normally be expected at mapping depth, i.e. about 0.5 m below ground surface, with estimated thickness well exceeding 0.5 meters. In all, the dataset entails 91 detailed soil type classes (JG2) aggregated into 13 main classes (JBAS), see also [45].

Noteworthy, the JG2 layer suffers from a marginal lack of coverage in some northern areas but, given the scarcity of DHS in these areas (21 affected DHA, 12 completely, 9 marginally), this was considered of lesser significance for the national results. SGU also assembles data on deeper, underlying soil layers (JD3), but due to limited and random coverage, this was not used.

Table 2. Input datasets for the screening process.

Input dataset	Name/Description	Geometry	Sources
1	Elevation	Raster (50x50m)	[41, 42]
	Meters above sea level		
2	Soil depth	Raster (10x10m)	[43, 44]
	Meters below ground level		
3	Soil type	Feature class layer (Polygon)	[45, 46]
	Swedish soil types in SGU ground layer JG2		
4	Land use	Feature class layer (Polygon)	[47]
	Interpreted satellite imagery annotated by land use classes.		

In Table 3, the characteristics of two selected soil type input datasets are presented by reference to JBAS and JG2 classification, where the corresponding two screenings represent a conservative (former) and a more progressive (latter) criteria selection.

3.1.4 Land use

The source for input dataset 4 in Table 2 was the Corine Land Cover (CLC) dataset made available by the European Environment Agency, here referring to Version 20 (V20u1), which represents final and corrected CLC2018 data [47]. The CLC inventory aims to standardize data collection on land in Europe in the support of environmental policy development and follows a 6-year update cycle [48]. The dataset relies on satellite imagery (Sentinel 2 and Landsat 8) which, by means of photo-interpretations, image processing, cartographic generalisations etc., facilitates the identification of different land uses, such as for example built-up areas (residential, commercial, industrial etc.), agricultural areas, forest lands, and several others. In fact, the CLC dataset employs a categorisation of 44 different land use classes (Label 3 level), divided into five main Label 1 categories.

Table 4 presents the characteristics of two selected land use input datasets by reference to Label 1 and Label 3 classification, where the corresponding two screenings represent a conservative (former) and a more progressive (latter) criteria selection.

3.2 Screening datasets by criteria selection

The analytical sequence outlined in Table 5 was deliberately arranged so as to begin with datasets with no screening alternatives. This logic was motivated by the principle to postpone, as far as possible, the introduction of parallel routes through the model. Hereby, the first and second screening datasets were assigned front positions since they involve only a single threshold value each. Consequently, the third and fourth screening datasets, both of which employ two screening alternatives each, were accordingly located at the

Table 3. Soil type classification by aggregated class (JBAS) and detailed class (JG2), with indication of qualification for the 1st and 2nd screening.

JBAS Name	JG2 classes [n]	JG2 Code	Screening 1	Screening 2
Bedrock	8	82, 823, 849, 850, 888, 890, 8950, 9950	Excluded	Same
Filling	2	200, 322	Included	Same
Gravel	3	33, 62, 8803	Included	Same
Glacial river sediments	4	50, 51, 55, 57	Included	Same
Clay	9	17, 19, 22, 40, 43, 44, 85, 86, 8186	Excluded	All excluded except “Postglacial coarse clay” (22) and “Glacial coarse clay” (44)
Till (Moraine)	4	93, 95, 97, 100	Included	Same
Moraine clay	5	98, 99, 101, 9792, 9794	All included except “Moraine fine clay” (99)	Included
Organic soil	7	1, 5, 6, 16, 75, 2306, 8175	Excluded	Same
Sand	7	10, 13, 21, 28, 31, 8804, 8809	Included	Same
Silt	11	9, 24, 39, 48, 79, 8802, 8806, 8919, 8937, 9010, 9060	Excluded	All excluded except “Postglacial coarse silt-fine sand” (79), “River sediments, coarse silt-fine sand” (8802), and “Flood sediments, coarse silt-fine sand” (9010)
Stone blocks	5	34, 66, 81, 92, 8814	Excluded	All excluded except “River sediments, stone blocks” (8814)
Water bodies	1	91	Excluded	Same
Other	7	36, 90, 1950, 2368, 2372, 8114, 9147	All excluded except “Moraine alternating with sorted sediments” (9147)	Same

Table 4. Corine Land Cover land use classification by Label 1 and Label 3 classes, with indication of qualification for the 1st and 2nd screening.

Label 1 Name	Label 3 classes [n]	Label 3 Code	Screening 1	Screening 2
Artificial surfaces	11	111, 112, 121, 122, 123, 124, 131, 132, 133, 141, 142	Excluded	All included except "Continuous urban fabric" (111) and "Discontinuous urban fabric" (112)
Agricultural areas	11	211, 212, 213, 221, 222, 223, 231, 241, 242, 243, 244	All included expect "Vineyards" (221), "Fruit trees and berry plantations" (222), and "Olive groves" (223)	Same
Forest and semi natural areas	12	311, 312, 313, 321, 322, 323, 324, 331, 332, 333, 334, 335	Exclusion of "Broad-leaved Forest" (311), "Coniferous Forest" (312), and "Mixed Forest" (313). All other classes included except "Bare rocks" (332) and "Glaciers and perpetual snow" (335)	Inclusion of "Broad-leaved Forest" (311), "Coniferous Forest" (312), and "Mixed Forest" (313). All other classes included except "Bare rocks" (332) and "Glaciers and perpetual snow" (335)
Wetlands	5	411, 412, 421, 422, 423	Excluded	Same
Water bodies	5	511, 512, 521, 522, 523	Excluded	Same

end of the sequence. This latter elaboration of alternative screenings served the general purpose of introducing sensitivities with respect to the effect of including coarser clay and silt soil type fractions, on the one hand, and forest and artificial land areas on the other hand.

As can be seen in Table 5, a total of six screening datasets were prepared for spatial analysis by means of

Table 5. Screening datasets created by application of criteria on used input datasets.

Screening datasets	Name/Description	Count	Geometry
1	Required slope	1	Raster (50x50m) Converted to dissolved polygon
	Criteria: Cells with slopes larger than 15% excluded. Description: Slope calculated for each grid cell as percent rise relative to surrounding cells.		
2	Required soil depth	1	Raster (10x10m) Converted to dissolved polygon
	Criteria: Cells with soil depth less than 10 meters excluded. Description: Soil depth statically defined by one default value as a minimum requirement.		
3	Required soil types	2	Feature class layer (Polygon) Dissolved
	Criteria: Screening 1: Exclusion of clay and silt in all forms (as well as rock, water and organic soils). Screening 2:, Same as screening 1 but with partial inclusion of clay and silt (courser fractions). Description: See Table 3.		
4	Available areas	2	Feature class layer (Polygon) Dissolved
	Criteria: Screening 1: Only agricultural and semi natural areas. Screening 2: Same as screening 1 but with the addition of forest areas and some artificial surfaces (e.g. industrial and commercial areas, airports, port areas, road and rail networks and associated land etc.). Description: See Table 4.		

criteria selection, where applied threshold values and attribute filters all were based on project consultancy recommendations and literature reviews [15].

4. Spatial analysis

The spatial analysis was performed in a GIS (Geographical Information System) [49], and the resulting suitable land areas were identified by sequential elimination of unsuitable areas. Hereby, the result datasets were created in sequence so that every new result layer included the results from the previous layer and so on.

4.1 Screening process and result datasets

As shown in Table 6, the screening process generated four levels of result datasets, where the four datasets at the fourth level, result datasets 4.1 to 4.4, depicts suitable land area candidates that meet the particular requirements under each respective criteria screening combination. If, at the end of the process, no suitable land area candidates are found, the conclusion would be that no (spatio-technical) potential for PTES exists. If, on the other hand, suitable land area candidates are found, this would mean that a potential indeed could be present.

4.2 Post-treatment procedure

Result datasets 4.1. to 4.4 were subjected to a post-treatment procedure, integrated into the GIS model, to identify and remove rendered suitable area candidates whose shape or size would not allow the construction of PTES according to predetermined project boundary conditions, e.g. a minimum required total PTES land area of 15,000 m^2, at square or slightly rectangular surface design, and a minimum storage volume of 50,000 m^3, both based on Danish practice and experience (see e.g. ref. [11]),

For this end, the concept of roundness, R_d [-], see Eq. (2), was suggested to define a quantity by which to determine whether a suitable area candidate of a given shape and size in fact could host a pit storage of the preconceived size and form. The definition of roundness is the ratio of a polygon area (area of the suitable area candidate) to the one of a circle with the same circumference as the considered polygon:

$$R_d = \frac{4\pi A}{C^2} \tag{2}$$

where A and C are the area and the circumference of the polygon in question. To qualify and be sufficiently large according to project boundary conditions, a suitable area

Table 6. Result datasets from the screening process.

Result datasets	Name/Description	Count	Geometry
1	Flat land	1	Feature class layer (Polygon)
	Description: Same as screening dataset 1 (dissolved polygon), areas with required slope.		
2	Deep soil and flat land	1	Feature class layer (Polygon)
	Description: One dissolved polygon layer outlining areas with required soil depth and required slope.		
3	Apt deep soil and flat land	2	Feature class layer (Polygon)
	Description: Each dataset is a dissolved polygon layer outlining areas with required soil depth, required slope, and required soil type (by one of two screenings): 3.1: Required soil type, screening 1. 3.2: Required soil type, screening 2.		
4	Suitable area candidates	4	Feature class layer (Polygon)
	Description: Each dataset is a dissolved polygon layer outlining areas with required soil depth, required slope, required soil type (by one of two screenings) and available areas (by one of two screenings): 4.1: Required soil type, screening 1, and available areas, screening 1. 4.2: Required soil type, screening 2, and available areas, screening 1. 4.3: Required soil type, screening 1, and available areas, screening 2. 4.4: Required soil type, screening 2, and available areas, screening 2.		

candidate would have to be larger or equal in size than that of the quota presented in Eq. (3):

$$Suitable\,area_{sufficient}\left[m^2\right] >= \frac{15{,}000\left[m^2\right]}{R_d^{\ 2}} \qquad (3)$$

By this definition, perfectly square-shaped candidate polygons with areas close to 15,000 m^2 will in fact have been rejected, which is not optimal. However, the definition used guarantees that any unsuitably shaped polygons with areas close to 15,000 m^2, i.e. extremely thin, narrow, or irregular by any other measure, will not be accepted. At this stage, the latter effect was considered most important.

