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Evaluating the Potential for Solar District Heating with Pit Thermal Energy Storage in Sweden

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Abstract. Sweden was among the first countries to install solar thermal plants for district heating (DH) as early as in 1970s. However, in recent years, the focus on solar DH installations has shifted primarily to Denmark and Germany, with only one recent installation reported in Sweden. Nonetheless, due to changes in the overall heating market, the use of large-scale storage (both with and without solar heat) is becoming increasingly important. Despite significant advancements in adopting DH systems, the combination of solar DH with PTES is not well studied from Swedish context. The economic and geological prerequisites for the deployment of PTES remain largely unexplored. This paper explores the integration of large-scale solar thermal systems into DH networks in Sweden, particularly highlighting the feasibility and potential of pit thermal energy storage (PTES) systems. Through findings from a national project, this paper assesses the techno-economic-geological viability of PTES alongside solar thermal collectors, providing insights into the project's methodological approach and initial findings.

Keywords: Solar District Heating, Pit Thermal Energy Storage, Geological Analysis, Techno-Economic Analysis

1. Introduction

District heating (DH) entails the centralized generation of heat, subsequently distributed to residential, commercial, and industrial entities within a localized area. As of 2022, DH networks globally contributed approximately 17 EJ of heat, to fulfil nearly 9 % of the global final heating and cooling demand. Predominantly concentrated in Europe, Russia, and China, these networks exhibit variances in commercialization and renewable integration across different regions [1]. For instance, Nordic-Baltic countries demonstrate a significant reliance on renewable sources, constituting above 50% of the fuel utilized for DH, whereas Southern Europe, Russia, and China mainly rely on natural gas and Oil as a main fuel [2], [3].

Large scale solar thermal systems can be integrated into district heating networks. The low-cost thermal energy from solar thermal collectors combined with a diurnal thermal storage can displace the use of boiler during mid-season periods and summer, resulting in solar fractions of 10-20% [4]. To increase the solar fraction, a seasonal storage (using boreholes, aquifers, rocks, water pits, etc.) is combined with heat sources to balance the mismatch between solar heat production and load demand. This system especially with boreholes and aquifers storage are well reported in many scientific publications [5]. Compared to other seasonal storage, pit thermal energy storage (PTES) offers lowest investment cost per m^3 especially at large capacities (above 50 000 m^3) and offers construction and operational flexibilities. Solar district heating (SDH), combined with PTES is particularly prevalent in Denmark and Germany. The success in these countries is driven mainly by favourable policy support, and technology development [6].

In Sweden, the heating source preference until 1950s was wood-fired furnaces, which were replaced by oil boilers up to the oil crises, when their market share started to fall in favour of district heating [7]. As of today, DH is well-established in Sweden, primarily used for multifamily dwellings. Currently, according to general statistics, there are over 550 DH systems operating across major towns and cities, representing annual heat deliveries in the range of 50 - 53 TWh. The direct emissions from heating sector in Sweden is 3 MT CO_2 eqv. (in 2019), with the aim to make this sector fossil free by year 2030 [8]. DH in Sweden primarily utilizes local resources such as biomass, municipal waste, and industrial waste heat, thus offering limited incentives to adopt solar heat. However, recent years have seen a resurgence in interest in solar heating systems, driven by increased competition for biomass from other sectors e.g (transportation) and rising fuel costs. A national study has concluded that the profitable potential capacity for SDH combined with PTES in Sweden is approximately 1.7 - 6 TWh, depending on the assumptions used in the calculations. This potential is primarily in small DH systems where biofuels are used for the baseload, resulting in high marginal costs in summer [9].

Large storage solutions, such as PTES can also play a significant role within the broader energy system perspective. PTES can store surplus solar heat, waste heat, and heat generated from low-cost electricity (either directly or via heat pumps) during summer for its use in the winter [10]. Furthermore, during peak load periods in mid-winter, PTES can be discharged to substitute the expensive peak fuels utilized by DH companies. This allows to improve system flexibility, reduction of operational costs and the reduction of the reliance on combustion fuels. However, the application of pit storage systems in Sweden remains limited, and there exists a knowledge gap regarding the feasibility. This limitation is largely due to the specific geological conditions required for PTES systems to be deemed economically viable. A national project from the Swedish Energy Agency (2022-2024) aimed to explore the techno-economic-geological suitability of PTES with solar thermal collectors. This paper provides an overview of the project, methodological approach, and results obtained thus far in this project.

2. Method

The project involves collaboration among four partners: two universities in Sweden (Dalarna University and Halmstad University), one industrial partner (Absolicon Solar collector AB), a manufacturer of concentrated solar thermal collectors, and one international consultant (PlanEnergi) [11]-[14]. The long-term objective of the project is to facilitate the integration of large-scale heat storage into Swedish district heating networks and to improve the understanding of how solar heating technology, in conjunction with PTES can contribute to Swedish DH system. The main research questions addressed are shown in Figure 1. Only the first two research questions will be addressed in this paper. For the third research question, as well as for the results from the entire project, a dedicated journal paper manuscript is planned in late 2024.

