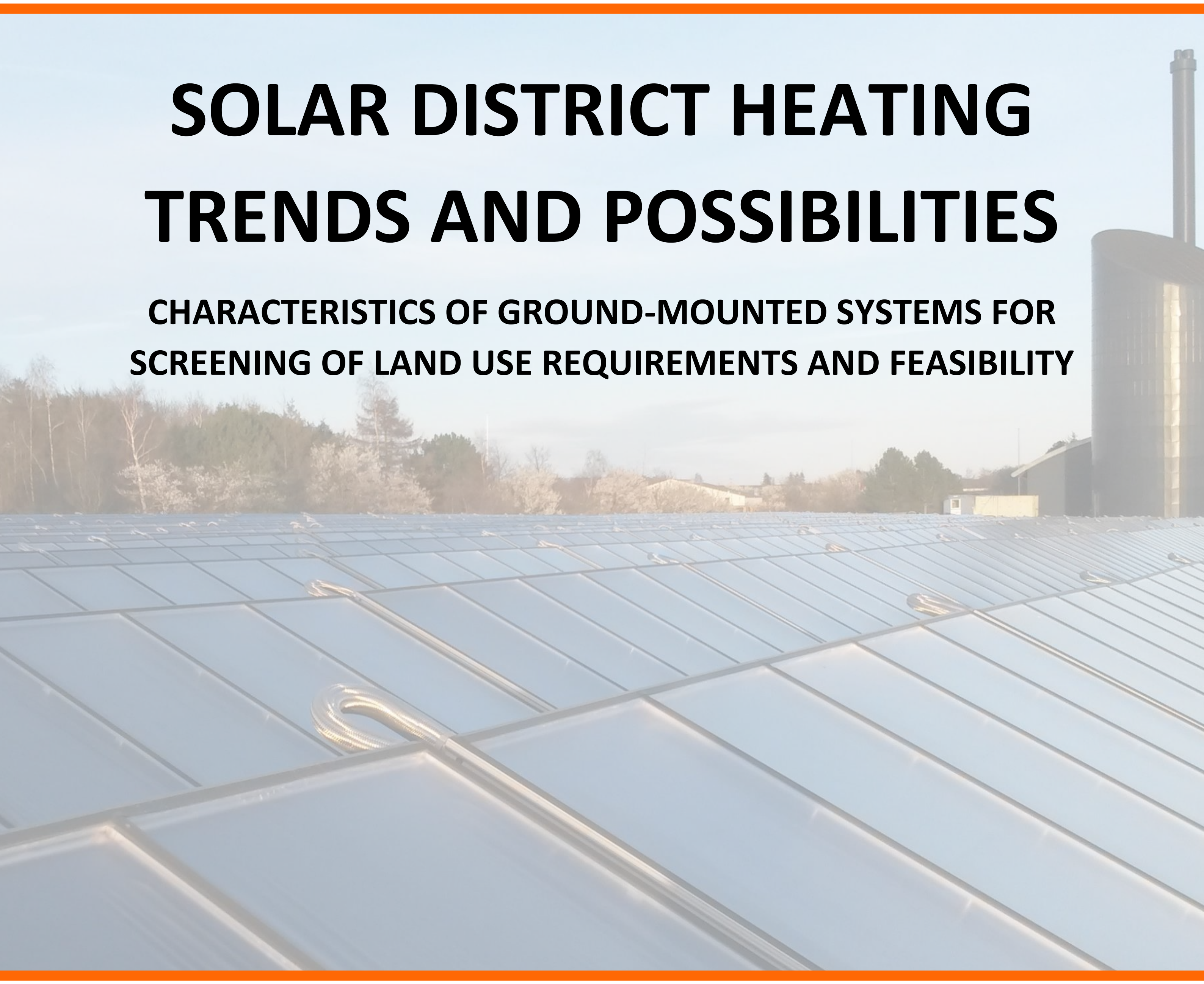
# SOLAR DISTRICT HEATING TRENDS AND POSSIBILITIES

## CHARACTERISTICS OF GROUND-MOUNTED SYSTEMS FOR SCREENING OF LAND USE REQUIREMENTS AND FEASIBILITY



Task 52
Solar Heat and Energy Economics in Urban Environments

SHC
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

**Solar District Heating Trends and Possibilities**

**–**

**Characteristics of Ground-Mounted Systems for Screening of Land Use Requirements and Feasibility**

Subtask B report in the IEA SHC Task 52 Programme

June 2018



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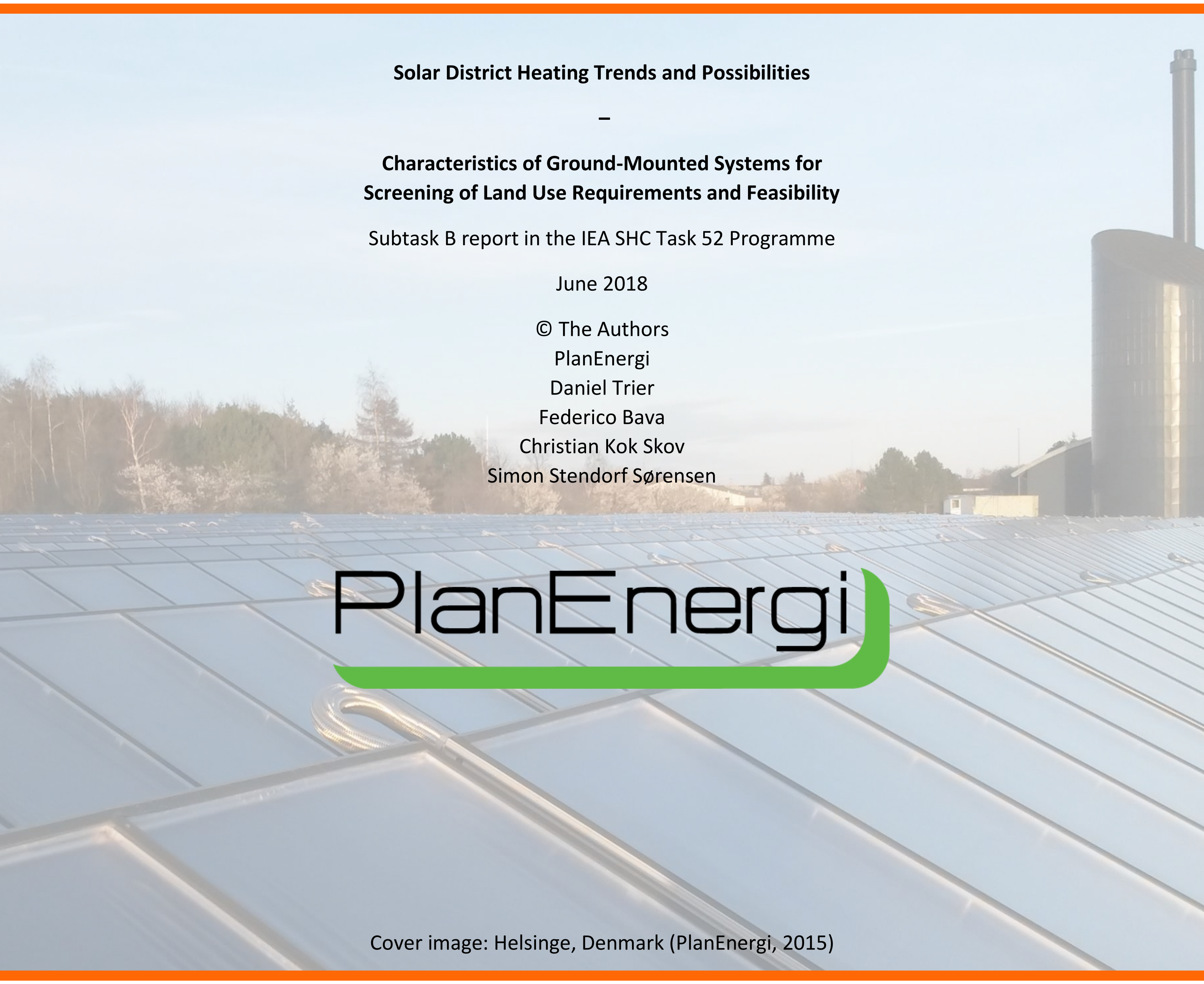

Cover image: Helsinge, Denmark (PlanEnergi, 2015)

Task 52
Solar Heat and Energy Economics in Urban Environments

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

# 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

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# IEA Solar Heating and Cooling Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is “to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.

The members of the IEA SHC collaborate on projects (referred to as “Tasks”) in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 61 projects have been initiated, 53 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45, 55)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42, 58)

In addition to the project work, there are special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding – working agreement with solar thermal trade organizations
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# Executive Summary

## Screening for Potentials by Applying Trends of a Well-Established Market

To reach a high solar fraction for a given town, a large number of roof mounted solar collector systems will in general be required, as the size of each system is limited by the roof area available. Given a certain area required to reach a specific solar fraction, a large ground-mounted system will often have a much lower total cost due to economy of scale. Hence, it is relevant to determine whether it would be more feasible to place large solar collector fields outside a town and supply heat to the district heating (DH) network through a transmission pipe, rather than to install many smaller solar heating systems on rooftops within the town. The analysis shows that the economies of scale of ground-mounted solar collector systems can normally compensate for the extra costs of transmission pipes, as long as these are not too long, so that the resulting total cost of solar heat can become acceptable.

This report aims at answering a few key questions regarding the development of large-scale solar thermal systems supplying DH networks, which will be referred to as “solar district heating” (SDH):

*We have seen a strong SDH development in Denmark in the past decade*
*– what are the characteristics of the Danish SDH systems?*

and

*Would it be possible to see a similar development in other countries?*

Danish SDH systems are analysed and the key trends are then applied consistently on a wide range of DH networks across Europe to investigate the possibilities for similar SDH deployments.

Obviously, the boundary conditions of a given town affect the feasibility of SDH. Hence, to identify the potentials in different countries, the characteristics of the local DH networks must be considered. The outcome can be considered a summary of a long list of “mini pre-feasibility studies” of the DH networks presented in this study. However, the focus of the study is not on specific results for each DH network, but rather trends in terms of potentials in the different countries.

The analysis is restricted to DH networks which do not have the availability of waste incineration (or “waste-to-energy” – WtE) and/or large amounts of excess heat nearby. This is because it does not seem logical to establish a SDH system in places where there is a need to cool down a similar/larger amount of excess heat (typically mainly/also during Summer where the SDH system would perform at its best). The focus is therefore limited to the most obvious possibilities for SDH. The results do not represent the total technical potentials, because of the following reasons. Firstly, though excess/waste heat may be available, there could be arguments against using it. Further analyses are required to determine in more detail where it would make sense to tap into the excess heat already available. Hence SDH might be a feasible solution also for some DH networks which were omitted from this study. Secondly, new DH networks are currently built, and some of these include solar thermal systems from the network commissioning date. This also includes systems located nearby WtE/excess heat sources. Hence, despite the database of existing DH systems being comprehensive, not all DH systems are included.

For these reasons, the analysis can be considered a first step in terms of quantifying and estimating feasibility of large-scale SDH potentials in Europe. The overall analysis is therefore referred to as “Solar District Heating – European Potentials version 1” or in short “SDHEP1”.

The focus on the European region is motivated by the data resources available. Nevertheless, the European countries in the analysis represent a wide range of different conditions (in terms of solar radiation, cost of land, etc.) and the results could be valid for similar conditions also outside Europe.

The results show that the typical Danish SDH system:

- is in the range of 5,000-15,000 $m^2$;
- has an annual solar collector yield of approximately 400 $kWh/m^2$;
- requires an investment of 1.3-3 million €
- financed by a long-term, low interest loan (e.g. 20-25 years, 2-3 % interest rate);
- covers 20 % of the DH demand in a
- relatively small town with around 4,000 inhabitants and
- located within 200 m of the DH network where
- it replaces natural gas in a CHP plant which has a
- diurnal storage having a volume of around 0.2 $m^3$ per square meter of collector installed.

## Key Points of the SDHEP1 Analysis

### The Scope of the Analysis Results in a Focus on Small Towns

When omitting DH networks with WtE or excess heat possibilities nearby[1], the overall DH demand potentially covered by solar heat is significantly reduced (79 %). This, however, does not necessarily mean that solar heating should in practice always be excluded for these DH networks. For different reasons, some excess heat sources may be uninteresting as long-term solutions, thus making SDH a realistic and feasible alternative.

Since the results of this study covers only part of the technical and economic potential for SDH, these should not be considered exhaustive, but rather an identification of ready-to-access options which could be exploited already now. To identify the full potential of SDH, larger cities and newly built DH networks should be considered in future studies, where solar heating systems may be located even further away from the end users – possibly combined with different heat sources and with large-scale heat storages, so as to improve the overall feasibility.