5. Results

The results presented in this section are all based on the data, approaches, and assumptions, described above. In terms of data types, the study outputs, created and available as geographical feature class layers, are here presented in exported tabular form and illustrated in a few map images. At current, the possibility of public result sharing, e.g. an online web-map service, is not a project priority.

5.1 Aggregated district heating areas

The new database on Swedish DHS distinguishes between three principal summation levels: the DHS level; the DHA level; and the aggregated district heating area (DHA*) level. The latter of these, indicated by asterisk annotation in the level abbreviation as well as in the naming of aggregations with more than one DHA, as illustrated in Figure 3 for the larger metropolitan areas of Gothenburg and Stockholm respectively, was added to facilitate final summation of national potentials without risk of double-counting due to overlapping DHA.

According to Table 7, the third summation level counts 356 DHA* (of which 28 with more than one DHA), the second 464 DHA, and the first 476 DHS, why it may be concluded that 71 out of the 547 tabular list DHS total were omitted in the aggregation. Typically, this omission resulted from no DHA rendering at a system location (too low heat demand densities) or system point source locations outside of rendered DHA (spatial mismatch). However, given the

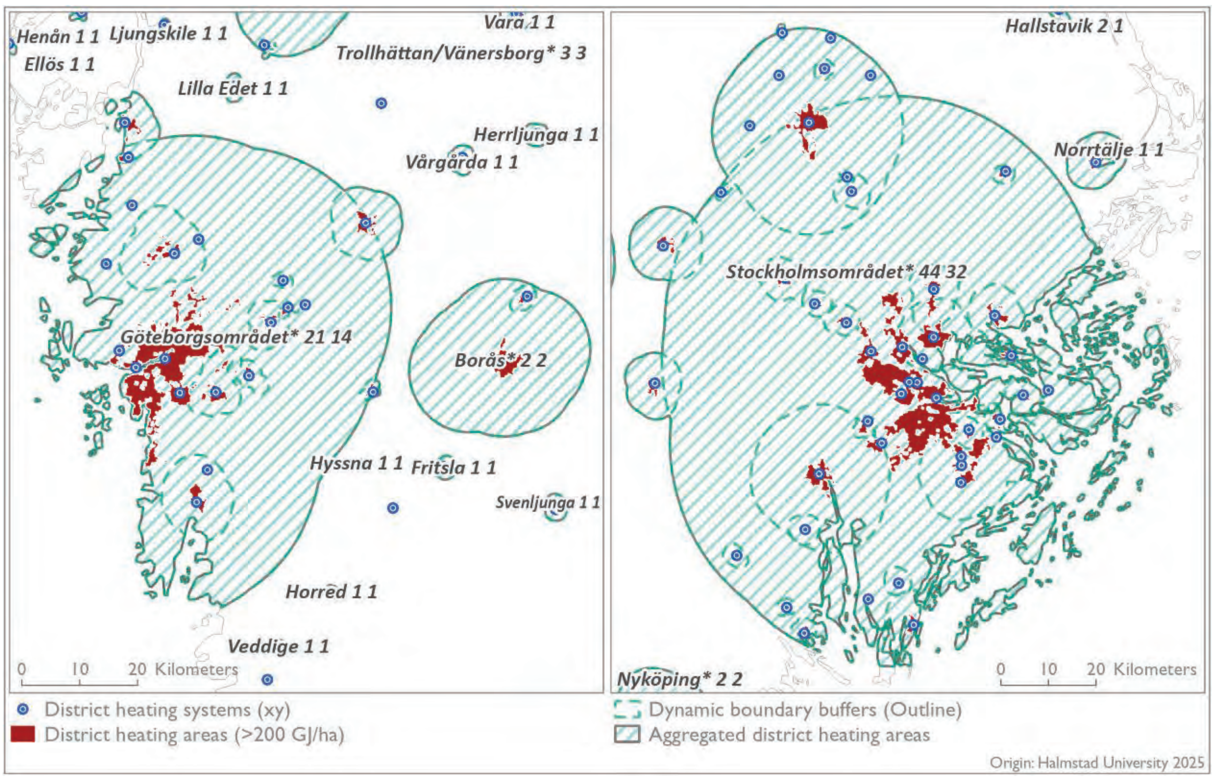

Figure 3. Three principal summation levels in the new database on Swedish DHS, exemplified for the larger Gothenburg area (at left) and the larger Stockholm area (at right), with count of DHS and DHA per DHA*.

Table 7. Total count, land area, population, and associated annual district heat deliveries, of aggregated district heating areas (DHA*), with count of DHA and DHS within them, by NUTS2 and NUTS3 administrative units.

NUTS2/NUTS3	DHA* [n]	DHA [n]	DHS [n]	DHA* [sqkm]	Pop. [kn]	Qs [GWh/a]
Mellersta Norrland	**36**	**40**	**41**	**2,257**	**248**	**2,226**
Jämtlands län	18	18	18	919	76	743
Västernorrlands län	18	22	23	1,338	172	1,483
Norra Mellansverige	**66**	**76**	**74**	**4,440**	**541**	**4,339**
Dalarnas län	23	26	26	1,520	178	1,504
Gävleborgs län	24	30	28	1,733	195	1,646
Värmlands län	19	20	20	1,186	168	1,189
Östra Mellansverige	**53**	**70**	**69**	**7,043**	**1,022**	**7,901**
Örebro län	14	18	16	1,481	248	1,584
Östergötlands län	13	19	19	2,615	369	2,845
Södermanlands län	8	9	9	491	89	612
Uppsala län	9	9	10	93	22	111
Västmanlands län	9	15	15	2,363	294	2,749
Övre Norrland	**42**	**50**	**48**	**3,228**	**389**	**3,861**
Norrbottens län	19	21	21	1,618	158	2,081
Västerbottens län	23	29	27	1,610	231	1,779
Småland med öarna	**69**	**72**	**69**	**3,575**	**529**	**4,043**
Gotlands län	5	5	5	163	28	209
Jönköpings län	22	23	25	1,609	231	1,625
Kalmar län	22	23	19	864	136	1,182
Kronobergs län	20	21	20	939	134	1,028
Stockholm	**3**	**34**	**47**	**8,797**	**2,509**	**14,890**
Stockholms län	3	34	47	8,797	2,509	14,890
Sydsverige	**34**	**51**	**53**	**3,872**	**1,054**	**6,180**
Blekinge län	8	10	9	423	128	641
Skåne län	26	41	44	3,449	926	5,538
Västsverige	**53**	**71**	**75**	**6,518**	**1,384**	**8,451**
Hallands län	9	9	7	647	138	812
Västra Götalands län	44	62	68	5,871	1,246	7,639
Grand Total	**356**	**464**	**476**	**39,730**	**7,677**	**51,891**

51.9 TWh/a heat delivery volume representative of the aggregate, compared to the 52.7 TWh/a tabular list total, omitted systems are generally small (~800 GWh total).

From Table 7, it may be seen that the effect of aggregation is more profound in regions which host larger city areas, relative to regions with a more rural character. For example, in Jämtlands län and Hallands län, no aggregation occurs at all (18 DHA* and 18 DHA, 9 DHA* and 9 DHA, respectively), whereas in Stockholms län, 34 DHA (47 unique DHS) are reduced to three aggregated district heating areas.

5.2 Suitable areas for PTES by scenarios

The four final results datasets are in the following synonymously labelled and referred to as four project scenarios, where sensitivities introduced in the third and fourth screening datasets result in:

- Scenario 1: All conservative
- Scenario 2: Progressive soil type, conservative land use
- Scenario 3: Conservative soil type, progressive land use
- Scenario 4: All progressive.

Table 8. Scenario 1: Suitable areas (SA) by aggregated district heating areas (DHA*), with count of DHA and DHS within them, by NUTS2 and NUTS3 administrative units.

NUTS2/NUTS3	DHA* [n]	DHA [n]	DHS [n]	SA [n]	SA [sqkm]	Area ratio (SA/DHA*)
Mellersta Norrland	**19**	**23**	**27**	**184**	**36**	**1.7%**
Jämtlands län	11	11	12	42	16	1.9%
Västernorrlands län	8	12	15	142	20	1.5%
Norra Mellansverige	**44**	**54**	**53**	**401**	**78**	**1.8%**
Dalarnas län	18	21	21	148	28	1.9%
Gävleborgs län	17	23	22	195	41	2.4%
Värmlands län	9	10	10	58	9	0.9%
Östra Mellansverige	**31**	**48**	**50**	**612**	**155**	**2.3%**
Örebro län	8	12	12	217	39	2.8%
Östergötlands län	10	16	16	285	98	3.9%
Södermanlands län	3	4	5	19	2	0.4%
Uppsala län	5	5	6	13	2	2.8%
Västmanlands län	5	11	11	78	13	0.6%
Övre Norrland	**27**	**35**	**35**	**436**	**95**	**3.3%**
Norrbottens län	11	13	13	253	61	4.5%
Västerbottens län	16	22	22	183	35	2.2%
Småland med öarna	**34**	**37**	**39**	**357**	**133**	**4.2%**
Gotlands län	1	1	1	3	0	0.4%
Jönköpings län	17	18	20	187	70	4.5%
Kalmar län	9	10	10	101	43	6.4%
Kronobergs län	7	8	8	66	20	2.4%
Stockholm	**2**	**33**	**45**	**149**	**21**	**0.2%**
Stockholms län	2	33	45	149	21	0.2%
Sydsverige	**32**	**49**	**52**	**1,022**	**1,183**	**30.6%**
Blekinge län	7	9	9	28	17	4.0%
Skåne län	25	40	43	994	1,166	33.8%
Västsverige	**35**	**53**	**60**	**658**	**327**	**5.1%**
Hallands län	5	5	5	144	142	22.6%
Västra Götalands län	30	48	55	514	185	3.2%
Grand Total	**224**	**332**	**361**	**3,819**	**2,028**	**5.3%**

Noteworthy, the subsequent account will focus exclusively on the 1st and 4th scenarios, the modelling extremes, since, in retrospect, it is clear that the effect of the alternative soil type selection (Screening 2, inclusion of coarser silt and clay fractions, as detailed in Table 3 and Table 5) was only marginal in most cases (Southern regions being the exception). Conversely, the effect of the alternative land use selection (Screening 2, inclusion of forest areas and some artificial surfaces, as detailed in Table 4 and Table 5) had a more substantial impact in general.