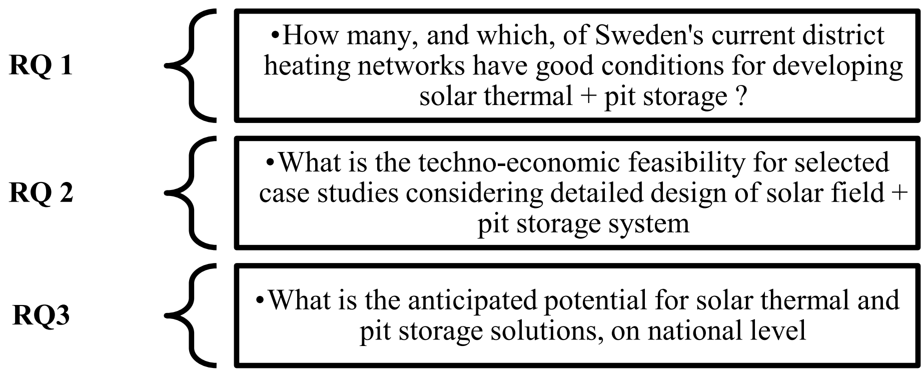

Figure 1. *Research questions addressed in the project (RQ = research question).*

To address the research questions, a multi-step approach is followed:

- Update of Swedish district heating database: An existing database developed in national and EU projects is updated with data from the national potential study from Swedish energy agency that identified locations with high economic viability for solar district heating [9]. For the identified locations, relevant data, including annual heating demand and fuel types used, are obtained to update a database of Swedish district heating systems. This data is crucial for the subsequent analysis phases. The updates made in Swedish database are explained in section 2.1.

- Calculation of collector area and PTES volume: Utilizing the gathered data, the necessary collector area, PTES volume, and land area requirements are calculated for different solar fractions (20%, 40%, and 60%). These calculations are based on pre-feasibility guidelines developed within an international project, ensuring a standardized approach to feasibility assessment (see section 2.2) [15].

- Establishment of geological pre-conditions: A set of geological preconditions necessary for the construction of PTES is established. These include soil type, soil depth, ground water level, and it's flow rate, which collectively inform a go/no-go decision for construction of PTES in the identified locations, as further detailed in section 2.3.

- Identification and selection of case studies: Through preliminary calculations, geological filters, and consultations with district heating companies, a pool of potential case studies is identified. From this pool, three promising sitess are selected for further analysis and for which system models are developed, leading to techno-economic analysis.

- Techno-economic analysis and system modelling: The selected case studies undergo a techno-economic analysis, where system models are developed in TRNSYS to simulate the operational dynamics and economic viability of integrating solar district heating with PTES.

- Geospatial Analysis and national potential estimation: To estimate the national potential and address the overarching research question, a geospatial analysis is conducted using geographic information system (GIS) tools. This analysis extrapolates the findings from the case studies to a national level, to spatially analyse and visualize the distribution and viability of PTES and solar heating solutions to better understand of their feasibility within the Swedish context.

The next sub-sections provide details about key activities conducted within the project.

2.1 Swedish district heating systems

For this part of the project, the objective is first to create a tabular list with updated information for all known district heating systems currently in operation in Sweden (statistics update), and, secondly, to convert this list into a new geographical feature class layer, by way of spatial analysis, which depicts these systems as polygon areas by their anticipated spatial spread and distribution (spatial update). The resulting new dataset from this part will be an upgrade for Sweden of an already existing dataset originating from the sEEnergies EU Horizon project (the "D5.1 District Heating Areas" dataset, February 2020 [16], [17] which itself was established on the basis partly of heat demand density data developed in the Heat Roadmap Europe EU Horizon project (data year 2015) [18], and partly on information from the Halmstad University District Heating and Cooling database, version 5 (data year 2016), in short HUDHC [19].

Hereby, the main aim of these updates is, on the one hand, to refresh and extend the list of known Swedish district heating systems by adding information from complementary and more recent sources and, on the other hand, to improve the geographical model representation by which these systems are projected as district heating areas. An additional aim is also to include information from an auxiliary list of Swedish district heating systems using refined versus non-refined biomass fuels, produced by Profu AB [9].

2.1.1 Statistics update

For the statistics update, the input dataset is the original Swedish extract from the HUDHC [19], which was based mainly on 2015 records published by former Svensk Fjärrvärme (Swedish District Heating Association), now managed by Swedenergy [20]. For the reference year, the original dataset included a total of 386 systems (372 with data on delivered heat) with an annual volume of delivered heat at some 47.1 TWh (~170 PJ).

For this project, the original dataset has served as reference as two main additional information sources have been elaborated: (1) the publicly available 2016 to 2021 time series dataset on Swedish district heat deliveries from the Swedish Energy Markets Inspectorate (EMI) [21], and (2) an internal record on annual Swedish district heat deliveries between 1996 and 2021 made available to the project under a non-disclosure agreement by Swedenergy [22]. Given the internal nature of the latter dataset, this was only used as additional reference for the final statistics update. By access to these two information sources, the total number of currently operating systems, as well as the total volume of annual heat deliveries, have been adjusted and updated by a sequence of data management activities (Clean-up) as well as by comparison to the original reference. Finally, information from the national feasibility study on solar district heat was added in terms of fuel type (refined biomass/wood chip).

As for the updated total number of systems, in-depth analysis of reported system locations (villages, towns, cities etc.), corresponding names and administrative regions, as well as occasional split of merged location reports, have constituted the essential activities performed. Regarding merged location reports, assumedly by reporting tradition, some utilities who operate several systems in different places report everything *en masse* under bundled labels which might include two, three, or even four different location names, often separated by hyphenation (close to 50 instances in the EMI dataset). Given our purpose – to identify actual district heating system locations – significant effort was required to disaggregate such data to single, unique location names, as well as to redistribute bundle-reported annual delivery volumes (volume distribution by population factors established for this purpose).

For the updated volumes on annual district heat deliveries, data management activities mainly consisted in rendering averages based on the available time series data, mainly for the years 2016 to 2021, under the assumption that such mean values may be representative of annual delivery volumes under fairly normal conditions. Key numbers for used input data in the statistics update are presented in Table 1.