### Identifying Suitable Areas

In a collaboration between the HRE project (www.heatroadmap.eu) and IEA SHC Task 52, a methodology has been developed involving a spatial analysis to estimate the land areas required for large-scale solar thermal systems. This represented the basis for the analysis of approximately 2,500 DH networks, corresponding to around 100 TWh of annual heat demand. An example of the investigated DH networks is seen in Figure 0.1.

[1] 20 km distance from the city boarder is used in this study.

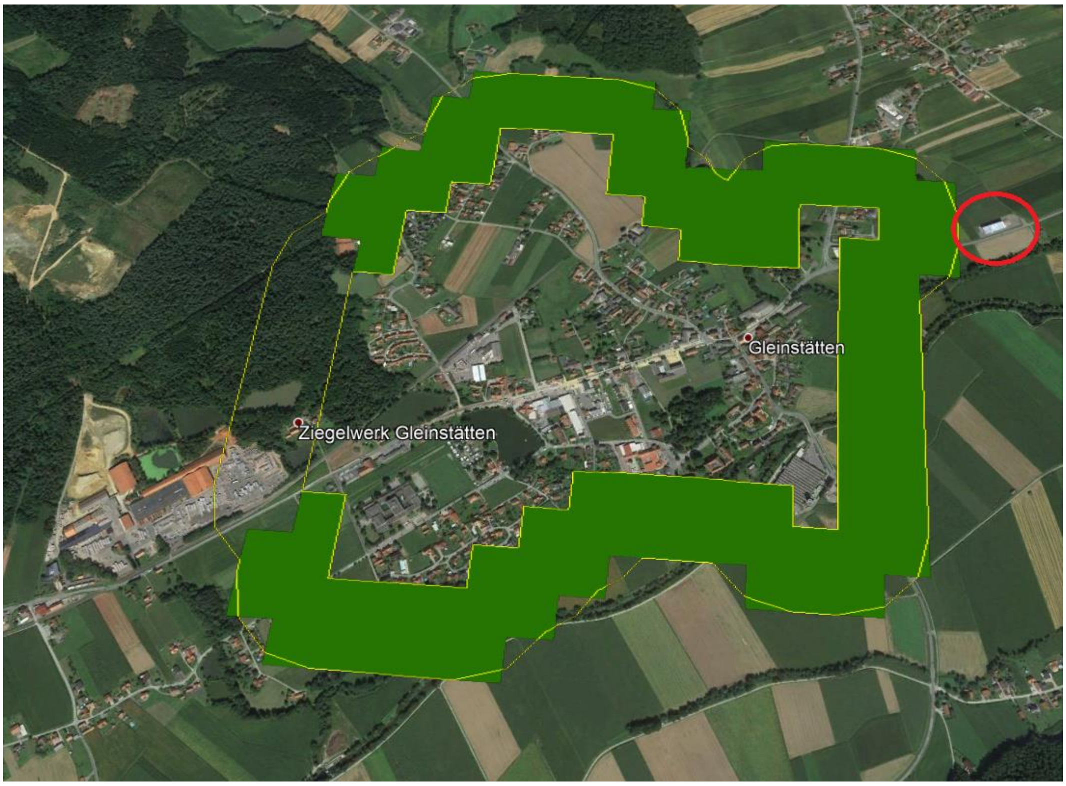


**Figure 0.1. Map of Gleinstätten (AT) highlighting identified potential areas in green in a 200 m wide zone outwards from the town boarder. Realised solar heating system highlighted with red circle east of the town. (Source of background map: Google Maps, 2017.)**

The results show that there does not seem to be issues in identifying suitable land areas for the investigated DH systems. As seen in Figure 0.2, almost the entire required area can be identified in the vicinity of the towns (i.e. within a reasonable distance).

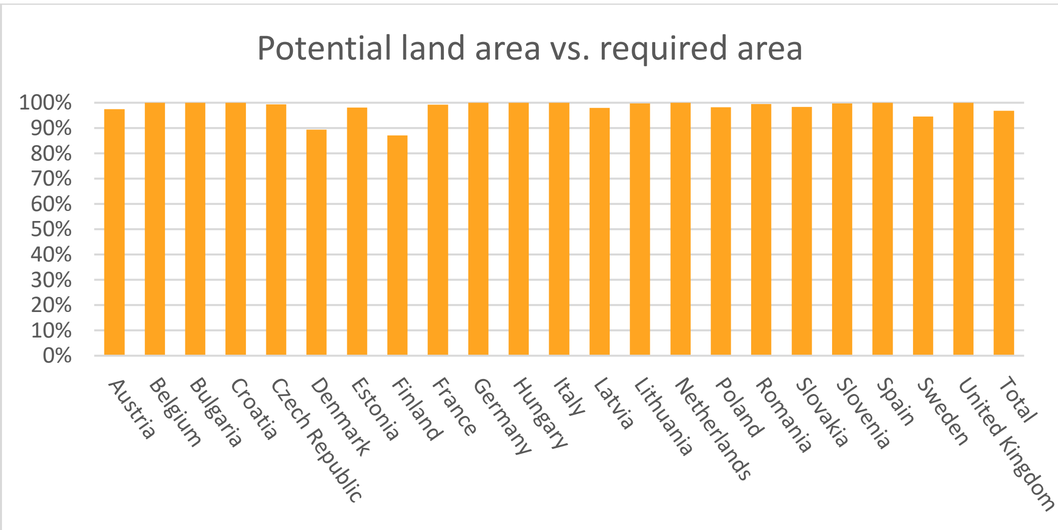


**Figure 0.2. Fraction of suitable land area which can be found within 200 m from a DH networks compared to the land area required to reach a solar fraction of approx. 20 %. It is seen that almost the entire required area can be identified near the DH networks.**

**Summarizing Possibilities to Deploy Economically Feasible SDH**

Applying cost figures for the potential SDH systems shows the feasibility of each individual SDH solution. The results can then be grouped by country to indicate where SDH deployment would be most feasible. The analysis indicates that the development of large-scale SDH is both technically and economically feasible in most European countries. In general, there seem to be plenty of suitable area to install large-scale solar collector fields, and many low-cost SDH systems (e.g. below 30 € per MWh of solar heat) have been identified, which encourages to exploit this potential. Targeting a solar fraction of 20 % of the annual heat demand in the investigated DH networks, the SDHEP1 analysis identifies approx. 20 GWh of potential annual solar heat of which more than 70 % is estimated to be achievable below 35 € per MWh of solar heat.

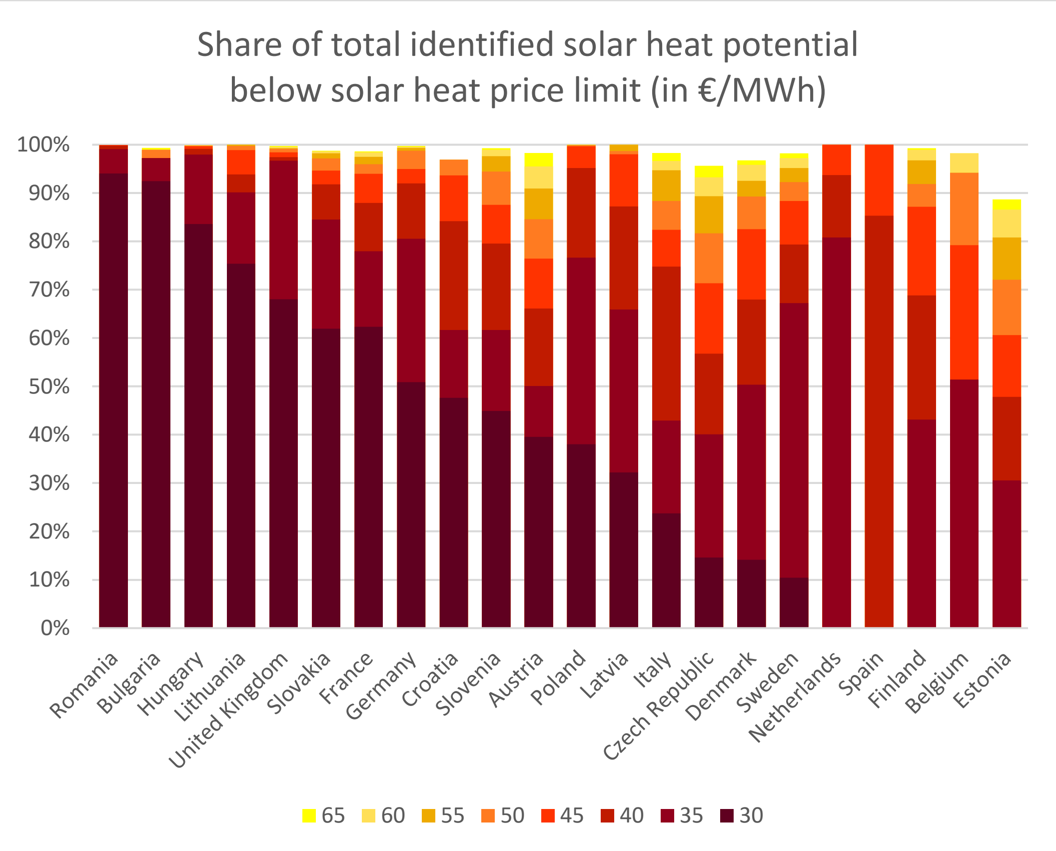


**Figure 0.3. Share of total identified solar heat potential depending on maximum solar heat price (in €/MWh in the legend) for the analysis targeting 20 % solar fraction. (Legend in € per MWh of solar heat.)**

As general recommendations it can be stated that, before ruling out SDH due to space limitations, it is relevant to consider that the collector field could be suitably located further away than usually thought to be relevant. Sizing up the systems can be an effective way to reduce the investment cost per square meter of collector, thus making SDH competitive with alternative solutions and high solar fractions possible. Good financing options can also play a key role to achieve feasible SDH solutions, just as taxation of fossil fuels can be an incentive to convert partially or completely the heat supply to renewable energy sources. Sharing of experiences in the SDH industry can ensure that the technology becomes widely known, mistakes are avoided, and the system performances are optimised.

# Content

# 1 Introduction

The market of large-scale solar district heating (SDH) systems in Denmark is often referred to as state-of-the-art. An evaluation of the Danish SDH systems is carried out to derive trends and highlight general characteristics in this sector. The goal is to answer a key question about the Danish SDH sector:

*We have seen a strong SDH development in Denmark in the past decade – what are the characteristics of the Danish SDH systems?*

The experiences from this well-established market are then applied to emerging markets in other countries to answer the question:

*Would it be possible to see a similar development in other countries?*

In this analysis, existing district heating (DH) networks are handled separately in "mini case studies" to investigate the following points:

- How much land area would be required for large-scale solar collector fields to cover a certain share of the annual DH demand?
- Could this land area be found near the town?
- Would such SDH system be considered economically feasible, i.e. how would the cost limits reduce the potentials?

The results are grouped together by country to identify promising SDH markets for networks without the option of waste incineration ("waste-to-energy" – WtE) or excess heat sources.

# 2 Trends in Danish Solar District Heating

During the past decade deployment of large-scale solar thermal plants in Danish DH systems has considerably increased. To verify whether this potential can be replicated in other European countries, this chapter analyses from a quantitative perspective a number of contextual factors – referred to as key conditions – which represent the circumstances which favoured the development of SDH. The outcome of selected trends is then applied to the European analysis described in section 3.

It should be noted that collector *gross* area has been used in this report, according to the international ISO standard [1].