In the 1st scenario, as presented in Table 8, 3,819 polygon areas qualified as suitable areas (SA) by meeting the roundness criteria (out of 37,592 candidate polygons). Altogether, these SA, located within 224 DHA* and in direct vicinity of 361 unique DHS, make up a total land area of 2.028 thousand sqkm (SA average: 0.53 sqkm) and represent a relative area share of 5.3% with regards to the aggregated boundary layer.

To illustrate, and further to emphasize the marked presence of opportunities present in Syd- and Västsverige (e.g. Skåne län and Hallands län), the results for the 1st

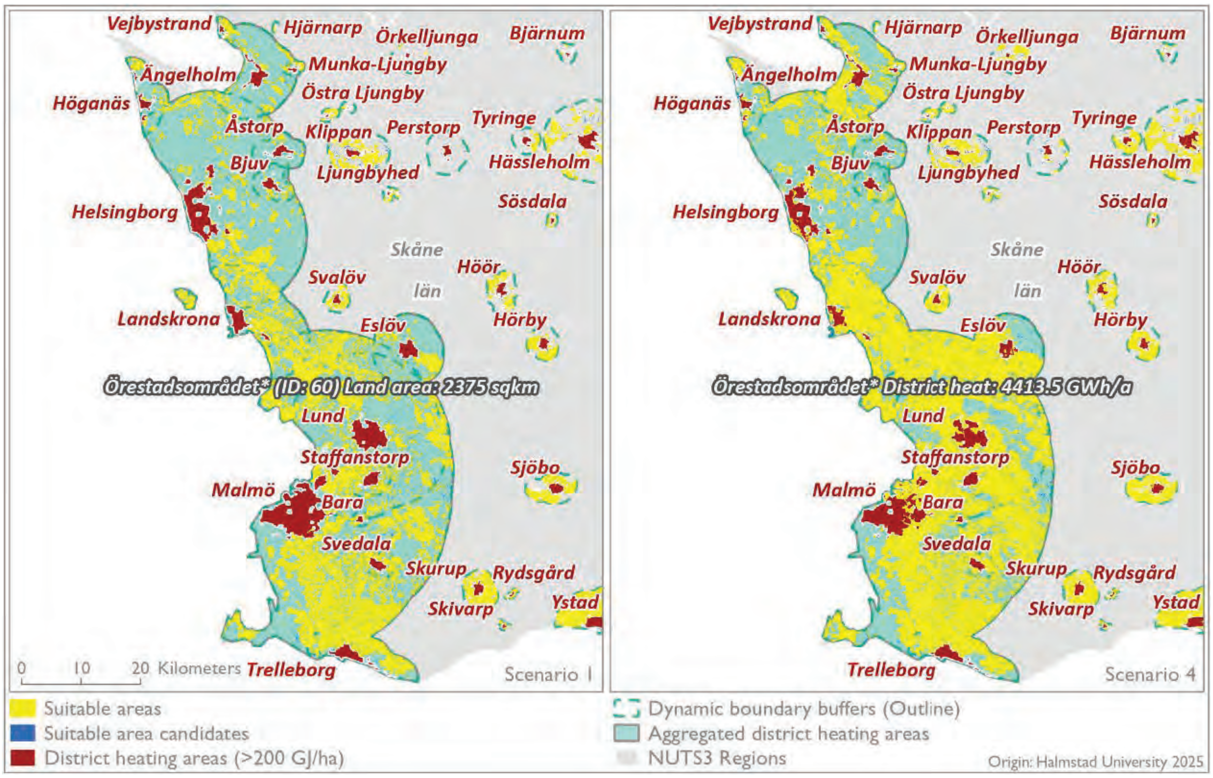

Figure 4. Map illustrations of suitable areas identified in Örestadsområdet* under the 1st (left) and 4th scenario (right).

and 4th scenarios are depicted for Örestadsområdet* in Figure 4. Similarly, the corresponding 1st and 4th scenario results are illustrated in Figure 5 for Göteborgsområdet* and in Figure 6 for Stockholmsområdet*.

As can be seen in these images, the 4th scenario, further detailed in Table 9, results in a considerable general increase in SA, and, relatively speaking, especially so in northern parts of the country. The total count of associated DHA* increases to 269, which corresponds to an approximate 20% increase compared to the 1st scenario. The total count of SA amounts here to 4,958 (out of 68,408 candidates), which corresponds to a relative increase of ~30%. However, the area sum of all SA in the 4th scenario is more than double that of the 1st scenario (5,164 sqkm, average: 1.04 sqkm). The impact of accepting forest and artificial land areas increases the area ratio in many northern regions, for example Norrbottens län (41.9%) and Västerbottens län (29.0%), well above the national average at 13.3%.

As mentioned, the results from this work consist mainly of geographical feature class layers and it should be noted that all identified SA, under each scenario, are designated unique ID-numbers for subsequent identification. This is exemplified in the last of three appendix map images, depicting three project case study locations: Figure 11 (Råneå), Figure 12 (Härnösand), and Figure 13 (Söderhamn).

5.3 National potential

If, from the above, a national potential for PTES was to be derived, it is vital to first state the extent and nature of the limitations and simplifications under which this analysis was made. First of all, given the recognized demotion of suitability upon its presence, consistent data on depth and flow characteristics of ground water was sought, but unfortunately not found. In fact, no single national-coverage dataset on Swedish ground water levels exists today (according to SGU). An internal ground water level and elevation dataset, created through Kriging interpolation based on several auxiliary datasets not further specified here, was developed in the project but used as reference only.

However, it should be emphasised here that the groundwater table and the groundwater flow are both crucial considerations for constructing a PTES. If the groundwater table is not lower than the PTES depth,

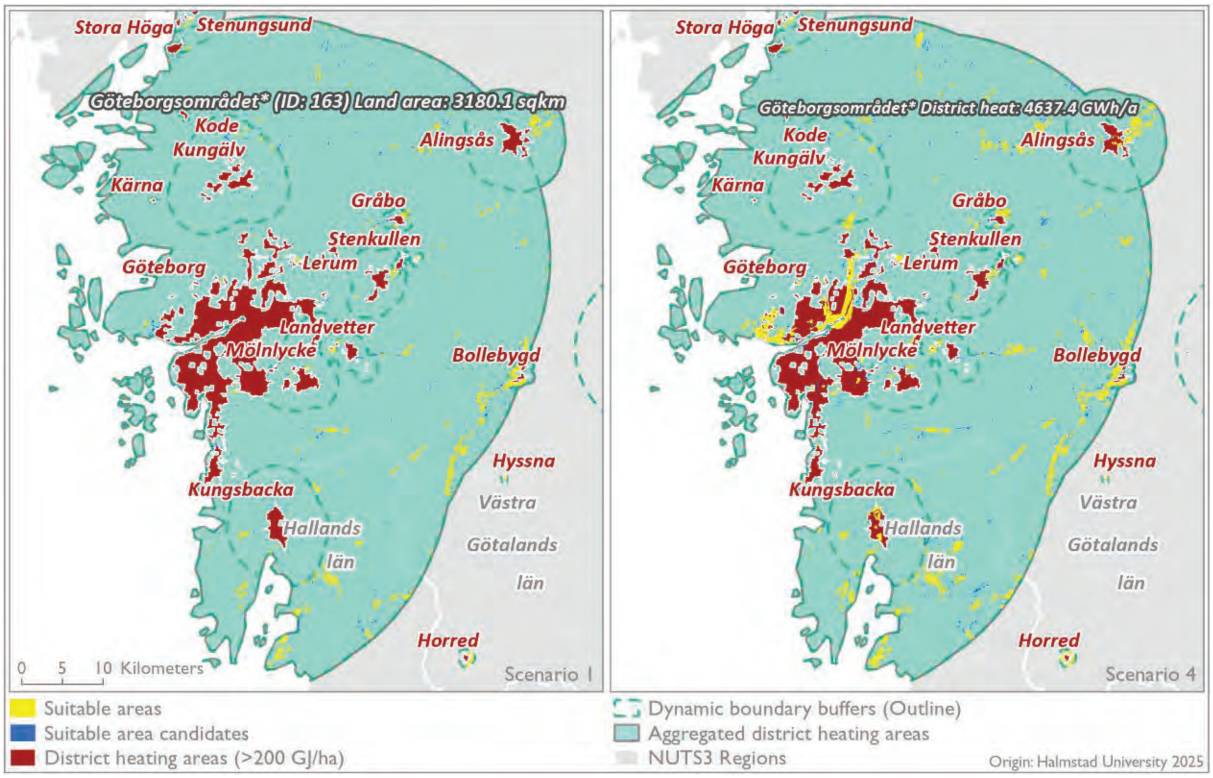

Figure 5. Map illustrations of suitable areas identified in Göteborgsområdet* under the 1st (left) and 4th scenario (right).