Table 1. *Overview of input datasets used for the statistics update on Swedish district heating systems. Energy volumes in [TWh/a]*

Dataset	**Count [n]**	**Match to HUDHC SE**	**Heat deliveries**	**Heat deliveries time reference**	**Comment**	**Source**
Original reference (HUDHC SE)	386	-	47.1	2015	Minor clean-up	[19], [20]
Public dataset (EMI)	486	379	51	Average 2016-2021	Major clean-up	[21]
Internal dataset (Swedenergy)	520	386	51.5	Average 1996-2021	Minor clean-up	[22]

2.2.1 Spatial update

The rendering of district heating areas was performed principally in alignment with what might be referred to as the "sEEnergies" approach which, among other, utilises data on heat demand density [16], experience-based feasibility thresholds for heat distribution expressed in the quantity of heat demand density, and various additional geographical datasets with, for example, location names. A prerequisite for this process is therefore access to an appropriate heat demand density dataset, preferably at high spatial resolution (hectare-level for this application). In addition, the approach requires information on built-up areas, that is, a dataset which spatially delineates urban areas, which is needed as a geographical reference and barrier feature in the rendering process.

As a further element of improvement, the national heat demand density dataset used in the project ("SDH_HDD_SE_2015"), was created as an arithmetic average on the basis of two previous datasets (calculated at raster cell level), both of which were associated with certain imperfections. The first, the original 100 x 100-meter Heat Roadmap Europe 2015 heat demand density raster dataset suffered from a general, model-inherent, tendency to emphasise inner-city densities (>3000 GJ per hectare), for further references see for example [18]-[20] while the second dataset; the corresponding 2015 baseline heat demand density raster dataset from the sEEnergies project [17], tended in the opposite direction (emphasising densities in rural areas, i.e. ≤200 GJ per hectare), which can be observed in *Figure 2*. The resulting dataset thus represents a somewhat more balanced anticipation of Swedish heat demand density distributions.

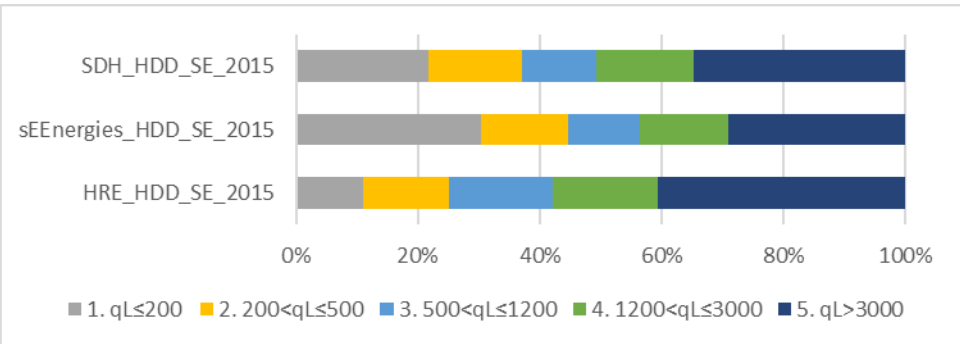

Figure 2. *Comparison of heat demand density (q_L) distributions in used input heat demand density datasets by five heat demand density classes (Unit: GJ/ha).*

Regarding absolute magnitudes of these residential and service sector heat demands, international energy statistics on fuel and energy final consumption for the year 2015 [23] was used as reference in combination with generic conversion efficiency-calculations adapted from the Stratego project (see e.g. Table 1 in [24], as summarised in Table 2. In consequence of the Stratego approach, where a particular focus at the time was to estimate electricity used for heating purposes (which still is difficult to derive from ordinary statistics alone), the total assessed heat demand at 78.9 TWh per year (283.9 PJ) may alternatively – if strictly using an average heat pump seasonal performance factor of 3.0 in anticipated residential sector applications – be perceived as having approached one hundred terawatt hours this year (98.3, corresponding to 353.9 PJ/a).

Table 2. *Reference data for Swedish residential and service sector heat demands in the year 2015, based on Stratego assessment method* [25] *and IEA Energy Balances [23]. Energy volumes in [TWh/a]*

	Residential sector		**Service sector**	**Total**
Heat demand (Excl. electricity for heating purposes)	40.7		18.8	59.5
Electricity share of total heat demand	26%		21%	-
Electricity used for heating purposes (Total)	14.3		5.0	19.3
Electric heat conversion technology	Heat pumps	Other electric	Other electric	**-**
Electric heat conversion technology (Market share)	68%	32%	100%	**-**
Electricity used for heating purposes (Conversion technology)	9.7	4.6	5.0	19.3
Heat demand (Total)	**55.0**		**23.8**	**78.9**
Conversion factors	300%	100%	100%	-
Electricity used for heating purposes (Conversion technology) - Weighted	29.2	4.6	5.0	38.8
Heat demand (Total) - Weighted	**74.5**		**23.8**	**98.3**

However, as also illustrated in *Figure 3*, none of the used input datasets reaches annual volumes of such magnitudes when aggregated to the national level. In fact, for the 2015 reference year, the HRE dataset sums up at 81.8 TWh (284.4 PJ); the sEEnergies dataset to 78.1 TWh (281.2 PJ), while the resulting project dataset amounts to 79.7 TWh (286.9 PJ). It remains uncertain how and to what degree electricity used in residential sector heat pumps was accounted for in the used input datasets. In this particular sense, the results from this project may represent a slight underestimation of actual heat demands, Still, it is likely that most residential heat pumps are used in single family houses located mainly in rural settings, which therefore should have less impact on the rendering process with its focus mainly on urban areas.