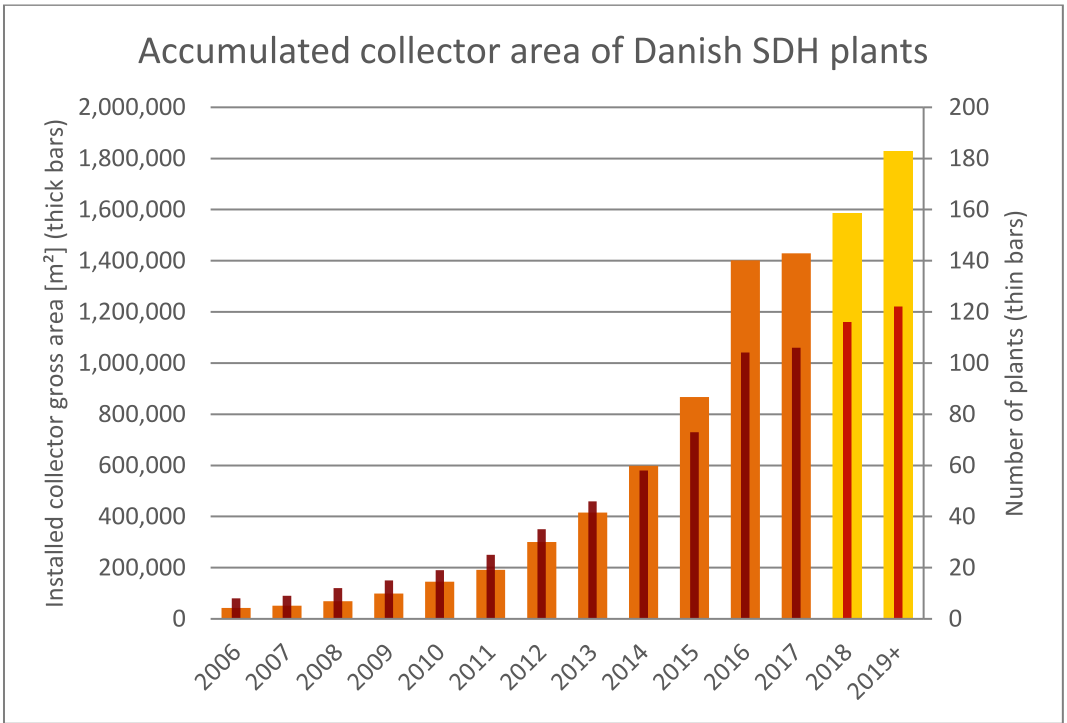


**Figure 1. Development in the installation of large-scale solar thermal plants in Denmark since 2006. The number of total installed plants exceeded 100 during 2016 (thin bars) and the total installed collector (gross) area is above 1.4 million m² as of 2017. (Planned systems are indicated with lighter colours.)**

## 2.1 Overview of Key Conditions and Trends in the Danish SDH Sector

A set of key boundary conditions regarding where and how SDH is implemented has been analysed to reveal trends representing key conditions for the deployment of large-scale solar thermal plants (such as typical solar fraction). The derived key conditions are then used for the analysis of potentials for a similar deployment of SDH in other European countries.

The investigated parameters are (not ranked according to importance):

- Size of solar collector field
- Annual SDH system yield
- Connection to district heating grid (distance)
- Population
- Heat demand
- Solar fraction
- Heat prices and primary fuel-type
- Storage capacity

- Land value and availability
- Political framework
- Experience of the DH utilities

## 2.2 Typical Technical Properties of SDH Systems in Denmark

### 2.2.1 Sizes and Investment Cost of Solar Collector Fields

Figure 2 and Figure 3 give an overview of the 104 SDH plants installed in Denmark at the end of 2016 including their collector area. The gross collector area ranges between 1,000 m² and 170,000 m². Most of the collector fields are smaller than 25,000 m², and only 9 of the 104 SDH systems are larger. However, there is a tendency that the newly installed collector fields are increasing in size. The managers of several DH plants have chosen to extend their solar collector field after some years, to increase the solar fraction of the DH network. In these cases, the solar collector fields (sometimes even split physically on different fields) are counted as one SDH system in the statistics.

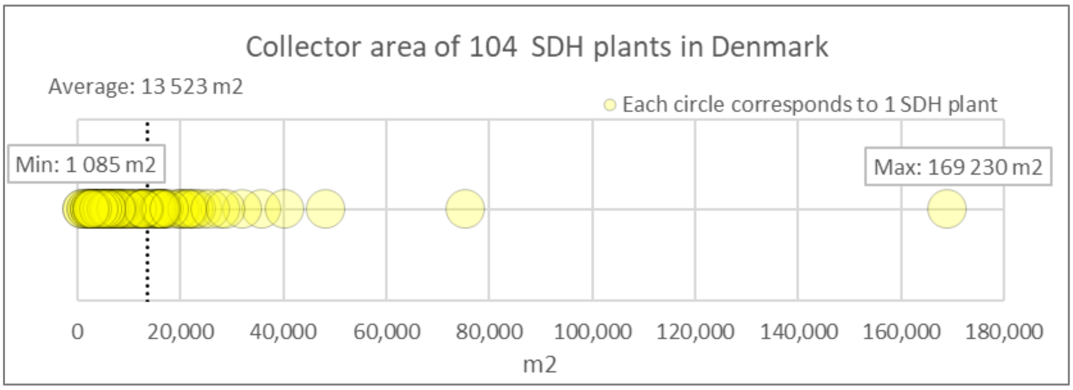


**Figure 2. Plotted span of the solar collector gross area of the 104 Danish SDH plants established until 2017. Each yellow circle corresponds to one DH plant.**

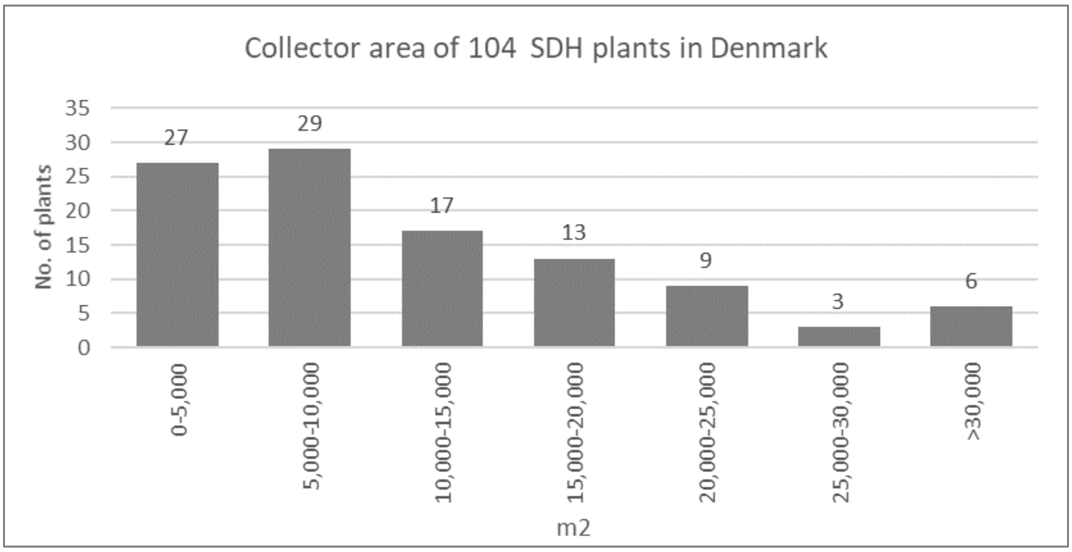


**Figure 3. Categorised span (5,000 m² per category) of the solar collector area of the 104 Danish solar district heating plants established until 2017.**

The price of large solar collector fields has been decreasing in Denmark. This has been caused by the large number of new installations, technology development and improved know-how. Another reason is the economies of scale, as there is a tendency of installing larger systems. Up-scaling the systems causes the start-up and fixed costs to have a smaller influence on the overall costs. A cost curve of the solar collector field price as function of the collector field size is shown in Figure 4, based on Danish experiences[2]. The price is for the complete collector fields and includes the collectors, pipes in the collector field, installation, main components for operation, control, regulation and supervision (CRS), but excludes site specific costs like building, thermal energy storage, transmission line, land area or ground levelling. For small plants the specific price is up to 350 €/m². For plants larger than 75,000 m² the specific cost is less than half (around 170 €/m²). Above this size, no further price reduction is expected due to economy of scale.

Most of the Danish plants are in the range of 200-250 €/m².

Note that all cost values in this report are excl. VAT.

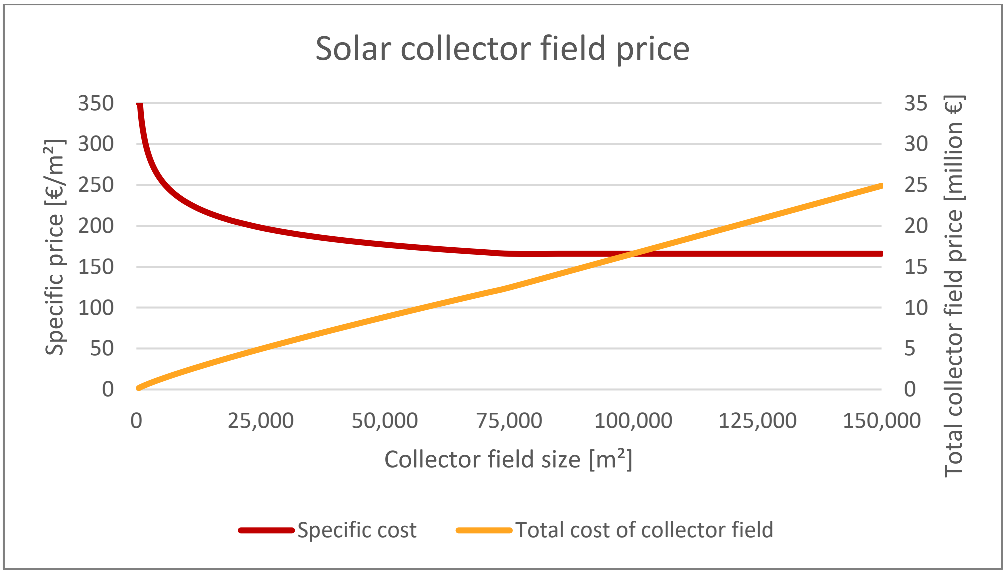


**Figure 4. Estimation of solar collector price per m² including mounting, installation, main components for operation and CRS, but excluding any costs for building, storage, transmission line, land area or ground levelling.**

Concrete blocks, which were previously used as foundation for the collector modules, are now often replaced by lighter steel profiles, which are hammered into the ground. This has led to lower costs and easier, faster installation. Additionally, there is no need for the ground to be completely levelled, since the collector field follows the field, resulting more “in line” with the landscape.

[2] The price curve is not derived from the same realised examples as the other trends in this section 2.2. This is because between the DH plants there are significant differences between the amount of additional equipment installed together with the solar collector field (e.g. some plants include a storage in a turnkey contract where others do not). Hence, the different investment costs are hard to compare directly in a reasonable way.

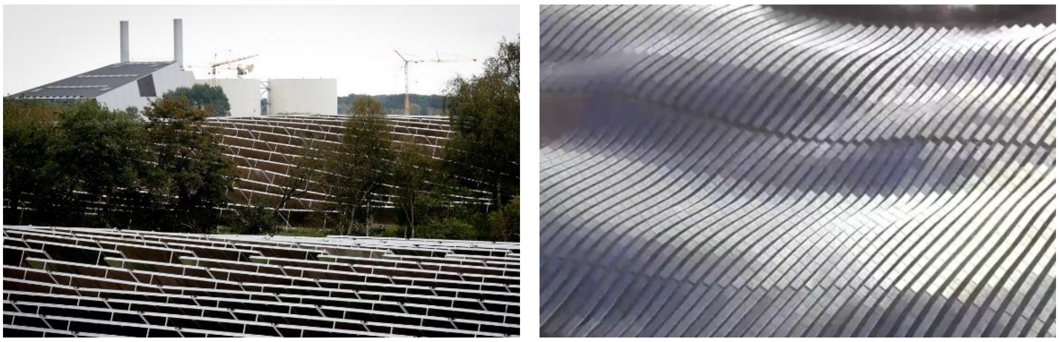

Figure 5. Two images of a solar collector field following the shape of the fields below at Silkeborg, Denmark [2][3].

Besides the decrease in the installation cost per unit area over the years (however small compared to the recent decline in PV costs), solar collectors have also seen a continuous improvement of their efficiency. As the average size of solar collector fields connected to DH plants has increased steadily over the past two decades, the combined effect of economy of scale and higher efficiency has led to an increasingly higher performance/cost ratio over the years.

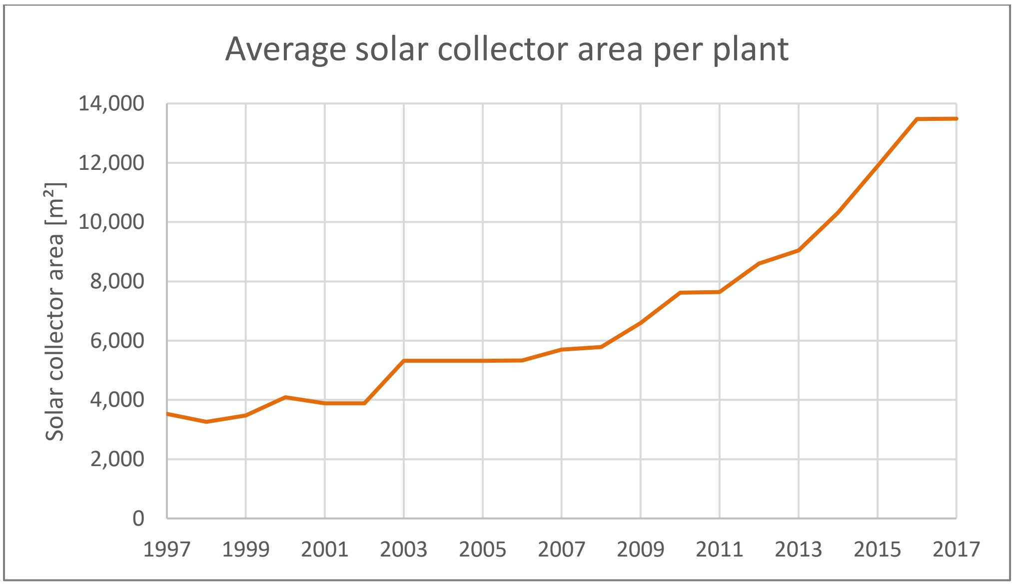


**Figure 6. Development in the average collector area per DH plant with a solar heating system installed.**

### 2.2.2 Annual Solar Radiation and SDH Yield

The annual yields[3] from 48 SDH systems (based on [4]) range between 321 and 500 kWh/m$^2$ with an average yield of 409 kWh/m$^2$ (gross area). The fraction of solar radiation on the collector plane which is converted to useful heat output from the collectors ranges between 27 % and 42 %, with an average of 36 %. The results for all plants are reported in Annex I – Annual SDH Yield and Efficiency.