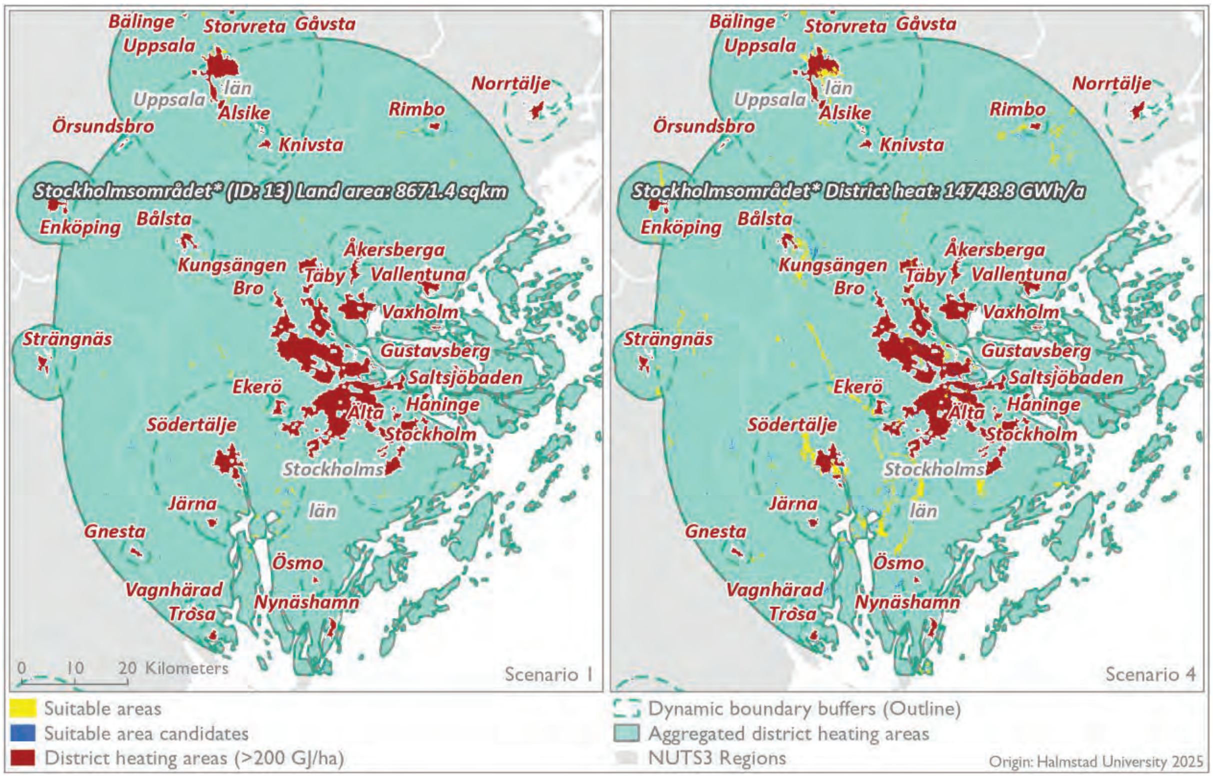

Figure 6. Map illustrations of suitable areas identified in Stockholmsområdet* under the 1st (left) and 4th scenario (right).

Table 9. Scenario 4: Suitable areas (SA) by aggregated district heating areas (DHA*), with count of DHA and DHS within them, by NUTS2 and NUTS3 administrative units.

NUTS2/NUTS3	DHA* [n]	DHA [n]	DHS [n]	SA [n]	SA [sqkm]	Area ratio (SA/DHA*)
Mellersta Norrland	**25**	**29**	**32**	**407**	**197**	**8.9%**
Jämtlands län	11	11	12	61	54	6.2%
Västernorrlands län	14	18	20	346	143	10.8%
Norra Mellansverige	**53**	**63**	**62**	**754**	**516**	**12.0%**
Dalarnas län	21	24	24	275	191	12.6%
Gävleborgs län	20	26	25	369	245	14.2%
Värmlands län	12	13	13	110	81	7.5%
Östra Mellansverige	**39**	**56**	**58**	**737**	**413**	**6.0%**
Örebro län	10	14	14	285	172	11.7%
Östergötlands län	12	18	18	278	174	6.7%
Södermanlands län	4	5	6	35	20	4.5%
Uppsala län	5	5	6	19	6	7.4%
Västmanlands län	8	14	14	120	41	1.8%
Övre Norrland	**32**	**40**	**40**	**819**	**1,027**	**34.9%**
Norrbottens län	11	13	13	395	560	41.9%
Västerbottens län	21	27	27	424	467	29.0%
Småland med öarna	**43**	**46**	**48**	**457**	**469**	**14.1%**
Gotlands län	1	1	1	1	3	2.2%
Jönköpings län	19	20	22	239	273	17.1%
Kalmar län	12	13	13	118	115	16.4%
Kronobergs län	11	12	12	99	77	8.9%
Stockholm	**2**	**33**	**45**	**317**	**129**	**1.5%**
Stockholms län	2	33	45	317	129	1.5%
Sydsverige	**32**	**49**	**52**	**701**	**1,784**	**46.1%**
Blekinge län	7	9	9	43	29	6.8%
Skåne län	25	40	43	658	1,755	50.9%
Västsverige	**43**	**61**	**67**	**766**	**628**	**9.7%**
Hallands län	8	8	7	122	217	33.5%
Västra Götalands län	35	53	60	644	412	7.1%
Grand Total	**269**	**377**	**404**	**4,958**	**5,164**	**13.3%**

additional costs would be incurred to lower the groundwater level before and during construction. Furthermore, groundwater flow may carry heat away from the sides and bottom of the PTES, hereby increasing heat losses. Since none of these factors were accounted for in the spatial analysis it is likely that this have resulted in certain overestimations of actual potentials. Conversely, the use of a static soil depth value, fixed at 10 meters, might have contributed to some minor underestimations, although unlikely, since the set depth represents a minimum requirement for large-scale PTES construction.

Secondly, the assumption that soil type remains uniform throughout the PTES depth (soil homogeneity), as depicted in soil maps, represent another simplification in the analysis. In reality, soil types can vary at different depths, and certain soil layers might not be suitable for PTES embankments. This could necessitate the removal and replacement of unsuitable soil, further increasing the costs. In-situ conditions relating to different cost levels for piping, for example those in dense urbans areas compared to those under rural conditions, also not considered in the analysis, represent additional factors of possible overestimations. In this respect it should also be stated that no coherent validation of the screening results was made, although the findings were evaluated for a limited set of case studies [15].

Thirdly, being a first-order assessment of a national spatio-technical potential, it must be emphasized not to mistake these preliminary findings for a dedicated techno-economic feasibility study, in which case a number of additional aspects would have had to be considered. For any real-world project, essential parameters such as land ownership, network connection points, DHS load profiles and operational strategies, local heat production alternatives, investment economics, regulations and permits etc., would all require investigation, why this assessment, generally speaking, most likely is an overestimation rather than the contrary.

With this in mind, it is clear that the overall spatio-technical potential for large-scale PTES in Sweden is extensive, with several thousand suitable areas generated under each scenario. The DHA* labelled "Örestadsområdet*", consisting of 18 unique DHS assembled under 15 DHA, has by far the largest sum of suitable area both in the 1st scenario, totalling at ~806 sqkm (left graph in Figure 7) and in the 4th scenario, totalling at 1,274 sqkm (left graph in Figure 8).

In the 1st scenario, Kristianstad* follows next (160 sqkm), thereafter Halmstad (96 sqkm), and then many other south and south-western DHA*. At 15th place, Gävle/Sandviken* (23 sqkm) appears as the first aggregated area with a more northern location. In the 4th scenario, however, several northern locations, e.g. Umeå (210 sqkm), Luleå (202 sqkm), clearly benefit from the inclusion of forest and artificial land areas, placing them at 2nd and 3rd place respectively.

If instead comparing the total area sum of SA per DHA* by the sum of annual district heat deliveries associated with these, as shown for the 1st scenario in Figure 7 at right, it can be seen that five Skåne län DHA* (Skurup, Rydsgård, Sjöbo, Tomelilla, and Kristiandstad*) top the list with values in the range of 0.47 to 0.68. A large ratio in this context would indicate a large likelihood of being able to find suitable areas for PTES that can support the DHS within the aggregated area. In the 4th scenario, at right in Figure 8, this situation is not changed dramatically, although a few northern locations, for example Sveg (0.59) and Piteå (0.50), make it into