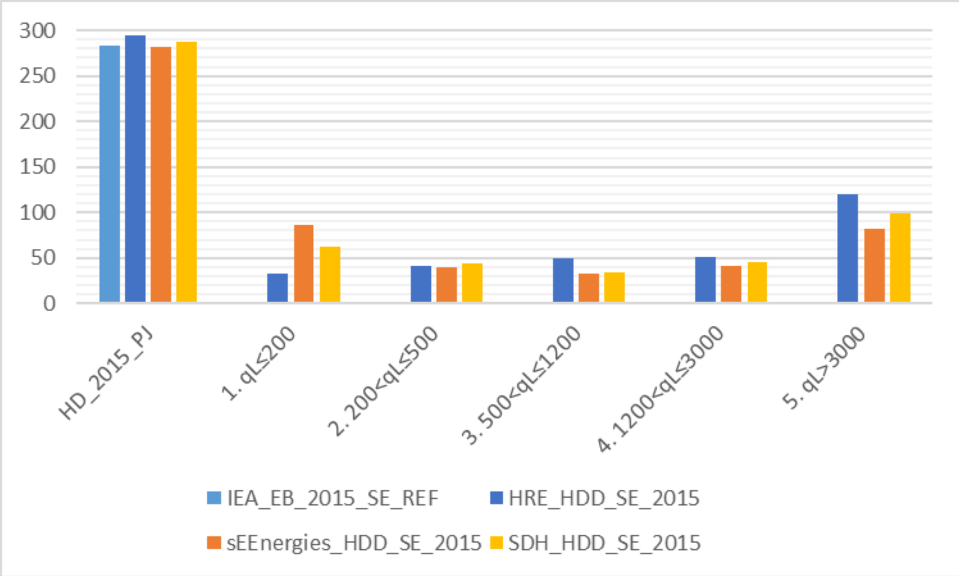

Figure 3. *Overview of reference and input heat demand datasets in total (PJ) and totals (PJ) for each of five heat demand (qL) density classes (Unit: GJ/ha).*

In the remaining steps of the spatial update, publicly available data on built-up areas (in this case hectare level satellite imagery interpretations as expressed in the European Settlement Map (ESM) [26] and location names (in this case the point-source GeoNames Gazetteer extract files for SE [27] was used, on the one hand, to create required reference and barrier features and, on the other hand, to assign location-specific names to these features.

Regarding the former, all ESM hectare cells were extracted, converted to polygons, eliminated in part (all parts smaller than four hectares), and finally selected for the resulting Urban Areas dataset if larger than nine hectares as coherent area (several iterations on the parameter settings for elimination and selection was performed to arrive at a most adequate representation). For the latter, a multi-step procedure was designed to assign a place name to each rendered Urban Area, a process which quickly can get complicated since in reality several locations may have the same name and several Urban Areas may consist of multiple polygons. In this case, a series of spatial join, sort, and dissolve operations were developed and used to arrive at a satisfactory result (11,240 Urban Areas in total, all attributed a location name).

2.2 Preliminary calculations for different solar fractions

One practical constraint in the installation of solar heating systems is the requisite land area for the placement of collectors and storage in proximity to the district heating network. This consideration is important to consider prior to finalizing the selection of case studies for national potential analysis, as well as being necessary for the estimation of national potential. Accordingly, the calculations for the required solar collector area, storage volume, and land area were performed for three different solar fractions (20%, 40%, and 60%). These calculations utilized a single data input (aggregated annual heating data) from the tabular list compiled in the initial stages of the project. The calculations were conducted in accordance with pre-feasibility guidelines developed within IEA-SHC Task 55. The assumptions made for the calculations are detailed in Table 3. A single-glazed flat plate collector is utilized as the reference to calculate the thermal output. For PTES, an inverted pyramid geometry is assumed to estimate the height and other geometric dimensions. Given a specific volume, the top side length and total depth are determined based on the data provided in [28], which are then used to calculate the footprint area of the PTES.

Table 3. *Parameters used for calculations regarding preliminary sizing of solar field and storage volume for 3 different solar fractions.*

Component	Parameters	Value	Unit	Remarks
Solar collector	Mean fluid temperature in the collector	75	°C	Average of supply and return temperatures
	Annual solar collector output (Qcoll)	0.45* GHI*Correction factor	kWh/(m^2.year)	Correction factor is derived based on figure 2.3.4 in [15]
	Reference GHI for calculations	1000	kWh/(m^2.year)	Reference for Stockholm weather
	Land area requirement for collector	3*Qcoll	m^2	
PTES volume	For 20% solar fraction	0.2	$m^3/m^2_{collector\ apr.}$	
	For 40% Solar fraction	1	$m^3/m^2_{collector\ apr.}$	
	For 60% Solar fraction	2	$m^3/m^2_{collector\ apr.}$	
PTES geometry	PTES shape	Inverted Pyramid		
	PTES total height (above + below terrain)	$0.9204.x^{0.2688}$	Meters	x is the storage volume in m^3
	PTES top side length	$2.2344.x^{0.3371}$	Meters	x is the storage volume in m^3
	PTES height above terrain	$0.0479.x^{0.4054}$	Meters	x is the storage volume in m^3

2.3 Geological criteria for PTES

The method for evaluating the feasibility of PTES in any given location involves analyzing geological characteristics to identify the most suitable areas, principally by eliminating those areas that are not suitable. These filters are applied to ascertain whether a site's geological conditions could potentially support the efficient and economical construction and operation of a PTES system. Datasets provided by the geological survey of Sweden, are utilized within ArcGIS to develop a GIS model, for visualizing the geological characteristics of potential sites [29]. The investigation focuses on the following parameters:

- Soil type analysis: Identifies the composition and properties of the soil, which influence thermal conductivity, excavation feasibility, and the suitability of the soil for constructing embankments for PTES. Certain soil types, such as coarse sand and Morain, are considered appropriate, while silt and organic soils are deemed unsuitable. Clay can be used for PTES, but at an additional cost, as the excavated soil cannot be utilized for embankments. The database used in the study assumes that the soil type is uniform throughout the depth, and therefore, it does not account for variations in soil composition, which could also impact the feasibility of PTES.