[3] Average values for data from the years 2012-2016 have been generated (for plants where data has been available).

### 2.2.3 Connection to District Heating System

This section treats the topic of the distance between SDH plants and DH networks. Figure 7 shows an example of a few DH networks (in red) and the distance (dotted line) to its SDH plant (yellow point).

Analysing the distance from 104 existing SDH plants to their nearest DH, it is found that 61 SDH plants (59 %) are located within existing DH network areas, while 43 (41 %) are located outside. The average linear distance from the 43 plants located outside DH networks is 177 m.

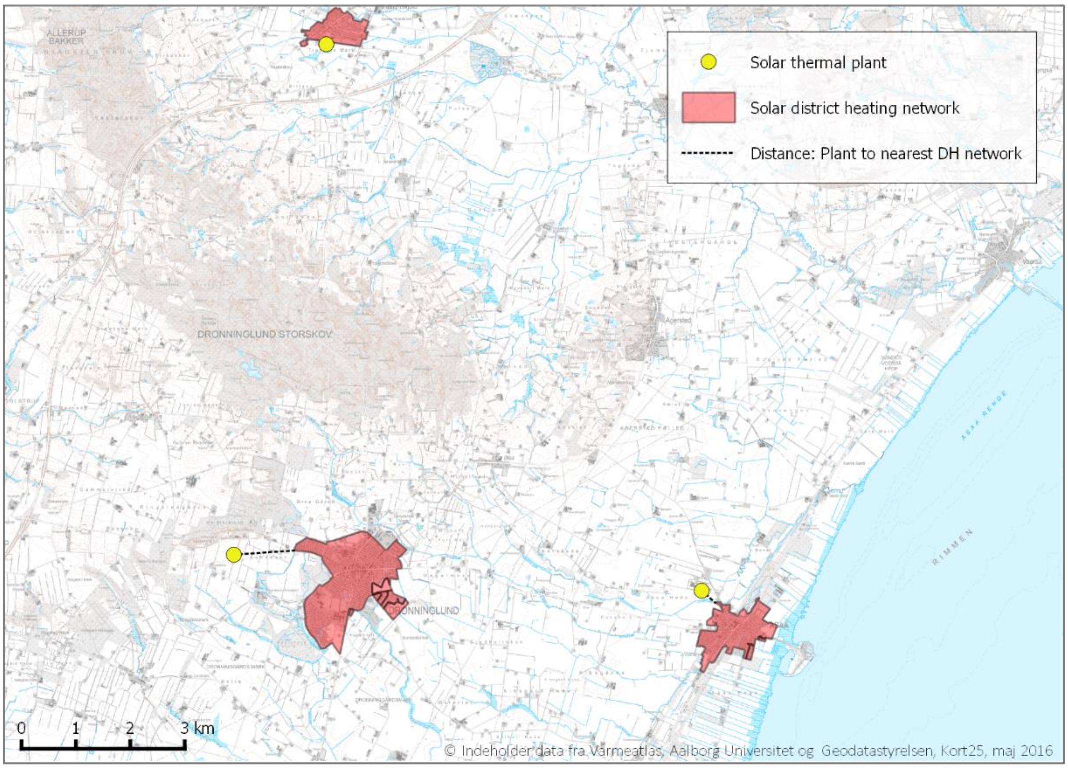


**Figure 7. Excerpt of the analysis of the linear distance from the 104 Danish solar thermal plants to the nearest DH network. The map shows the location of three existing large solar thermal plants and their linear distance to the nearest DH network. Note that the yellow circles do not reflect the actual size of the SDH plant.**

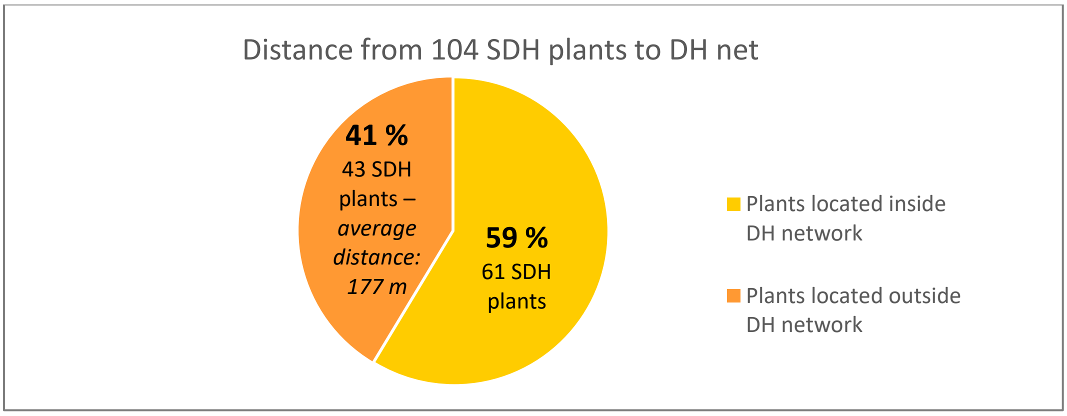


**Figure 8. The share of the 104 solar thermal plants located outside/inside existing DH networks is 41 % and 59 % respectively. The average distance from the 43 plants located outside DH networks to their respective DH network is 177 meters.**

It is important to notice that the analysed distance is the linear distance from the solar thermal plant to DH network, not the actual length of the DH pipeline, and is therefore an indicative distance only. The actual length of the DH pipeline to the DH network depends on other conditions, such as existing infrastructure. Often the connection is established directly between the SDH system and the DH plant.

In Denmark arable land can often be purchased or rented for SDH purposes relatively close to the DH network – at least in the case of smaller DH grids. Hence, the Danish examples are not necessarily an upper limit for such distances.

The location of the any solar collector field is a critical parameter affecting the feasibility in terms of its impact on total costs (i.e. adding transmission pipes between the collector field and the DH network).

The excavation costs related to transmission pipes depend strongly on labour cost and the type of soil to be excavated (e.g. along a street, in the roadside or across streets).

Another important factor affecting the transmission line costs is where the transmission line can be connected to the DH network, i.e. is the network able to cope with the solar heat or is it necessary to connect the transmission line to the DH plant.

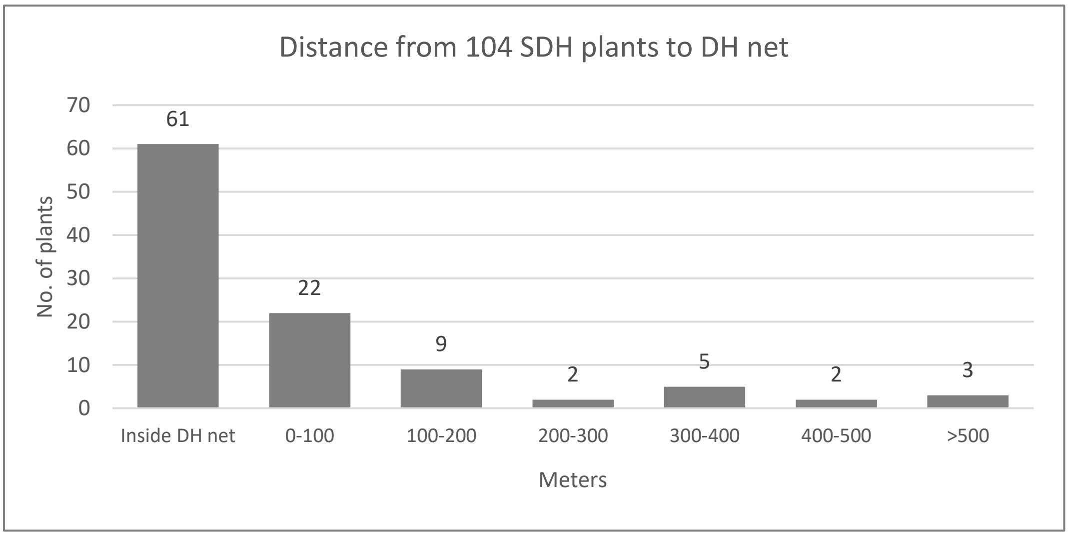


**Figure 9. Linear distance from the 104 Danish solar thermal plants to their DH networks.**

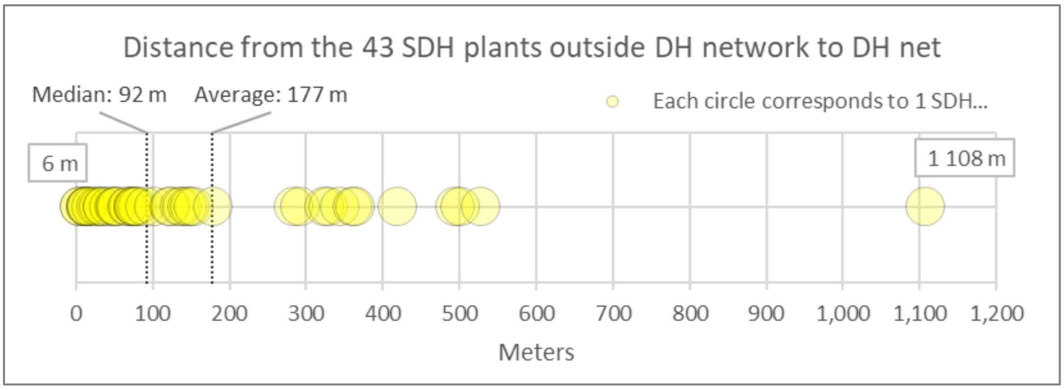


**Figure 10. Linear distance from the 43 of the 104 Danish solar thermal plants located outside DH networks to the nearest DH network. Each yellow circle corresponds to one solar thermal plant. The average distance is 177 m. The longest distance is 1,108 meters, while the shortest distance is 6 meters.**

### 2.2.4 Population

This section treats the topic of the town sizes, where the existing SDH plants are connected. The town populations range between 250 and 44,000 inhabitants. Figure 11 and Figure 12 show that most of the SDH plants in Denmark are connected to small towns. Among the 104 SDH plants, 96are located in towns with less than 10,000 inhabitants. The average town utilising SDH has around 4,000 inhabitants.

The figures show that SDH is particularly suitable for small towns. There are several reasons for this. Firstly, the market is not yet fully developed; small DH plants have been the front-runners in the technology of SDH. Secondly, in Denmark the heat prices are on average much higher in smaller towns. This is due to higher relative network heat losses (due to the low heat density of the networks) and a high heat production price (mainly due to use of natural gas, which is heavily taxed). In large towns district heat is typically produced in large combined heat and power (CHP) plants burning waste, biomass or coal.

Additionally, the land areas suitable for solar collector fields are usually closer to the DH plants in smaller towns. There are no indications that available land is the main limiting factor for larger towns. This was proven when the SDH plant in Silkeborg (44,000 inhabitants, 169,230 m² of collector area) was installed in 2016.