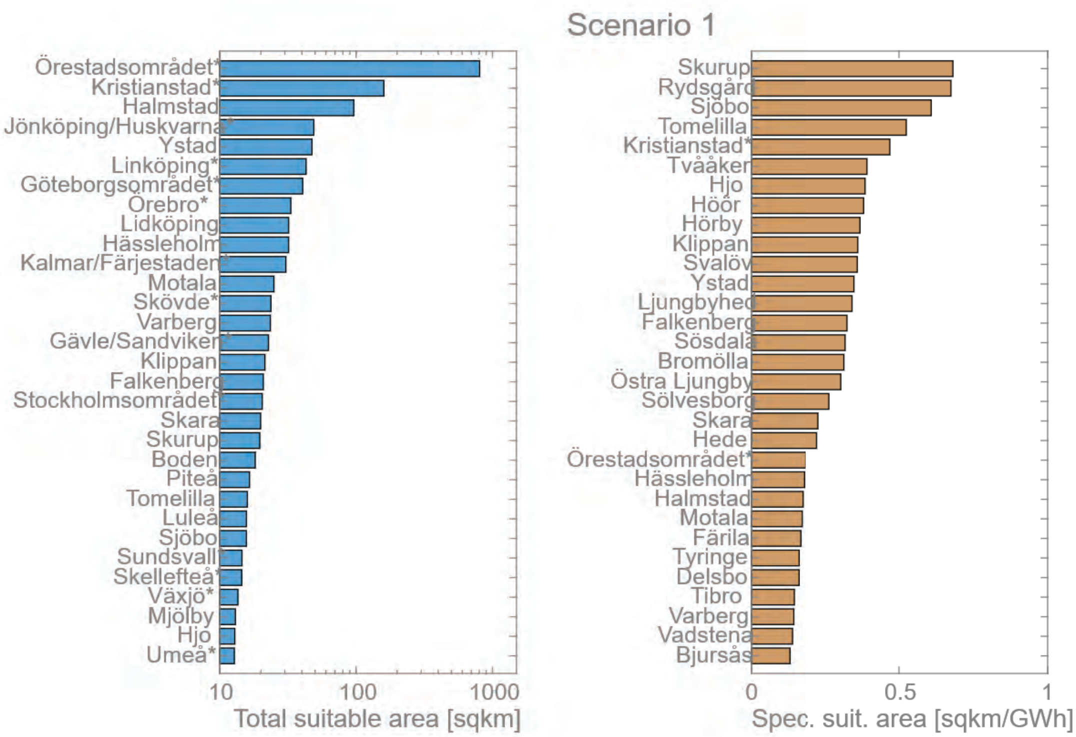

Figure 7. Scenario 1: Area sum of SA per DHA*, at left, and ratio of total sum of suitable areas (sqkm) by sum of annual district heat deliveries (GWh/a) per DHA*, at right.

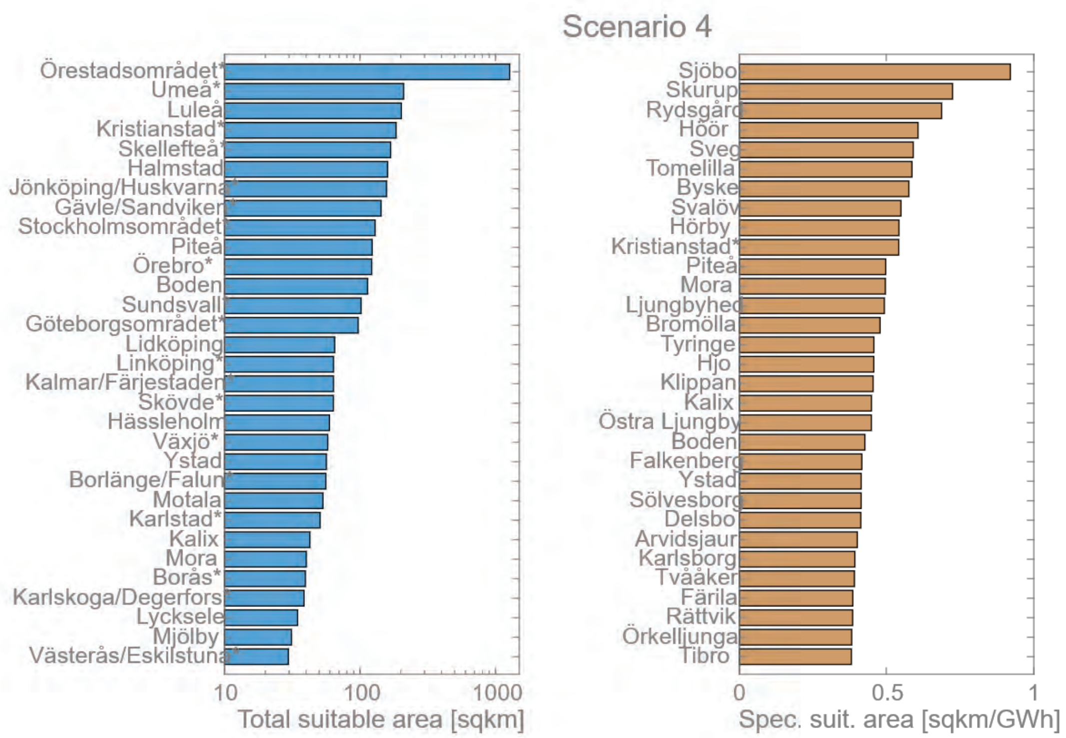

Figure 8. Scenario 4: Area sum of SA per DHA*, at left, and ratio of total sum of suitable areas (sqkm) by sum of annual district heat deliveries (GWh/a) per DHA*, at right.

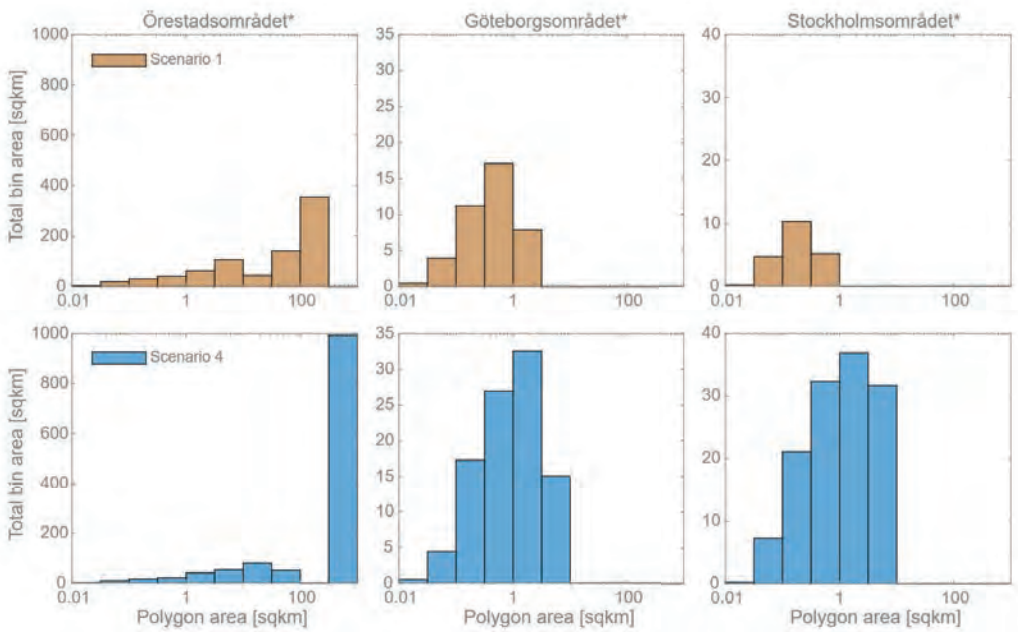

Figure 9. Distribution of SA polygon areas [sqkm] in the 1st scenario (top) and the 4th scenario (bottom) for the three largest metropolitan areas of Örestadsområdet*, Göteborgsområdet*, and Stockholmsområdet*.

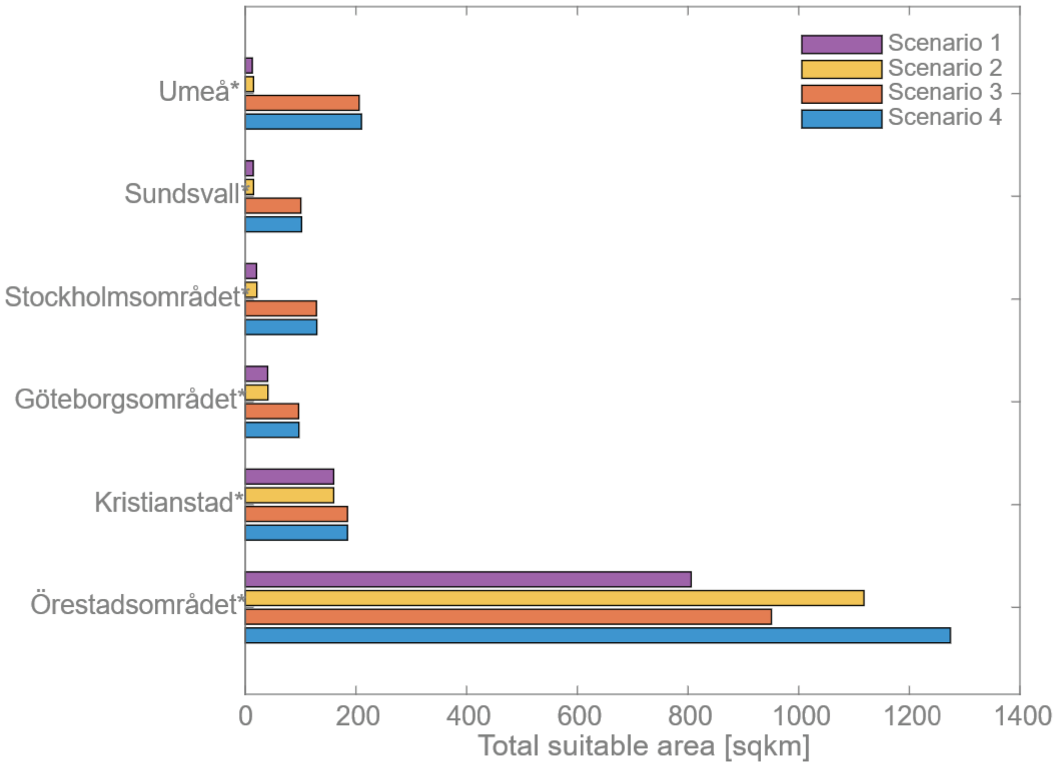

Figure 10. Total suitable area for all four scenarios and six DHA* representative of a north-south distribution.

the top 15, an interval with values ranging from 0.46 to 0.92.

The character of the identified SA can be further described by displaying the distribution of area sizes by total bin areas, as shown in Figure 9 for the three largest metropolitan areas with respect to the 1st and 4th scenarios. A majority of the total suitable area in Örestadsområdet*, in both scenarios, is found in very large polygons (probably just one polygon) with an area above 100 sqkm or more, whereas the case in both Göteborgsområdet* and Stockholmsområdet* is more fragmented with more smaller areas.