- Soil depth: The depth of the soil layer above the bedrock influences the volume of storage that can be achieved without encountering bedrock. A minimum depth of 10 meters is used as a criteria for GIS study.

- Groundwater level assessment: The groundwater levels in relation to the pit's bottom are used for PTES suitability. For locations with flowing groundwater, a groundwater level to be at least 3 meters below the PTES bottom surface is preferred. This stipulation is designed to mitigate the potential for water flow to negatively affect the thermal performance of the storage. A higher groundwater level than this minimum can be used, particularly for static water conditions. The example of Dronninglund illustrates a practical application of these criteria, where the groundwater depth was only 1 to 1.5 meters below the pit bottom. To accommodate the PTES, groundwater levels were artificially lowered. The groundwater levels are monitored only in a few locations in Sweden, and there is a lack of a national-level database for groundwater. In order to overcome this limitation, the less reliable "brunnarkivet" has been exploited for interpolating groundwater levels throughout the country.

- Ground water flow rate: The rate at which groundwater flows is important to consider. However, no dataset explicitly detailing groundwater flow rates was available. This is planned to address in the next stages of the project.

Based on the geological criteria outlined and information obtained from preliminary land area calculations, several case studies were identified as suitable for the three required case studies for computer modelling. The case studies along with other results are shown in the next section.

3. Results

The sections outline the findings from the project, presenting results linked to updates from the Swedish district heating system database. The outcomes from preliminary calculations for various case studies are detailed. This is followed by specific example of results derived from geological filters applied to one specific case study.

3.1 Update on Swedish district heating

The overall results from the statistics update are presented in Table 4. In total, as compared to the original reference count of 386 Swedish district heating systems (see Table 1), the new dataset includes 547 systems believed to be in operation. Relatively speaking, this is a ~42% increase in total system counts. As can be further distinguished from Table 4, a majority of these systems were represented in both the original reference (HUDHC) as well as in the new EMI dataset, however a significant number of systems previously not accounted for (168) was also found in this source.

Table 4. *Summary of the Swedish District Heating Systems (SEDHS) tabular list, version 5: SEDHS – number of DH systems; Population in thousands; Q – heat demand.*

	Not in Profu list			In Profu list			Grand total		
Input dataset	**SE DHS [-]**	**Pop. x1000 [-]**	**Q [TWh/a]**	**SE DHS [-]**	**Pop. x1000 [-]**	**Q [TWh/a]**	**SE DHS [-]**	**Pop. x1000 [-]**	**Q [TWh/a]**
EMI_Only	126	436	4.3	42	141	0.7	168	577	5.0
HUDHC_EMI_Both	160	6220	41.9	142	738	4.1	302	6958	46.0
HUDHC_Only	33	94	1.3	44	93	0.4	77	187	1.7
Grand Total	319	6750	47.5	228	972	5.2	547	7723	52.7

Table 4 further specifies the number of systems that were among those included in the auxiliary list of Swedish district heating systems using refined versus non-refined biomass fuels (the Profu list). 228 systems from this auxiliary list are indeed represented in the new grand total and it is further noticeable that most of these systems seem to be smaller ones, since they represent only a minor fraction (5.2 terawatt hours per year) out of total heat deliveries (the new total at 52.7 TWh per year). Noteworthy, in relative terms, this new total is merely a ~12%

increase compared to the reference at 47.1 terawatt hours per year, which might imply that the majority of newly added systems are located in smaller towns and villages. This is, however, important for this project as the economic viability of solar thermal has been shown to be greater for networks supplied using refined fuel (wood pellets), and these are always in smaller systems due to their great energy cost but lower maintenance cost.

As for the spatial update, the results may perhaps best be presented by first illustrating the rendering process in overview, as presented in *Figure 4*. Starting from the right side in this figure, here exemplified for the Malmö/Lund area in the southern part of Sweden, the right-most map shows the underlying raster image with the share of built-up areas per hectare, which was used among other parts in the rendering process of Urban Areas. Based on this, in the centre map, the resulting new heat demand density dataset for Sweden is depicted by use of five heat demand density classes. By summarising these heat demand densities by the corresponding Urban Areas (Zonal Statistics) and by subsequent aggregation to regional and national levels, information on the total residential and service sector heat demand, thus spatially distributed to Urban Areas, may be gathered, as presented in Table 5.