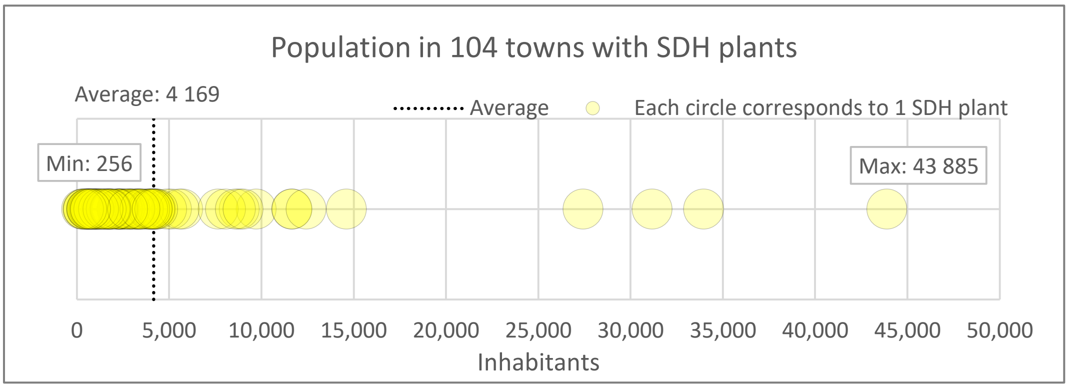


**Figure 11. Population of the 104 Danish towns where large-scale solar thermal plants have been installed. Each yellow circle corresponds to one town. The average town population is 4,169 inhabitants, with the smallest town having 256 inhabitants and largest 43,885 inhabitants.**

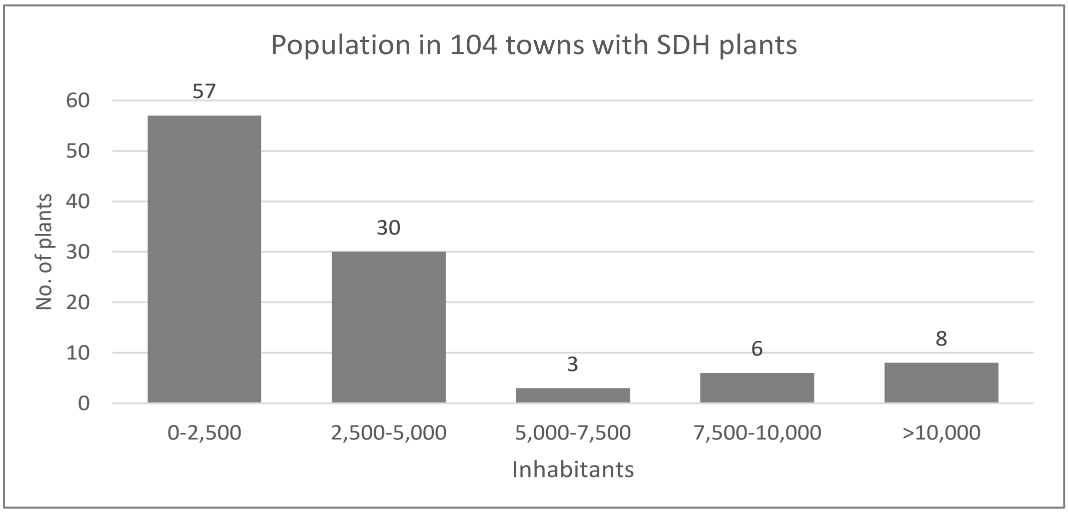


**Figure 12. Categorised span (2,500 inhabitants per category) of the population in the 104 towns where SDH plants have been established until 2017. Note that in general most, but not all inhabitants in each town with DH are connected to their respective DH grid.**

### 2.2.5 Heat Demand

This section treats the topic of heat demands, heat densities and the collector areas relative to the heat demands of the towns where the existing SDH plants are connected.

Figure 13 and Figure 14 show that the heat demands range between 3,000 and 380,000 MWh. This is a wide range, indicating that there must be other potential SDH networks around Europe. The average heat demand per DH network is around 40,000 MWh. It should be noted that a few systems connected to larger cities pushes the average upwards. The median heat demand is 22,519 MWh. Hence, the typical SDH system is not connected to large DH networks.

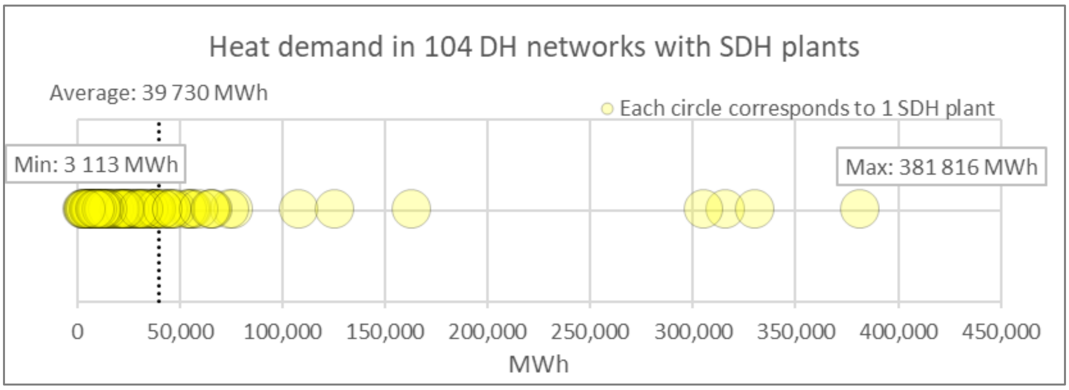


**Figure 13. Heat demand of DH networks with SDH installed.**

Figure 14 shows that most of the systems are connected to DH grids with annual demands no higher than 40,000 MWh.

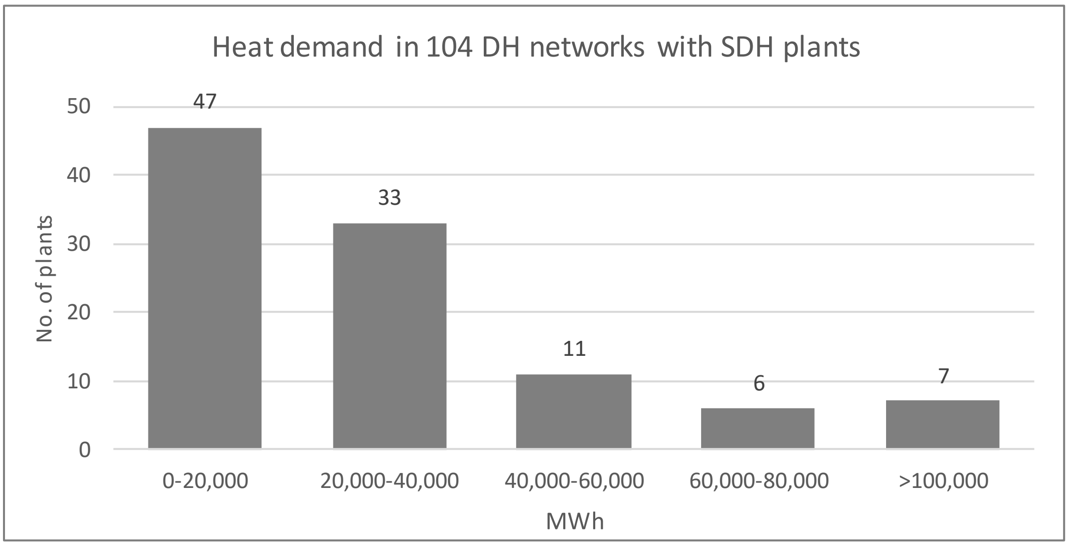


**Figure 14. Heat demands of the 104 DH networks with solar thermal plants.**

Figure 15 shows a map of the heat demand density in Denmark. The island of Bornholm in the Baltic Sea, which does not have SDH, is not shown. The location of each SDH system is highlighted with a yellow circle. It is seen that the SDH plants are not located near larger cities, except for a few relatively small ones in the outskirts of Copenhagen. In the central part of Jutland (west of Aarhus) the currently largest SDH system is represented by the yellow circle around the red area representing the town of Silkeborg. A larger version is seen in Annex II – Heat demand density and location of SDH systems in Denmark.

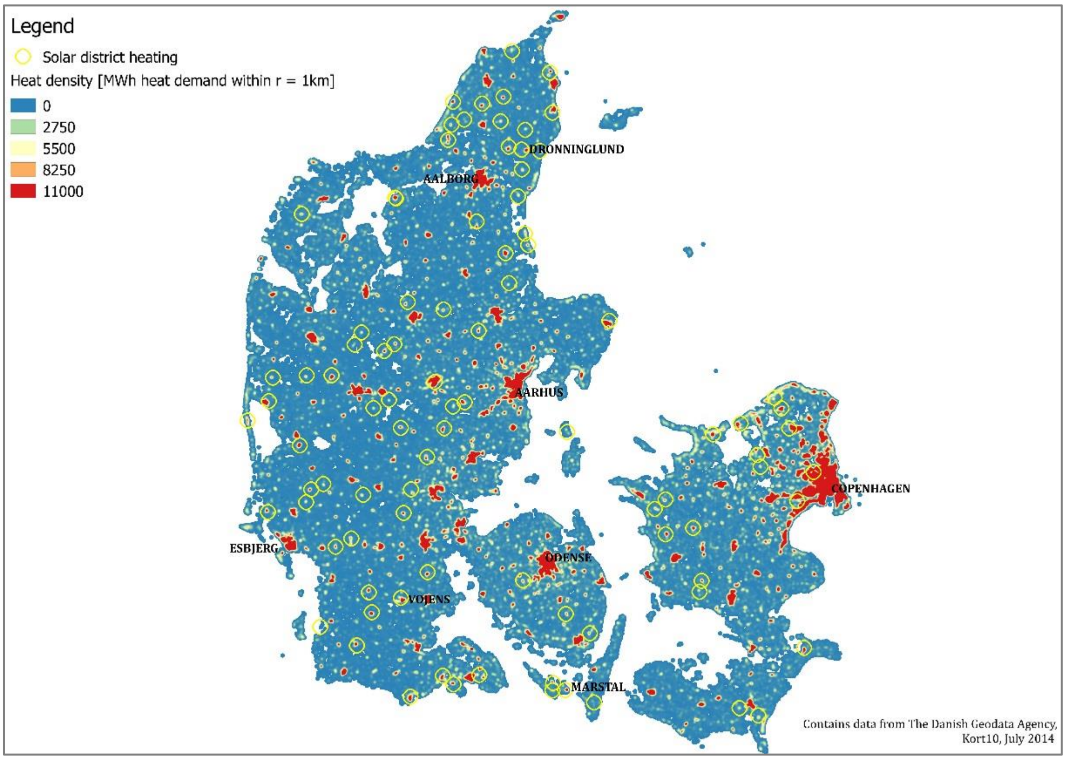


**Figure 15. Heat demand density in Denmark (excl. Bornholm) together with the location of solar district heating plants (min. 1,000 m²). The legend represents annual heat demand in MWh within a radius of 1 km.**

Figure 16 shows the range of the ratio between installed collector area (in m²) and annual DH demand (in MWh). Grouping the data points of Figure 16 results in the bar chart of Figure 17 where it is seen that most systems present a ratio of approximately 0.5 m²/MWh, which is also the national average value. The range is wide though, from 0.01 m²/MWh (small collector field, large town) to 1.8 m²/MWh (aiming at high solar fractions).

The optimal ratio for each DH system depends on the boundary conditions such as temperature levels and alternative heat production units of the DH plant as well as the heat storage capacity. For very small ratios heat storage can be omitted (at least if the remaining heat production units are flexible). On the other hand, all Danish systems with a ratio larger than 1 m²/MWh include a seasonal thermal energy storage.

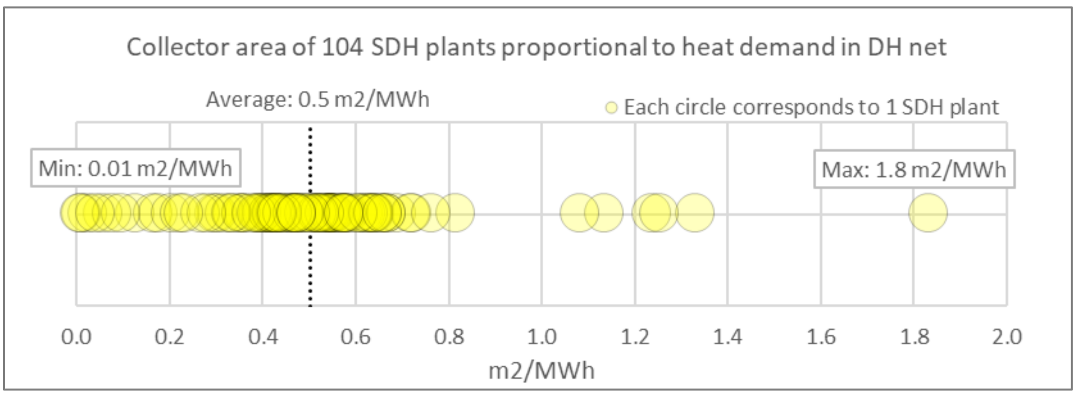


**Figure 16. Ratio between the installed collector area and the DH heat demand of 104 Danish SDH systems.**

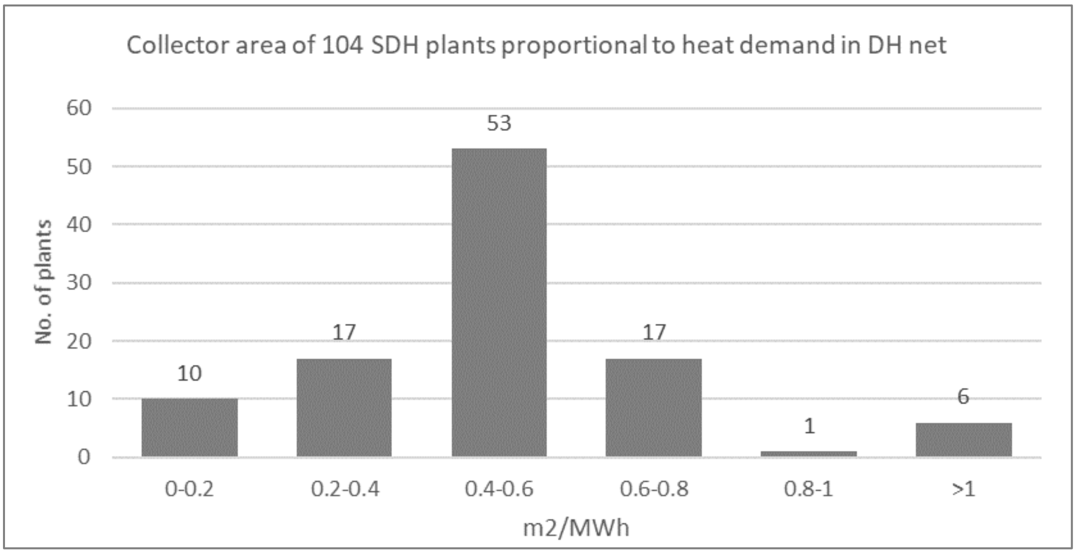


**Figure 17. Ratio between the installed collector area and the DH heat demand of 104 Danish SDH systems.**

### 2.2.6 Solar Fraction

Instead of the ratio between collector area and annual heat demand, the solar fraction (SF), can alternatively be used, based on the solar heat production. Throughout this report the SF is considered the share of heat delivered to the DH network which is covered by solar heat. Figure 18 shows how the SF varies from one DH plant to another, but most values are concentrated around approximately 20 %. Figure 19 shows that most systems are in the range of 16-24 %.