In confirmation of what has been subtly suggested in the above, a distinct general difference, a difference of latitude one might say, is indeed present in these results. Southern parts of Sweden display more promising potentials than their northern counterparts, as illustrated in the scenario diagram of Figure 10. This difference might not exist locally, since feasible conditions also exist in many northern locations. However, generally speaking, and especially if not permitting any exploitation of broad-leaved, conifer, or mixed forest areas, as well as no industrial or commercial areas, airports, ports, road and rail networks etc., the likeliness of finding a suitable PTES land area in the north should be considerably smaller than finding one in more southern locations.

6. Conclusions

To conclude, this paper has presented in summary the work to investigate and assess the availability of suitable land for the construction and operation of pit thermal energy storages within cost-effective heat transmission distances of district heating systems. This availability was referred to as the national spatio-technical potential in Sweden and was characterized as a first-order assessment, meaning a first general outlook over territorial aspects and properties not previously studied from an elevated viewpoint. Three distinct research questions were raised and here are their answers:

Firstly, yes, it is possible to perform a first-order assessment based on publicly available data, but of course, only by whatever data that indeed is publicly available. In this case, four relevant data parameters (elevation, soil depth, soil type, and land use) allowed for exactly such a "first-order" assessment, but nothing more. This raises the legitimate, general question of whatever value first-order assessments may have, since they do not provide perfect certainty, are difficult to verify (although case study comparisons were made in the project), and certainly cannot replace necessary detailed investigations in real-world cases (e.g. ground water depth and movement, in-situ soil depths, specific soil constitutions etc.). The value, however, lies in a first orientation and a guiding light where before there was only fog and mist.

Secondly, excessive, must be the short reply. Suitable areas for pit storages amass, under both conservative and progressive criteria selections, substantial land areas in a majority of the aggregated district heating areas studied. Average sizes of unique suitable areas range from roughly a half to one square kilometre in the most conservative and progressive cases, respectively. In total, the national sum of suitable areas ranges from two to more than five thousand square kilometres under the two criteria extremes, but, noteworthy, many locations are also found empty of suitable areas and thus associated with no potentials at all. Hereby, it may be concluded that suitable land areas should be possible to find in most cases, but there may be local exceptions to this general rule.

Thirdly, yes, there seems indeed to exist characteristic differences across the national territory, differences of latitude one might say, at least by reference to the used data parameters. Perhaps it should come as no surprise for a large and north-south elongated country like Sweden but results clearly reveal more promising potentials in southern parts of the country compared to more northern parts. As stated above however, this difference might not exist locally since feasible conditions also exist in many northern locations, but nationally, yes.

Future work could develop the approach further by extended investigations concerning useful input data parameters and the influence and consequences of associated selection criteria. For example, the inclusion of forest areas and certain artificial areas proved to have a generally strong impact in this study. Concerning the latter especially, it would be interesting to learn more about what particular artificial areas, e.g. industrial and commercial, airports, road and rail networks, ports, green urban areas etc., that can constitute potential suitable areas in the future, since the larger the district heating system, the larger the need for large-scale seasonal storages in the sustainable energy system of tomorrow.

Author contribution (by CRediT roles)

Conceptualization: UP, CB; Data curation: UP, LSG; Formal analysis: UP, FO, LSG, PS, CB; Funding acquisition: UP, CB; Investigation: UP, FO, LSG; Methodology: UP, LSG; Project administration: UP, CB; Resources: UP, CB; Software: UP, LSG; Supervision: CB; Validation: UP, CB; Visualization: UP, FO; Writing – original draft: UP; Writing – review & editing: UP, PS, CB. The authors declare no conflict of interest.

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Supplementary material

Heat transmission threshold distance.pdf

References

[1] Lund, H., Østergaard, P.A., Connolly, D., Ridjan, I., Mathiesen, B.V., Hvelplund, F., Thellufsen, J.Z., and Sorknæs, P., Energy Storage and Smart Energy Systems. International Journal of Sustainable Energy Planning and Management 11(0) (2016) p 3-14. DOI: https://doi.org/10.5278/ijsepm.2016.11.2.

[2] Guelpa, E. and Verda, V., Thermal energy storage in district heating and cooling systems: A review. Applied Energy 252 (2019) p 113474. DOI: https://doi.org/10.1016/j.apenergy.2019.113474.

[3] Gadd, H. and Werner, S., *Thermal energy storage systems for district heating and cooling*, in *Advances in Thermal Energy Storage Systems: Methods and Applications*. 2015. Elsevier Inc. Available at (2025-04-15): https://doi.org/10.1533/9781782420965.4.467

[4] Tosatto, A., Dahash, A., and Ochs, F., Simulation-based performance evaluation of large-scale thermal energy storage coupled with heat pump in district heating systems. Journal of energy storage 61 (2023) p 106721. DOI: https://doi.org/10.1016/j.est.2023.106721.

[5] Helden, W., Leusbrock, I., Odonovan, K., Reisenbichler-S, M., Riegler, T., Knabl, S., Wallner, G., Peham, L., Pugstaller, R., Muser, C., Drucker, P., Moser, M., Ochs, F., Tosatto, A., Dahash, A., Bianchi-Janetti, M., and Seidnitzer-Gallien, C., *Giga-scale thermal energy storage for renewable districts - Publishable Final Report*. 2021. Available at (2025-04-15): https://www.researchgate.net/publication/368636139_Giga-scale_thermal_energy_storage_for_renewable_districts_-_Publishable_Final_Report.

[6] Gadd, H., Atabaki, M.S., Gong, M., Möllerström, E., Norrström, H., Ottermo, F., Persson, U., Sánchez-García, L., and Werner, S., *70 New Possibilities for District Heating*. 2024. Report 2024:1040. Energiforsk, Swedish Energy Research Centre. Available at (2024-08-29): https://energiforsk.se/rapporter/70-new-possibilities-for-district-heating/.

[7] Xiang, Y., Xie, Z., Furbo, S., Wang, D., Gao, M., and Fan, J., A comprehensive review on pit thermal energy storage: Technical elements, numerical approaches and recent applications. Journal of Energy Storage 55 (2022) p 105716. DOI: https://doi.org/10.1016/j.est.2022.105716.

[8] EU-Treasure. *Demonstrating large pit thermal energy storages*. 2024. [cited 3 March]. Available at: https://www.treasure-project.eu/.

[9] Dannemand Andersen J., Bødker L., and Jensen M.V. *Large Thermal Energy Storage at Marstal District Heating* in *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*. 2013. Paris, France. Available at (2025-03-12): https://www.cfms-sols.org/sites/default/files/Actes/3351-3354.pdf.

[10] PlanEnergi, *SUNSTORE 3, Phase 2, Implementation*. 2015. Final Report. PlanEnergi. Available at (2025-03-12): https://planenergi.eu/wp-content/uploads/2023/09/SUNSTORE-3-Phase-2-Implementation.pdf.

[11] Danish Energy Agency, *Technology Data – Energy storage*. 2018. Version number: 0009. Danish Energy Agency and Energinet. Available at (2025-03-12): https://ens.dk/en/analyses-and-statistics/technology-data-energy-storage.

[12] Eurostat, *SHARES (Renewables). Energy from renewable sources. SHARES detailed results*. 2024. Downloaded datasets for 2004 - 2020 and 2021 - 2022. Eurostat. Your key to European statistics. European Commission. Luxembourg. Available at (2024-07-03): https://ec.europa.eu/eurostat/web/energy/database/additional-data#Short%20assessment%20of%20renewable%20energy%20sources%20(SHARES).

[13] Saini, P., Persson, U., Sánchez García, L., Ottermo, F., and Bales, C. *Evaluating the Potential for Solar District Heating with Pit Thermal Energy Storage in Sweden* in *International Sustainable Energy Conference - Proceedings*. 2024. Graz, Austria. Available at (2024-07-08): https://www.tib-op.org/ojs/index.php/isec/article/view/1214.

[14] Persson, U., Saini, P., Sánchez-García, L., Ottermo, F., and Bales, C. *Data categories and selection criteria for an evaluation of the potential for solar district heating with pit thermal energy storage in Sweden* in *Book of Abstracts: 10th International Conference on Smart Energy Systems*. 2024. 10-11 September, Aalborg, Denmark: Aalborg University and Energy Cluster Denmark. Available at (2025-03-17): https://urn.kb.se/resolve?urn=urn:nbn:se:hh:diva-55640.

[15] Bales, C., Persson, U., Saini, P., Ottermo, F., and Sánchez-García, L., *Final Report: Solar district heating with pit storage for Swedish conditions*. 2025. Högskolan Dalarna, Borlänge. Available at (2025-04-16): https://urn.kb.se/resolve?urn=urn%3Anbn%3Ase%3Adu-50446.

[16] Østergaard, P. and Sperling, K., Towards Sustainable Energy Planning and Management. International journal of Sustainable Energy Planning and Management 1 (2014) p 1-5. http://dx.doi.org/10.5278/ijsepm.2014.1.1.

[17] Østergaard, P.A. and Maestosi, P.C., Special Issue: Tools, technologies and systems integration for the Smart and Sustainable Cities to come. International Journal of Sustainable Energy Planning and Management 24(0) (2020). https://doi.org/10.5278/ijsepm.vol24.

[18] Lund, H., Østergaard, P.A., Connolly, D., and Mathiesen, B.V., Smart energy and smart energy systems. Energy 137 (2017) p 556-565. https://doi.org/10.1016/j.energy.2017.05.123.

[19] Thellufsen, J.Z., Lund, H., Sorknæs, P., Østergaard, P.A., Chang, M., Drysdale, D., Nielsen, S., Djørup, S.R., and Sperling, K., Smart energy cities in a 100% renewable energy context. Renewable and Sustainable Energy Reviews 129 (2020) p 109922. https://doi.org/10.1016/j.rser.2020.109922.