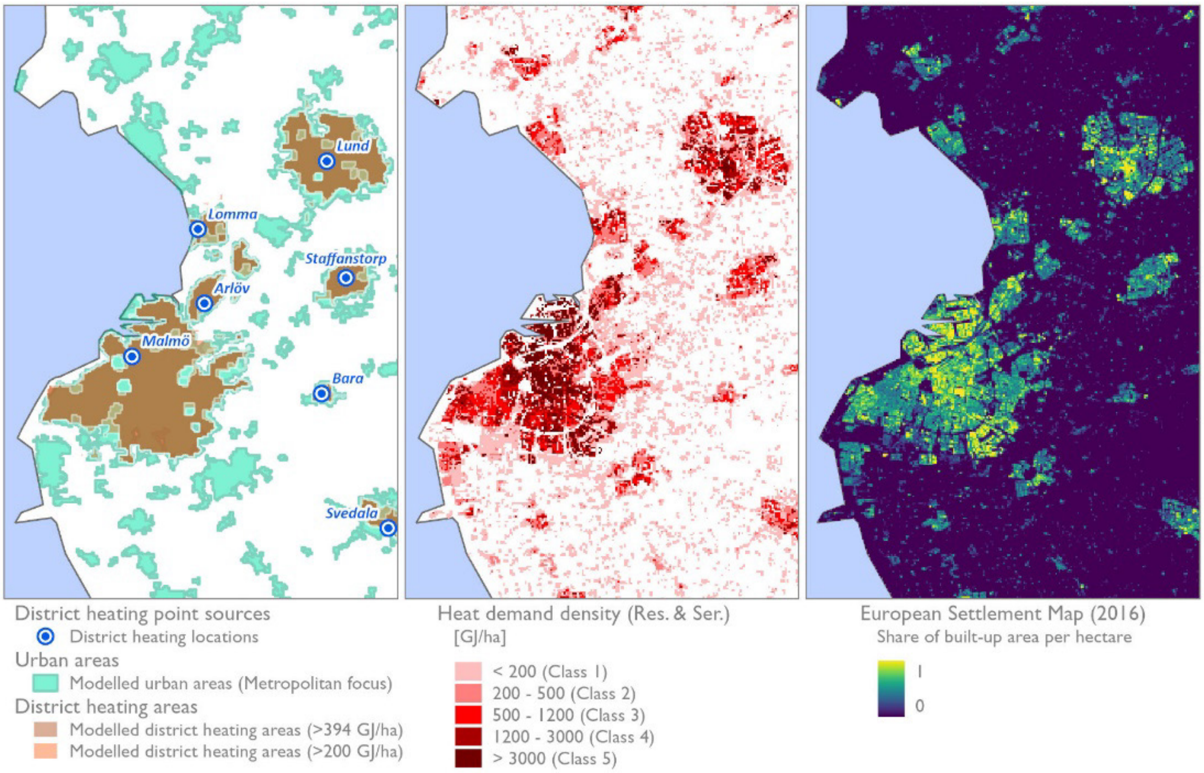

Figure 4. *Three maps of the Malmö/Lund area in the Southern part of Sweden to illustrate the results and the process to model Urban Areas and District Heating Areas (left) based on residential and service sector heat demand densities at the hectare level (centre), in turn based partly on underlying satellite imagery quantifying the relative share of built-up areas per hectare (right).*

For the final determination of District Heating Areas, at left in Figure 4, the main reference was the above-mentioned summation of heat demand densities by Urban Areas, wherein the zonal statistics results may be expressed as accumulated totals by each discrete heat demand density level present in the dataset. By inverse sorting, that is by summarising all heat demands from the cell with the highest heat demand density all the way downwards until the total sum thereby acquired matches the statistical total for Swedish district heat deliveries in the reference year, e.g. 52.7 terawatt hours per year, as outlined in Table 4 above, all raster density cells upon which the rendering could be performed would be identified – if accepting the general modelling idea that district heat is delivered primarily to high heat demand density areas, then to areas with lower heat demand densities and so forth. As it happened, based on the used input data, this match occurred at the heat demand density level of 394 gigajoules per hectare, which therefore was used as the principal threshold. For reasons of adaption and fit depending on metropolitan versus rural settings, alternative threshold levels were also used to model alternative projections, where the corresponding level at 200 gigajoules per hectare is included in *Figure 4* as reference.

Table 5. *Summary of modelled Urban Areas (UA) and rendered District Heating Areas (DHA) from the spatial update, by Swedish NUTS3 regions under the main heat demand density threshold (394 GJ/ha)*

	Urban Areas				**Distict Heating Areas**			
NUTS3 Name	**UA** [-]	**Pop. x1000** [-]	**Q** [TWh/a]	**$A_{L,UA}$** [km²]	**DHA** [-]	**Pop. x1000** [-]	**Q** [TWh/a]	**$A_{L,UA}$** [km²]
Blekinge	186	159	0.8	159.7	8	125	0.6	10.4
Dalarna	719	245	2.6	657.2	21	173	1.5	37.0
Gotland	141	33	0.5	98.3	4	28	0.2	8.4
Gävleborg	633	226	3.0	679.5	22	185	1.6	46.8
Halland	260	259	1.7	229.7	7	156	1.0	31.2
Jämtland	566	92	1.0	471.2	8	65	0.7	15.1
Jönköping	392	314	2.1	299.5	21	229	1.6	40.2
Kalmar	763	187	1.8	558.1	11	127	1.1	27.0
Kronoberg	211	150	1.1	132.2	15	127	1.0	23.6
Norrbotten	377	204	2.1	435.8	18	155	2.1	34.7
Skåne	899	1215	9.9	946.7	38	901	5.3	182.8
Stockholm	555	2202	15.1	867.6	19	1911	10.0	317.2
Söderm-anland	315	243	2.0	354.9	13	193	1.6	40.3
Uppsala	508	321	2.6	344.1	18	264	1.8	49.0
Värmland	677	211	2.1	618.2	16	164	1.2	30.6
Västerbot-ten	691	264	2.2	546.6	25	229	1.8	46.1
Västernor-rland	663	206	2.1	662.8	16	158	1.3	36.0
Västman-land	356	240	2.3	364.9	11	214	2.0	53.7