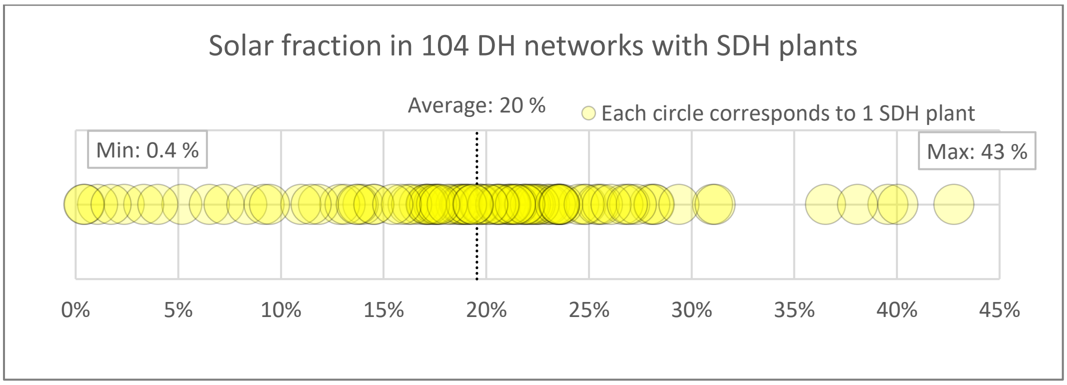


**Figure 18. Plotted span of the SF (i.e. solar thermal production/heat demand at grid in related DH net) in the 104 Danish solar thermal plants. Each yellow circle corresponds to one SDH plant. The average solar fraction is 20 %, while the highest solar fraction is 43 %. Lowest solar fraction is 0.4 %.**

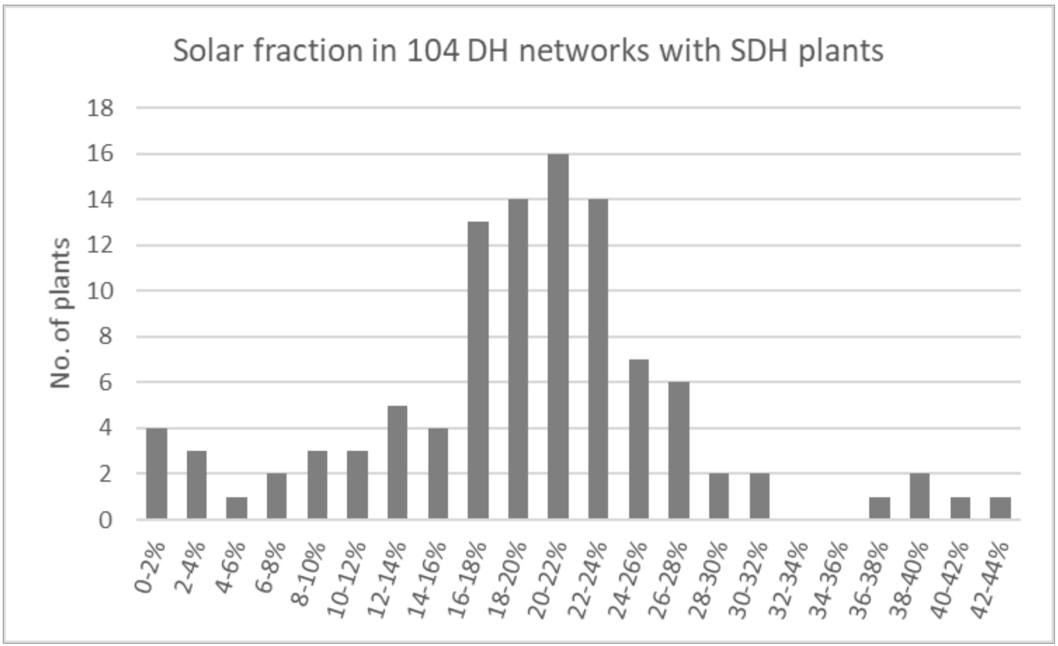


**Figure 19. Categorised span of the solar fraction in the 104 Danish DH grids with large-scale solar thermal plants.**

The SF is plotted against annual DH demand in Figure 20. The heat production from the solar thermal plants is estimated from either the measured yearly thermal performance of each system or the average performance value of 409 kWh per square meter of collector area. The orange line shows the average SF (not weighted according to heat demand quantity) and represent a SF of 20 %.

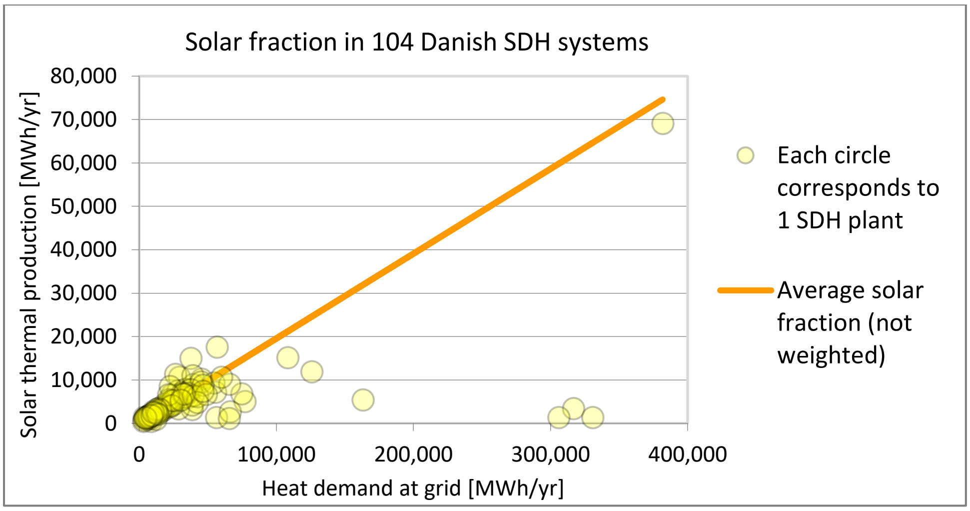


**Figure 20. Estimated heat production from the 104 Danish solar thermal plants as function of the DH network heat demand.**

In Figure 21 a zoom of Figure 20 shows more clearly the trend of 20 % solar fraction for small DH demands. Nine SDH plants are omitted in Figure 21 compared to Figure 20 due to the changed axes.

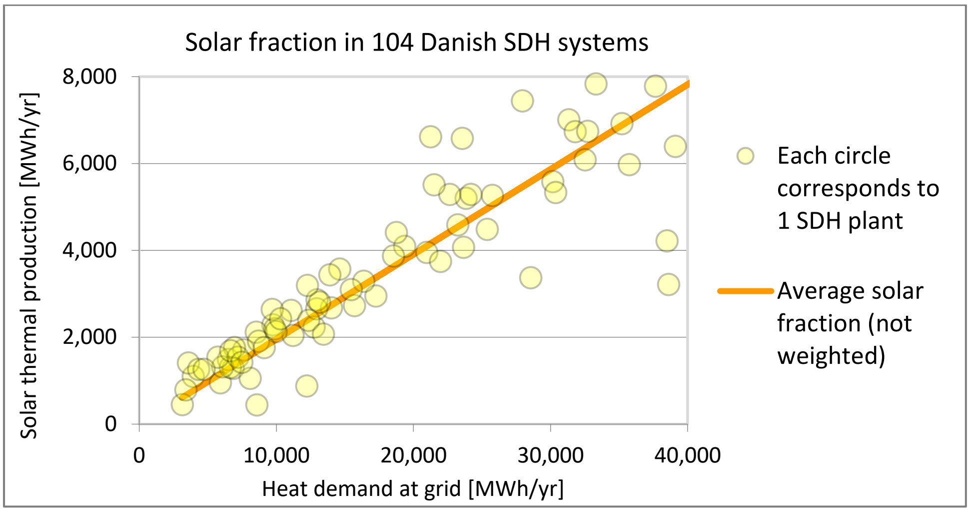


**Figure 21. Zoom of Figure 20 above to illustrate the trend of SF for DH demands in smaller grids.**

***Typically, a Danish SDH system covers around 20 % of the DH plant's demand***

For the Danish conditions a SF of around 20 % corresponds to the amount of solar heat which can be supplied to a DH network without the need for active measures to avoid stagnation of the collector field. If the calculations are more detailed in the dimensioning and/or the operators implement a careful control strategy to make sure that the storage and/or collectors are not overheating (i.e. by means of night cooling), the SF can be slightly increased without additional precautions. The nigh cooling option consists of circulating the fluid in the solar collector loop during night-time in order to cool the storage down. In this way, the storage is able to handle the solar heat produced the upcoming day, as the collector field in most cases[4] cannot be shut off. Safety procedures based on weather forecasts and on the state of charge of the storage can be implemented in the control strategy of the plant. However, efficient collectors may only be able to cool down around 1/3 of one day's heat production during the night. Hence, this solution cannot handle too oversized systems. The higher temperatures in the solar collectors, which result from the high water temperature in the storage, entails that the collector efficiency is worse than during normal operation. This "helps" reduce the solar heat production during the day. It is also possible to raise the network temperature slightly, so to increase temporarily the network thermal losses and avoid overheating.

In some cases, the economic optimisation results in a deliberate oversizing of the system, thus requiring active cooling in some periods during the summer. Due to the limited options for night-time cooling described above, dry-coolers are in this case required. It may seem counterintuitive, e.g. for DH utilities who are used to strive for increased efficiency and minimised losses, to dissipate solar heat to the ambient. However, even so, the investment in the extra collectors (to "oversize" the SDH system) and in the active cooling components is outweighed by the fact that the SDH system can cover a larger share of the heat demand in spring and autumn.

[4] Concentrating solar collectors such as parabolic trough collectors (PTC) can be defocused, effectively shutting off the solar heat production. This option is used in the SDH plant in Taars (Denmark) where a hybrid solution mixing flat plate collectors and PTC is installed.

***A cooling system to cope with surplus heat may be economically feasible and can help reach a higher solar fraction without the need of seasonal storage***

### 2.2.7 Heat Prices

Figure 22 shows the production price per MWh heat based on different primary fuel types and is based on data provided by 55 DH plants displaying their costs for heat production in 2015/2016. The primary fuel type is here defined as fuel accounting for at least 90 % of the total heat production from the DH plant. In many cases the DH supply consists of a mix of various fuels, thus making it difficult to separate the total costs associated to each fuel/heat production unit. This is the reason for the relatively low number of examples shown in the figure. However, Figure 22 gives an indication of the cost-competitiveness of large-scale solar thermal plants compared to other DH plant technologies. Note that the numbers in Figure 22 are meant as examples to compare with and do not reflect systems with a solar heating system installed.