[20] Sköldberg, H., Holm, J., and Rensfeldt, A., *Värdet av säsongslager i regionala energisystem – modellberäkningar av sex typsystem (The Value of Seasonal Storage in Regional Energy Systems - Model Calculations of Six Type Systems)*. 2019. Rapport 2019:624. Energiforsk. Available at (2025-03-04): https://energiforsk.se/media/27170/vardet-av-sasongslager-i-regionala-energisystem-energiforskrapport-2019-624.pdf.

[21] Energimyndigheten, *Solvärme i Sverige - En studie med fokus på potential, ekonomi och bidrag till energi- och klimatmål (Solar heat in Sweden - A study with focus on potential, economy, and contributions to energy and climate targets). ER 2021:32*. 2021. Energimyndigheten (Swedish Energy Agency), Eskilstuna. Available at (2025-03-21): http://www.energimyn-

digheten.se/nyhetsarkiv/2022/ny-rapport-visar-potentialen-for-storskalig-solvarme-i-fjarrvarmenat/

[22] Trier, D., Skov, C.K., Sørensen, S.S., and Bava, F., *Solar District Heating Trends and Possibilities. Characteristics of Ground-Mounted Systems for Screening of Land Use Requirements and Feasibility. Technical Report of IEA SHC Task 52, Subtask B – Methodologies, Tools and Case studies for Urban Energy concepts*. 2018. PlanEnergi, Copenhagen. Available at (2025-04-15): https://iea-shc.org/Data/Sites/1/publications/SDH-Trends-and-Possibilities-IEA-SHC-Task52-PlanEnergi-20180619.pdf.

[23] HUDHC, Halmstad University District Heating and Cooling Database_version 5 (2016 update by date 2019-09-30). 2019. Halmstad University, Sweden.

[24] Swedenergy, Energy supply to cogeneration, district heat production, and district heat deliveries 2015 (SE: Tillförd energi till kraftvärme och fjärrvärmeproduktion och fjärrvärmeleveranser 2015). Downloaded dataset: Tillförd energi till kraftvärme och fjärrvärmeproduktion och fjärrvärmeleveranser 2015.xlsx. 2024. Swedenergy - Energiföretagen Sverige. Available at (2024-02-26): https://www.energiforetagen.se/statistik/fjarrvarmestatistik/tillford-energi/tillford-energi-till-fjarrvarme-och-kraftvarme/.

[25] Energimarknadsinspektionen, Tekniska uppgifter - fjärrvärme (Technical information - district heating). 2024. Energimarknadsinspektionen (Energy Market Inspectorate). Available at (2024-03-01): https://ei.se/om-oss/statistik-och-oppna-data/tekniska-uppgifter---fjarrvarme.

[26] Swedish Energy Markets Inspectorate, Delivered heat by price area, technical data. Ver: 3.00, Datum: 221129 (SE: Levererad värme per prisområde, tekniska uppgifter. Ver: 3.00, Datum: 221129). Downloaded dataset: Levererad värme per prisområde tekniska uppgifter - fjärrvärme.xlsx. 2023. Energimarknadsinspektionen (Ei). Swedish Energy Markets Inspectorate. Available at (2024-02-26): https://ei.se/om-oss/statistik-och-oppna-data/tekniska-uppgifter---fjarrvarme.

[27] Swedenergy. 2023. Personal communication with N. Burstein 2023-03-16. Shared internal dataset: District heat deliveries per location and per year 1996-2021.xlsx (SE: Fjärrvärmeleveranser per ort och per år 1996-2021.xlsx). Swedenergy - Energiföretagen Sverige.

[28] sEEnergies. *sEEnergies - Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems*. 2020. [cited 21 June]. Available at: https://www.seenergies.eu/.

[29] sEEnergies Open Data Hub, Referenced dataset: "D5.1 District Heating Areas". 2022. Europa-Universität Flensburg. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): https://s-eenergies-open-data-euf.hub.arcgis.com/search?categories=d5.1.

[30] Fleiter, T., Manz, P., Neuwirth, M., Mildner, F., Persson, U., Kermeli, K., Crijns-Graus, W., and Rutten, C., *D5.1: Excess heat potentials of industrial sites in Europe (Revised version). Documentation on excess heat potentials of industrial sites including open data file with selected potentials*. 2020. sEEnergies - Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2025-03-21): https://doi.org/10.5281/zenodo.4785411.

[31] HRE4. *Heat Roadmap Europe Resource Center*. 2020. [cited 21 March]. Heat Roadmap Europe: Low-carbon heating & cooling strategies for Europe. Available at: https://heatroadmap.eu/.

[32] PETA 4.3, The Pan-European Thermal Atlas (Peta, version 4.3). Dataset: "Heat Demand Densities 2015 (HRE4)". 2018. Heat Roadmap Europe - A low-carbon heating and cooling strategy for Europe. Available at (2018-12-10): https://heatroadmap.eu/peta4/.

[33] Persson, U., Möller, B., and Wiechers, E., *Methodologies and assumptions used in the mapping. Deliverable 2.3: A final report outlining the methodology and assumptions used in the mapping*. 2017. Heat Roadmap Europe 2050, A low-carbon heating and cooling strategy. Available at (2018-12-10): https://heatroadmap.eu/wp-content/uploads/2018/11/D2.3_Revised-version_180928.pdf.

[34] European Commission: Joint Research, C., Pafi, M., Ferri, S., Halkia, M., Siragusa, A., and Sabo, F. The European settlement map 2017 release – Methodology and output of the European settlement map (ESM2p5m). Publications Office, 2016. https://data.europa.eu/doi/10.2760/780799

[35] JRC, European Settlement Map (ESM). Copyright European Commission, European Settlement Map 2016. 2017. Joint Research Centre, Institute for the Protection and Security of the Citizen, Global Security and Crisis Management Unit. European Commission, Brussels. Retrieved originally 2017-07-21 from (https://land.copernicus.eu/pan-european/GHSL/european-settlement-map/EU%20GHSL%202014?tab=download). Available at (2024-03-04): https://ghsl.jrc.ec.europa.eu/datasets.php.

[36] Geonames, Features for country with iso code SE. Licensed under Creative Commons BY 4.0 (CC BY 4.0). Link to licence: https://creativecommons.org/licenses/by/4.0/. No changes made. 2023. Opendatasoft. St. Gallen, Switzerland. Available at (2023-05-23): https://download.geonames.org/export/dump/.

[37] IEA, *World Energy Balances (2019 Edition)*. 2019. International Energy Agency, Paris.

[38] Persson, U. and Werner, S., *Quantifying the Heating and Cooling Demand in Europe. Work Package 2. Background Report 4*. 2015. Stratego: Multi-level actions for enhanced Heating & Cooling plans. Project No: IEE/13/650. Available at (2024-02-23): https://heatroadmap.eu/wp-content/uploads/2018/09/STRATEGO-WP2-Background-Report-4-Heat-Cold-Demands.pdf.

[39] Persson, U., Wiechers, E., Möller, B., and Werner, S., Heat Roadmap Europe: Heat distribution costs. Energy 176 (2019) p604-622. DOI: https://doi.org/10.1016/j.energy.2019.03.189.

[40] sEEnergies Open Data Hub, Referenced dataset: "BL2015 HD100 total". 2022. Europa-Universität Flensburg. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): https://s-eenergies-open-data-euf.hub.arcgis.com/maps/886d9e7864ca4c53a67172d523a588c0/about.

[41] Lantmäteriet, Höjddata, grid 50+ NH 2020 (tif) Elevation data, grid 50+. 2023. © Lantmäteriet. GSD Geografiska Sverigedata. Available at (2023-08-22): SLU GET (Geodata Extraction Tool) Service.

[42] Lantmäteriet, *Terrain Model Download, grid 50+ NH*. 2022. Product description. Document version: 1.6. Lantmäteriet (Swedish Land Survey). Available at (2024-08-12): https://www.lantmateriet.se/en/geodata/our-products/product-list/terrain-model-download-grid-50/.

[43] SGU, *Produkt: Jorddjupsmodell*. 2024. Produktbeskrivning (Product description). Sveriges geologiska undersökning (SGU). Available at (2024-08-12): https://resource.sgu.se/dokument/produkter/jorddjupsmodell-beskrivning.pdf.

[44] SGU, Jorddjup_10x10m (tif). 2023. Raster dataset, Jorddjup (Soil depth). Produkt: Jorddjupsmodell. © Sveriges geologiska undersökning (SGU). Available at (2023-08-24): SLU GET (Geodata Extraction Tool) Service.

[45] SGU, *Produkt: Jordarter 1:25 000 – 1:100 000*. 2024. Produktbeskrivning (Product description). Sveriges geologiska undersökning (SGU). Available at (2024-08-13): https://resource.sgu.se/dokument/produkter/jordarter-25-100000-beskrivning.pdf.

[46] SGU, Jordarter_25_100k_jg2. 2023. Vector dataset, Jordart, grundlager JG2 (Soil types, ground layer JG2). Produkt: Jordarter 1:25 000 - 1 000 000. © Sveriges geologiska undersökning (SGU) Available at (2023-09-27): SLU GET (Geodata Extraction Tool) Service.

[47] European Environment Agency, CORINE Land Cover 2018 (vector/raster 100 m), Europe, 6-yearly - version 2020_20u1, May 2020. 2020. © European Union, Copernicus Land Monitoring Service 2024, European Environment Agency (EEA). Available at (2024-05-29): https://land.copernicus.eu/en/products/corine-land-cover/clc2018#general_info.

[48] Copernicus, *Corine Land Cover*. 2024. Copernicus: Europe's eyes on Earth. Available at (2024-08-13): https://land.copernicus.eu/pan-european/corine-land-cover.