Västra Götaland	1327	1419	11.3	1154.9	53	1132	6.9	229.3
Örebro	425	289	2.0	338.1	14	247	1.6	38.7
Östergöt-land	576	445	3.7	445.0	18	368	2.8	73.2
Grand Total	**11240**	**8924**	**71.8**	**10364.9**	**376**	**7149**	**47.5**	**1371.3**

From the above, it may be concluded that the update on Swedish district heating systems resulted in a considerable increase of District Heating Areas compared to the sEEnergies reference. Whereas the latter arrived at a total of 226 DH-A (Actual District Heating Areas, see table 22 in [17] this update counts 376 District Heating Areas in total under the main threshold (464 at the 200 gigajoule per hectare threshold). Noteworthy, some heat demand volumes are lost in the spatial analysis process, which results in a total heat demand allocated to Urban Areas at 71.8 terawatt hours per year, compared to the anticipated national total at 78.9 terawatt hours per year (see Table 2).

3.2 Results for the case studies

The results from the Swedish tabular list were utilized to estimate the necessary collector area and PTES volume required to achieve various solar fractions. The results are shown for collector area needed to meet a 20% solar fraction. As anticipated, the required collector area correlates with the heat demand, with the three most populous cities: Stockholm, Göteborg, and Malmö displaying larger bubble sizes in Figure 4. These sizes correspond to significant collector area requirements of 5 million square meters for Stockholm, 2 million square meters for Göteborg, and 1.3 million square meters for Malmö, respectively.

To contextualize the land area requirement for solar collectors and pit storage in Sweden needed to achieve a 60% solar fraction, it is estimated to be 600 km². This figure constitutes merely 0.2% of the total geographical area of Sweden. From a scientific perspective, this highlights the feasibility of significantly increasing the contribution of solar energy to the district heating network without necessitating an extensive portion of the national land.

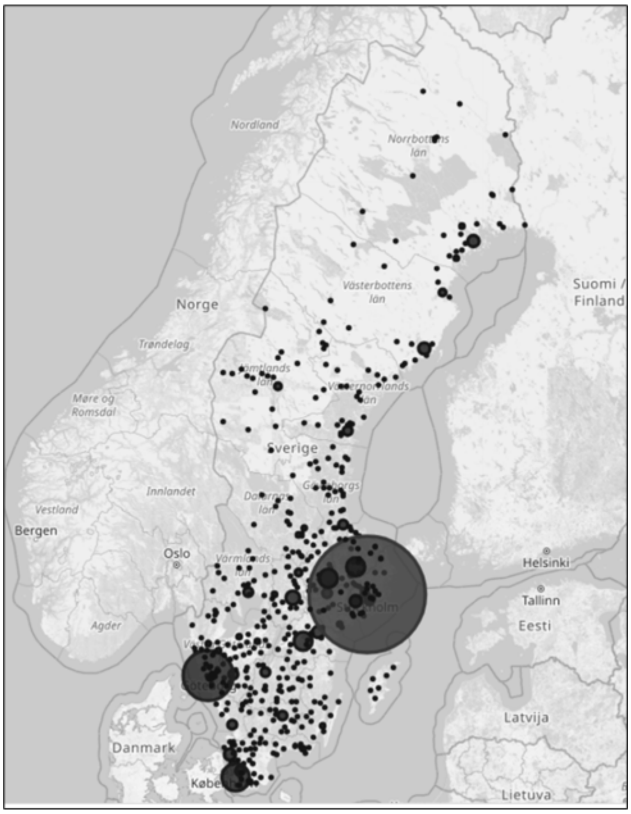

Figure 5. *Collector aperture area required to meet 20% of the heating demand for analysed locations. The diameter of each circle represents the collector area, adjusted with a zoom-out factor of 10 000 to ensure visibility of all locations. It is important to note that the size of the circles is not proportional to the actual geographic coverage area of the collector in each specific location.*

Based on interest and contacts from municipalities, eight locations have been identified for potential case studies. The location and annual heating demand of these potential case studies are depicted in Figure 5. Table 4 presents the required solar collector area and storage volume to meet 20%, 40%, and 60% of the annual heating demand for each case study.

Following the application of geological filters, three case studies were selected for system modeling using TRNSYS, focusing on the techno-economic evaluation of the solar district heating system. The selected case studies are Härnösand, with an annual heating demand of 177 GWh; Söderhamn, with a demand of 123 GWh; and Råneå, with 22 GWh. These locations offer a diverse range of heating demands, and geographical locations and thus can provide valuable insights into the scalability of SDH + PTES across different scales.

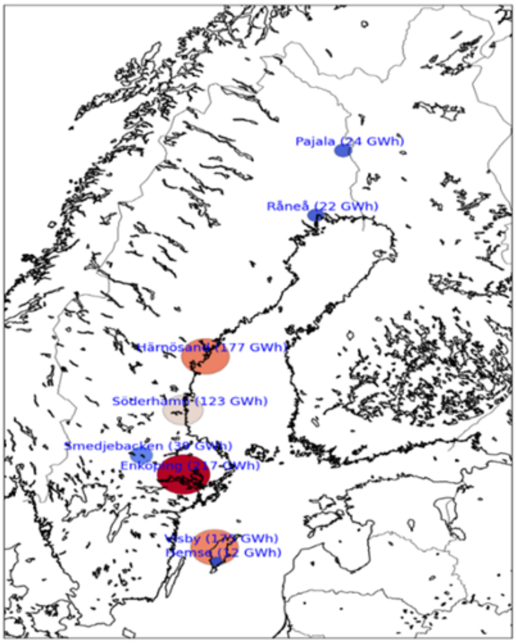

Figure 6. *Heat demand, and geolocation of identified case studies.*

Table 6. *Solar collector area and storage volume for three different solar fractions (SFs) in selected case studies, which are screened for geological analysis.*