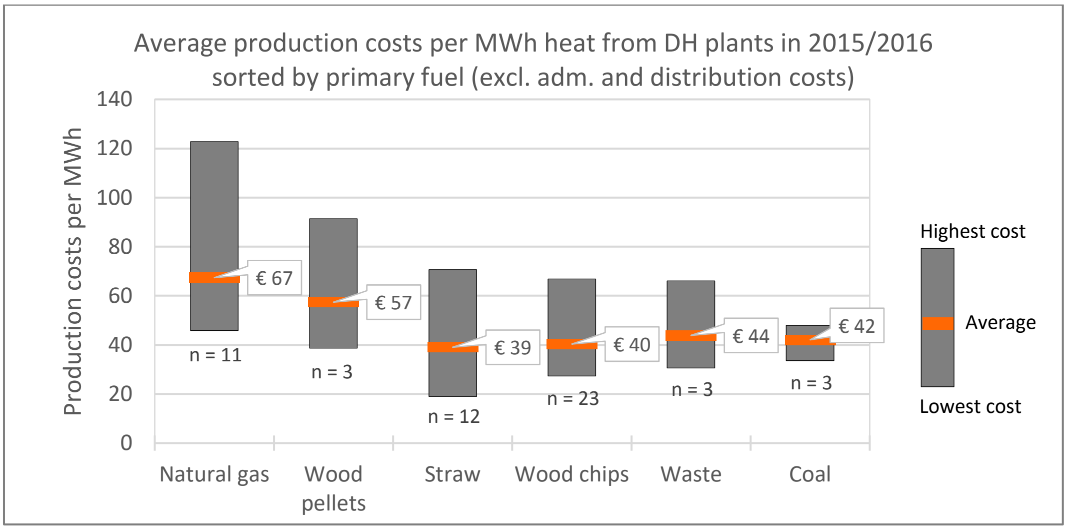


**Figure 22. Production costs per MWh for DH plants using different primary fuels. These can be compared to the average production cost for solar thermal. Distribution costs and administrative costs are not included. Data source: Benchmarking statistics of Danish district heating companies [5].**

Installation of SDH plants is also affected by other circumstances than the mere fuel costs. Disposing of urban waste by incineration automatically produces heat, which can be utilised in the DH network, thus making SDH less feasible. It should be noted that the data in Figure 22 include both CHP and heat-only plants. Most of the plants using natural gas or waste are CHP plants, so they produce both heat and electricity. In these plants, part of the heat production costs generates an additional income from electricity sold, which should be deducted. For a natural gas-based CHP plant in the upper end of the scale in Figure 22, the deduction of costs could be in the range of 20 €/MWh [6]. The figure shows that DH plants using natural gas as primary fuel typically have the highest production cost. Hence, SDH solution are more feasible when they replace natural gas-based heat, rather than straw, wood chips, waste incineration or coal[5].

5 Coal is stated to be phased out in Denmark as of 2030 [7].

Figure 23 shows the consumer heat price (incl. both fixed and variable costs for the consumers). As the DH utilities are by law obliged to be non-profit[6], the consumer price reflects all the costs for the DH company, including down-payments for the network. Hence, the differences in age of the network, fuel mix, number of consumers, heat density of the towns etc. result in a wide spread of heat price for the consumers.

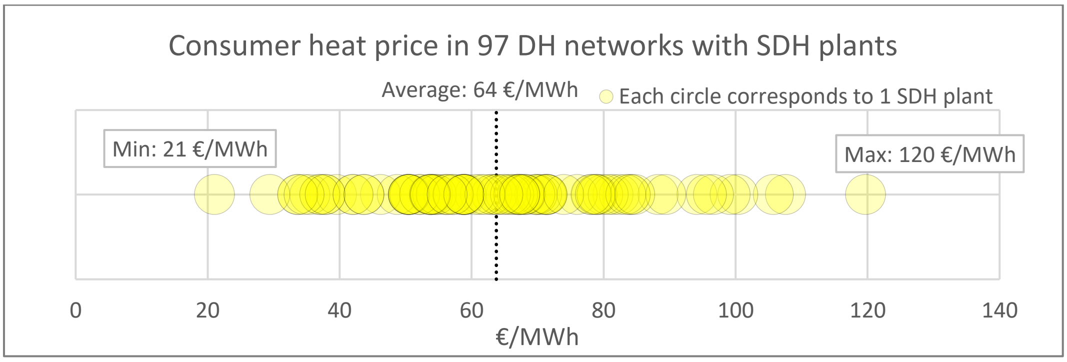


**Figure 23. Plotted span of the price per MWh heat for district heating consumers located within 97 district heating grids where solar thermal plants have been installed.**

### 2.2.8 Primary Fuel of DH Plants

Figure 24 shows the primary fuel of the DH plants installing a solar heating system. It is seen that most of plants use solar heat to reduce their natural gas consumption. The feasibility of natural gas-based CHP operation is very dependent on the electricity spot market prices. In Denmark the increased share of volatile renewable energy (VRE) production from wind power and secondarily from PV systems has resulted in fewer and fewer hours of CHP operation per year for many decentralised plants. In electrical grids with increasing shares of VRE, the economy of a traditional fossil fuel-based CHP plant, which does not take part in the "green transition", is continuously worsened. The general trend of a transition towards low-carbon technologies used in DH plants can create feasible configurations, where large-scale storages can be used both for short and long-term storage, and by heat sources other than solar thermal. This can represent a further possibility for SDH, where solar thermal systems may result unfeasible when considered *separately*, but they may become an interesting and viable solution when combined with large-scale storages and other technologies in an intelligent way.

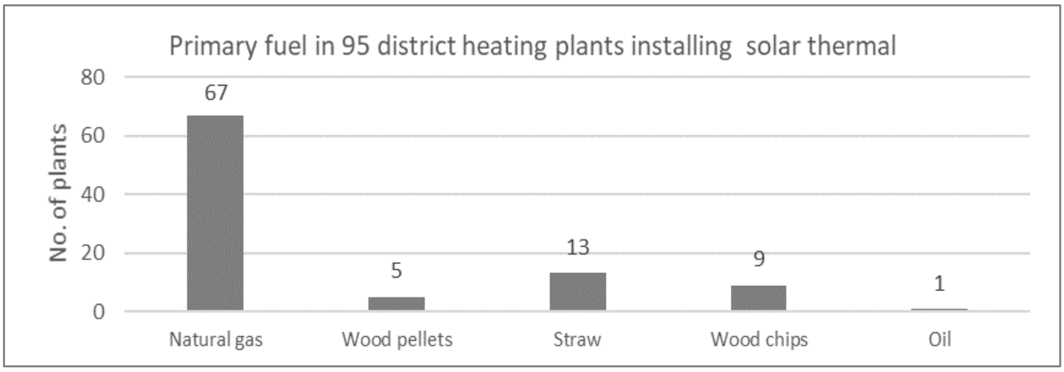


**Figure 24. Primary fuel of 95 DH plants where SDH have been installed [8].**

[6] See section 2.3.1.

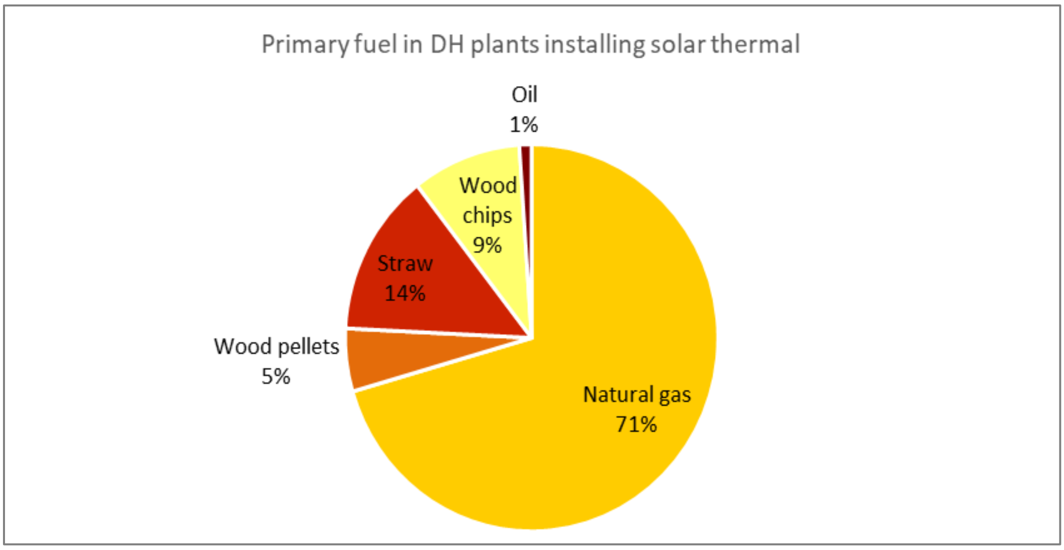


**Figure 25. Primary fuel (i.e. dominating the fuel mix in terms of heat supply) for 95 DH plants where SDH have been installed.**

### 2.2.9 Storage Capacity

The typical solution for SDH plants is a cylindrical steel tank located above ground, used as diurnal storage. The tank is insulated and covered by an outer shell keeping the insulation dry. There is no water in the very top of the tank, as the tank is not pressurised and there must be room for thermal expansion and contraction. A nitrogen supplying system installed in the top of the tank avoids corrosion caused by ambient air.

Typically, a steel tank is already installed at the DH plant, when SDH is considered. This is because most plants interested in a solar heating system (as mentioned) are natural gas fired CHP plants, which use an accumulation tank to even out the demand fluctuations and to produce electricity and heat when the fluctuating[7] electricity price is high, even if there is no need for heat. The heat is then stored until there is need for it, i.e. when the electricity price is low and it therefore is not feasible to run the CHP unit.

**Figure 26. Solar collector field at Helsinge (Denmark) with storage tank and the natural gas fired CHP DH plant in the background [9].**

[7] The electricity spot market has very fluctuating electricity prices at different hours, days, weeks and months of the year.

Figure 27 shows the V/$A_c$ ratio for 43 SDH plants in decreasing order. As the tanks are not necessarily sized based on the solar collector field, a fairly wide spread is observed.

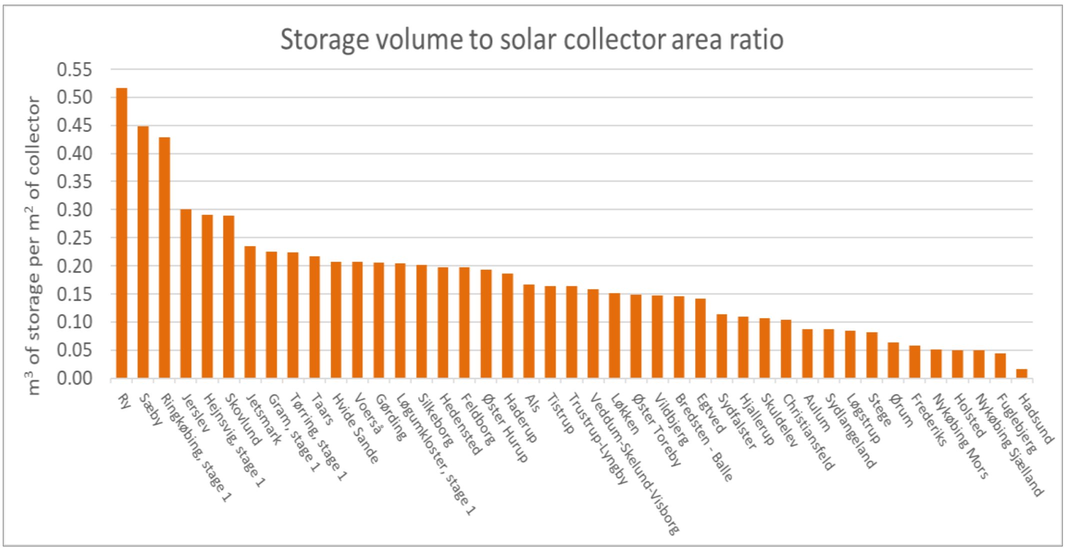


**Figure 27. Ratio between storage volume and collector area for 43 SDH plant examples.**

For seasonal storages there is no a typical ratio between storage volume and collector area (V/$A_c$-ratio), as this ranges between 1.7 and 2.9. This wide range is caused by differences in the storage construction and different circumstances of the associated DH plants (i.e. operation strategy, fuel mix, etc.) The storage is most feasible, when it is not only used to store the solar heat produced in summer until winter, but also as a buffer throughout the year. An example of this use is seen in Figure 28, where the charged/discharged amount of heat are shown on a monthly basis. While other seasonal storages may involve only minor or no discharge during summer, this storage is continuously used the whole year. Hence, the solar heat is not necessarily stored several months before it is used, which minimises the losses to around 10 % on average. In some cases, the economy of the overall DH supply is optimised by using the storage also for other production units than the solar collector field. In fact, the main goal of the DH utilities is to achieve the lowest possible heat price for their customers, which requires a holistic approach – especially when the number of heat production options is increased.