[49] ESRI. *GIS Software for Mapping and Spatial Analytics*. 2025. [cited 2025-04-08]. Available at: http://www.esri.com/.

Appendix 1: Case study maps

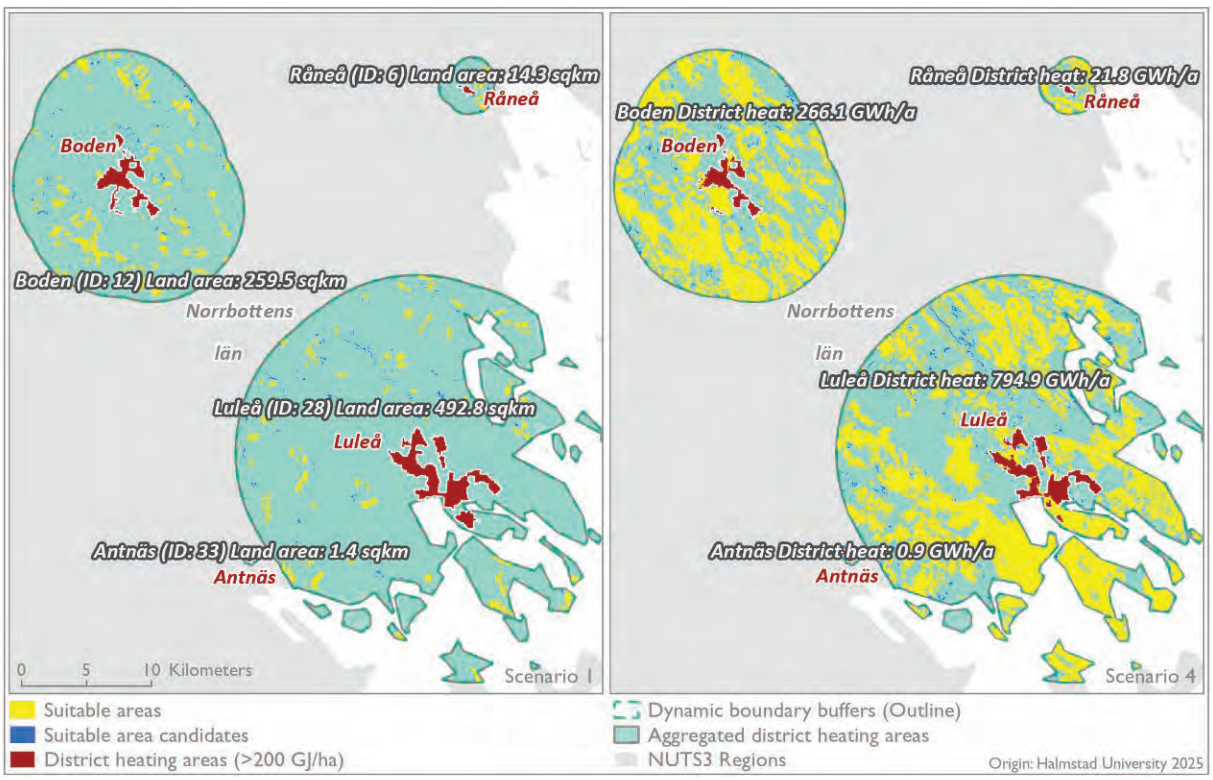

Figure 11. Map illustrations of suitable areas identified in Råneå and neighbouring cities under the 1st (left) and 4th scenario (right).

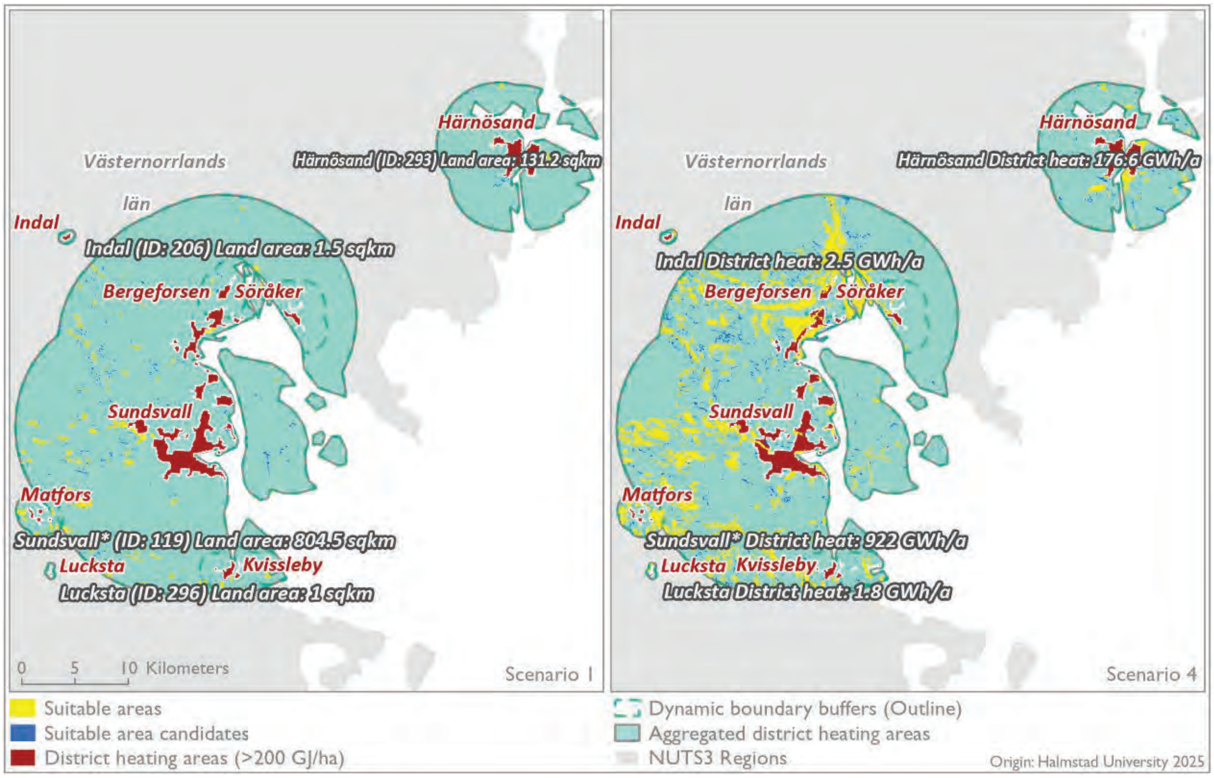

Figure 12. Map illustrations of suitable areas identified in Härnösand and neighbouring cities under the 1st (left) and 4th scenario (right).

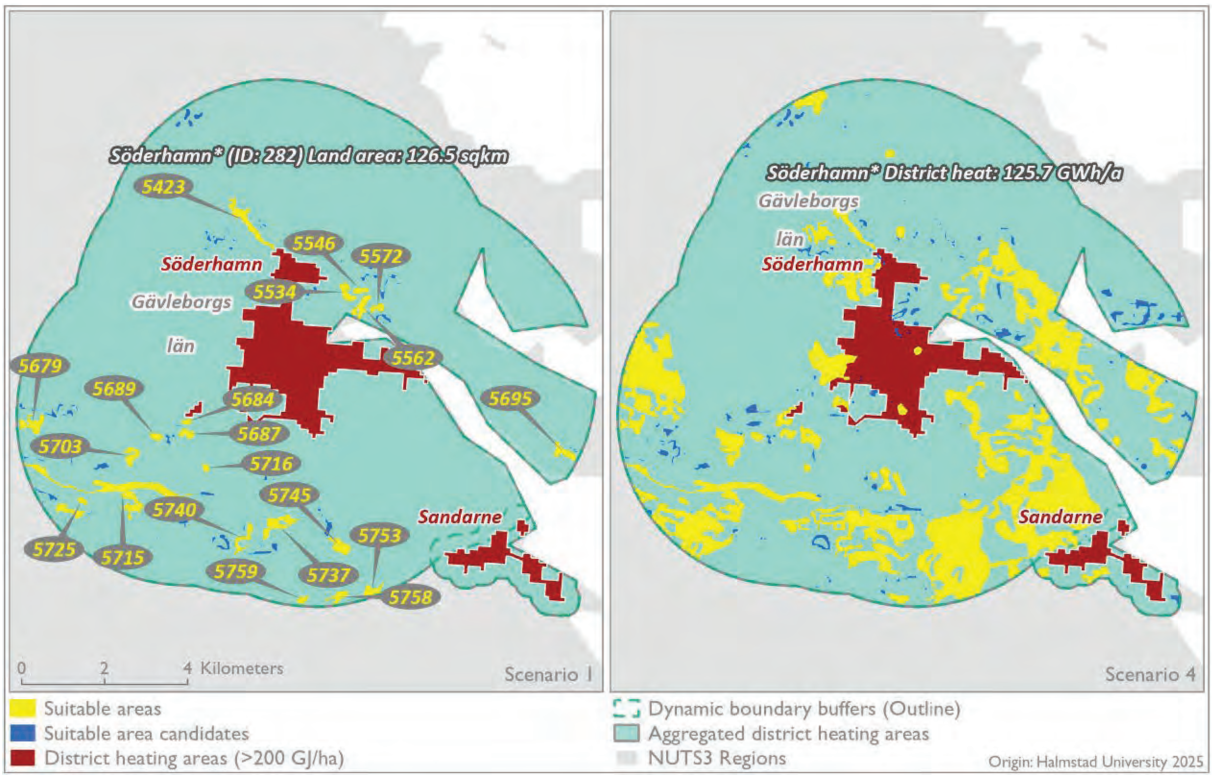

Figure 13. Map illustrations of suitable areas identified in Söderhamn under the 1st (left) and 4th scenario (right). Identified suitable areas in the 1st scenario presented with associated ID-numbers for illustration.