	Solar collector area (1000*$m^2_{aperture}$)			PTES storage volume (1000*m^3)		
City name	**SF 20%**	**SF 40%**	**SF 60%**	**SF 20%**	**SF 40%**	**SF 60%**
Söderhamn	77	155	233	19	155	467
Visby	111	222	333	27	222	666
Råneå	13	277	41	3	27	83
Pajala	15	30	46	3	30	92
Hemse	7	15	23	1	15	47
Enköping	137	275	412	34	275	825
Härnösand	112	224	336	28	224	672
Smedjebacken	24	49	74	6	49	149

The geological conditions of the Råneå case study are depicted in Figure 7. These figures highlight the soil types, soil depth, and land area that are appropriate for PTES. Within the area deemed suitable for PTES, the prevalent soil type identified is Morain (shown by green color). The soil depth, indicated by a red gradient, exceeds 20 meters at the chosen location. Additionally, the water depth in this area reaches 18 meters. In the next stages of the project, system models in TRNSYS are developed to evaluate the techno-economic feasibility of the PTES for three selected case studies.

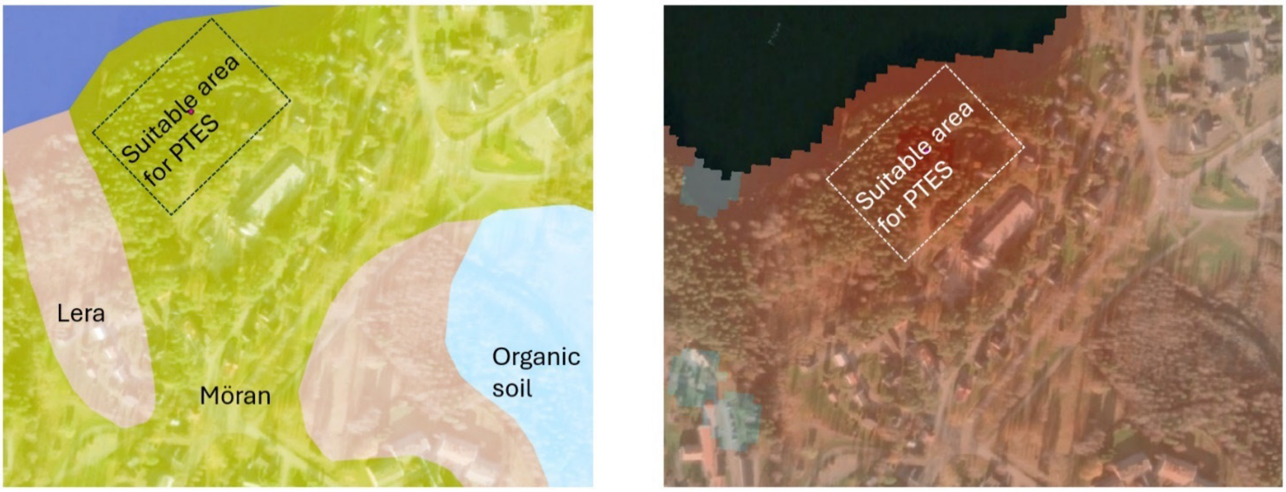

Figure 7. *Soil type (left) and soil depth (right) mapping for case study of Råneå*

4 Conclusions and discussions

Evaluating the potential for using solar collectors in combination with PTES in DH systems in Sweden is intricate and involves many different aspects. A clear view of the district heating systems is a necessity, in particular concerning the heat demand and the heat sources, in order to determine where it might be practically and economically reasonable to replace existing heat sources with solar collectors and PTES. This motivates an update and refinement of the Swedish DH database, as well as estimating the geospatial extension of the DH systems. The latter is needed on order to define the search space for reasonable locations of the solar collectors and the PTES. A related aspect is the required land area for the solar collectors and the PTES, which has been estimated for a range of solar fractions. There are many criteria to be fulfilled for the location of the PTES, including for example adequate soil types, not too shallow groundwater level and low groundwater flow. The groundwater considerations pose a particular challenge as reliable groundwater data is only available at a small number of points nationally. Still, existing databases are expected to be capable of providing a reasonable indication of the groundwater conditions. This is work in progress.

Three cities for case studies have been selected for modelling of the dynamics between the solar collectors, the PTES and the DH system. The cases have been selected to cover a range of heat demands and are furthermore geographically spread out. Suitable locations for a PTES have been pointed out within the case studies. The dynamics is simulated using TRNSYS, based on time series of historic heat demand and solar irradiation data. The fact that suitable PTES locations could be found within the case studies indicate a likely potential for this combination in Sweden. However, a national study is needed to adequately quantify this potential, which is the planned next step of the project. The outcome of the case studies will form an input to the GIS-based process of evaluating the national potential.

In conclusion, a methodology for evaluating the potential for solar collectors and PTES in DH systems in Sweden has been presented. Initial results on the Swedish DH systems data, and the case studies were also outlined.

Data availability statement

The presented analysis is based principally on publicly available data, for which references are provided at each corresponding instance. Concerning resulting datasets from the analysis, the project is currently considering appropriate forms and possibilities for public sharing of such materials.

Author contributions

Puneet Saini: Conducted the scientific work explained in section 3.2. Writing and review.

Urban Persson: Conducted the scientific work explained in section 3.1. Writing and review.

Luis Sánchez García, Fredric Ottermo, Chris Bales: Contribution to conceptualization, methodology, results, writing and review.

Competing interests

The authors declare that they have no competing interests.

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