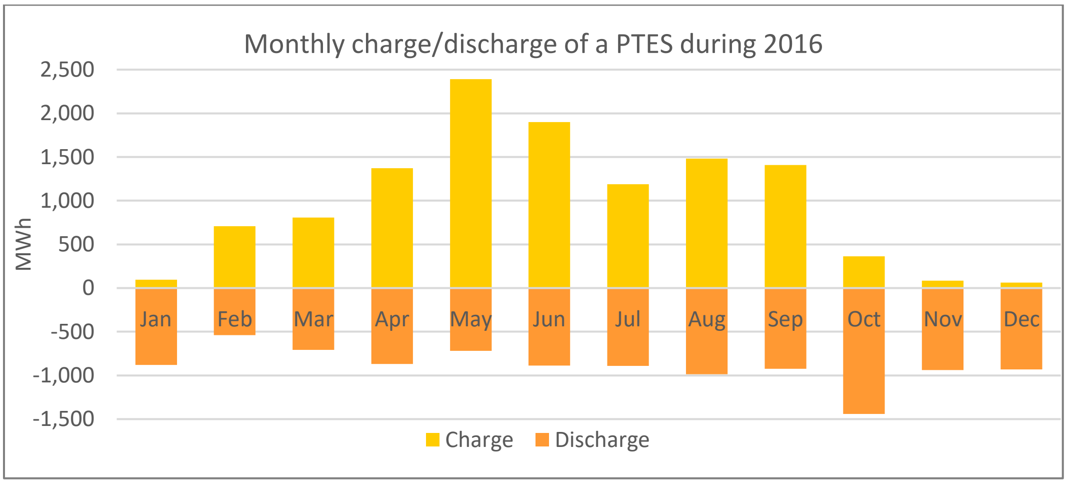


**Figure 28. Example of a monthly charging and discharging profile of a pit thermal energy storage (PTES).**

### 2.2.10 Land Availability

Approximately 62 % of the total area of Denmark is covered by agricultural land [10]. Hence, when the option of converting such areas to a solar collector field, the possibilities are typically abundant.

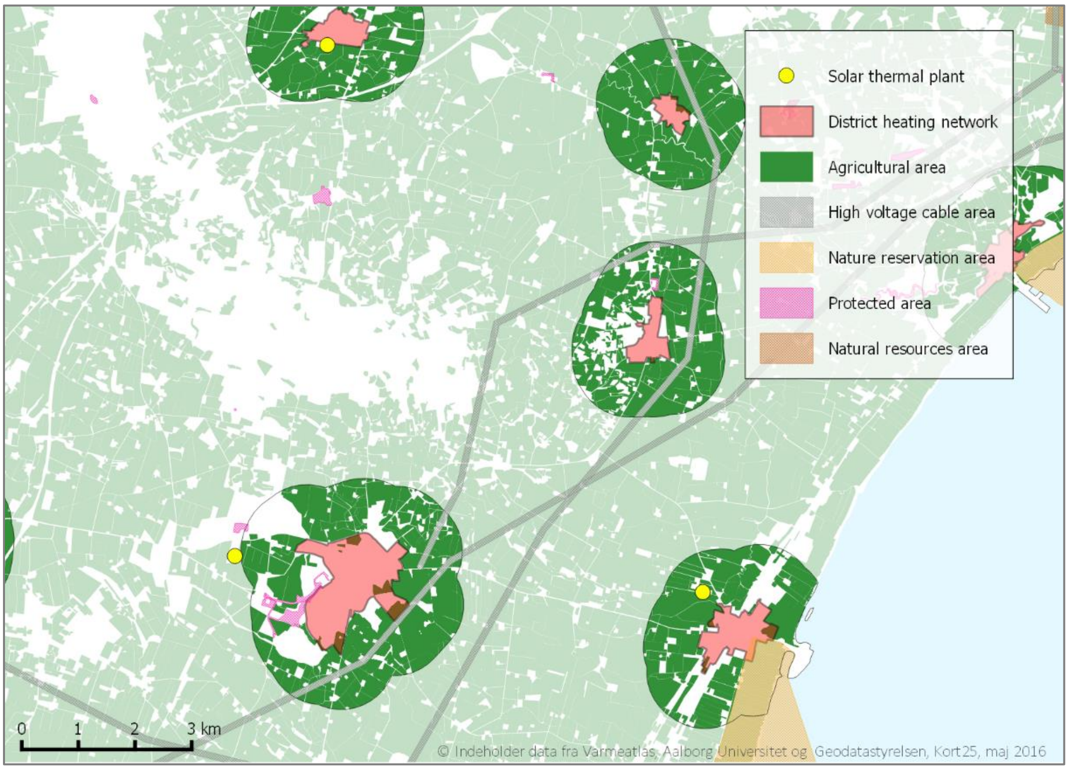


**Figure 29. Excerpt of analysis of potentially available agricultural land area within a radius of 1,000 meters of existing district heating grids in Denmark.**

From the results of section 4.1.2, it is seen that in general the availability of land does not seem to be particularly more significant in Denmark than in other countries.

When land areas to establish SDH systems have to be purchased, its cost is obviously affected by the "supply and demand effects" of the market for trading land. Since the land cost may be higher close to towns and cities, there could be an optimum distance to locate the collectors. However, in practice the price negotiations will often be affected by local circumstances (such as the local farmer's plan for the land). Hence, an estimation of optimum distance in a further study would most likely make more sense for bigger scales than what is typical today. The comparison with other European countries shows that the value for Denmark is close to the average of the other countries.

## 2.3 Non-technical Framework for SDH in Denmark

### 2.3.1 Political Influence and Financing

As mentioned above, the natural gas is often the most expensive fuel for DH production, when it is used in boilers. In this case, the combined taxes can be almost in the same range as the gas price itself. In case of CHP plants, the decreased electricity prices entail fewer hours of operation per year and lower feasibility for this type of plants. Hence, there is a strong incentive to invest in alternative heat sources, such as a solar thermal energy.

The “cost-of-service” (or “non-profit”) principle is applied by law for the Danish DH companies, which means that consumer prices must reflect the true cost of heat production. This also means that for the DH utility long-term investments are not considered a problem, while their access to cheap financing improves the economic feasibility. They are typically owned by the consumers themselves or the local municipality. Without any shareholders who expect a profit from their investment, there is in general no requirement for a short-term return of investment. At the same time, the utilities have access to cheap financing through the Credit Institution for Local and Regional Authorities in Denmark (“Kommunekredit”) [11] which means that there is a municipality guarantee of the loan thus making interest rates in the range of 2-3 % possible. This kind of long-term loans is very suitable for investments in renewable energies, such as solar thermal. By making long-term strategies, the utilities can also take risk management into account. With various heat production units, it is possible to optimise the fuel mix and system operation, and to be less affected by the price of a single heat source. If the gas price increases, a gas-based CHP plant will immediately be affected, while a DH plant with different heat supply options can choose a different configuration, thus coping better with price fluctuations.

An indirect incentive to the Danish SDH development has been the requirement for all DH utilities to obtain a certain amount of energy savings each year. If a utility cannot reach the required savings, it has to buy credits from another utility, which has a surplus of “energy saving credits”, because it was able to *exceed* its energy saving target. These credits are quoted on a stock market on their own, thus varying in price per MWh of saved heat. Previously, the first year of solar heat production counted as energy savings, thus creating a surplus of valuable credits for the utility, which could pay back a part of the investment. This option ended in December 2016, which pushed many utilities to complete several solar thermal plants before this deadline. A new agreement [12] limits the amount of credits which are created by a SDH system to the first 8,000 MWh, which correspond to an installed solar collector area of around 20,000 $m^2$. However, this agreement is presently limited until the summer of 2019.

### 2.3.2 Facilitating a Green Transition of the Heating Sector

While increasing taxation of fossil fuels or introducing mandatory energy savings may be an unpopular political agenda for some stakeholders, a carefully structured framework with incentives for renewable energies can counterbalance the associated cost increase, thus leaving all stakeholders with the same cost range while facilitating a green transition. From the national government’s point of view, the renewable energy incentives (be it subsidies, tax reductions or similar) can possibly be balanced by increased taxes of fossil fuels to counterbalance the economic impact on the state budget. For the utilities the knowledge of “what is coming” (e.g. continuously increased taxes on fossil fuels) together with favourable framework for renewable energy-based solutions can guide them towards a green transition in their long-term planning without increasing costs compared to the business-as-usual scenario. Equally important on the political agenda is that the end consumers are not necessarily affected (since their heat price is determined by the total costs for the utilities).

***Increasing fossil fuel taxes can incentivise renewables. With a stable political framework, the utilities can plan their transition to avoid a cost increase***

In general DH makes it possible to change the heat supply mix for all consumers in the network all at once. This means that a green transition of DH systems is possible with fewer stakeholders involved compared to individual heating solutions. This, combined with the fact that economy of scale is critical for SDH, means that the solar thermal development have seen a significant growth over the last years, which the market for individual solutions have not been able to follow.

### 2.3.3 The (S)DH Community

As the DH utilities are non-profit, there is no reason to maintain good ideas and/or solutions inside a DH utility (in order to keep or expand a certain market share). Therefore, a systematic sharing of experiences is encouraged and facilitated by the Danish District Heating Association. This has increased the awareness of the SDH technology and its potentials, and improved the reliability of the systems (since others in the community are warned about experienced problems).

## 2.4 Summary of Trends in Denmark

Some trends can be derived, although all values have significant spreads:

- The average area of the solar collector field is around 13,500 m$^2$. This value has been increasing over the years, because new plants tend to be increasingly larger and existing DH plants often expand their solar heat capacity some years after the installation of their first solar collector field.
- The typical annual yield is around 400 kWh/m$^2$, but the yield depends on temperature levels of the DH network, storage capacity, operation strategy (i.e. the combination with other units) and the yearly solar radiation (which differs even within a small country like Denmark).
- The distance from collector field to the DH network is typically within 200 m.
- SDH is often installed in smaller towns having up to 5,000 inhabitants or around 60,000 MWh of annual DH demand.
- The SF is typically around 20 % for systems without seasonal storage (and around 40 % in the few examples with seasonal storage).
- The heat prices are typically higher in DH plants mainly based on natural gas, which is also the type of plants where SDH have been installed more frequently.
- The ratio between storage volume and collector area varies significantly. The average value is around 0.2 m$^3$/m$^2$, which fits with feasibility studies for new SDH. The wide spread is caused by the fact that many DH plants have storages already installed before installing the solar collector field (which improves the overall feasibility).
- Land availability is in general not an issue for the smaller Danish towns which consider SDH.
- Non-profit rule means that long-term investments are not considered a problem, while access to cheap financing improves the economic feasibility.
- Taxation on natural gas (and penalties if continuous efficiency improvements in the heat supply are not achieved) have increased the interest for alternative heat supply options by making the business-as-usual scenario more costly.
- Stakeholders share their experiences with the SDH technology to avoid errors and continuously improve system performances.

# 3 Methodology of the European SDH Potential Analysis

## 3.1 Steps of the Analysis – Methodology Overview

The aim of the analysis is to identify suitable areas outside existing DH networks, where it could be feasible to establish large-scale SDH. Since it may not be relevant to establish SDH where there is surplus heat from waste incineration plants and/or excess heat facilities, the analysis is limited to DH networks which are not near this type of sources. This limitation is explained further in section 3.2.4 and is included to make sure that the identified potentials as feasible as possible to be realised in practice. However, this restriction can also be considered quite conservative, as SDH may be applicable also in several of the DH systems which are neglected in this study. Hence, the identified potentials are a place to start for the widespread deployment of large-scale SDH.

***The analysis is a first step of investigating European SDH potentials referred to as "SDHEP1". It will only reveal part of the technical potential for SDH***

The analysis follows the path illustrated in Figure 30 and is based on a number of selected[8] DH systems in Europe. From these DH systems a pre-defined radius is used to identify the surrounding area to be investigated. This area is screened to reveal whether there is land available, where a ground-mounted solar collector field connected to the DH network could be installed. The experiences described in chapter 2 forms the basis of the analysis.

The targeted SFs are 20 % and 40 % with respect to the DH demand at the plant. The cost and thermal losses of the required connection between the solar collector field and the DH network is included together with a predefined required storage investment and its associated losses.

When the required area and corresponding (possibly limited) suitable areas have been identified for each individual DH network, the cost of producing the solar heat is estimated.

The analysis results are split into the following sections:

- Defining the DH networks which should be included in the analysis (excluding networks where other options may be preferred to SDH)
- Availability of land for ground-mounted solar collector fields (for the investigated DH networks)
- Estimations on costs for the solar heat (including all costs) and how different predefined cost limits affect the investigated potentials.
- Applying cost limitations to highlight how maximum acceptable solar heating costs will limit the potentials.

[8] See section 3.2.4 Restricting the List of DH Networks

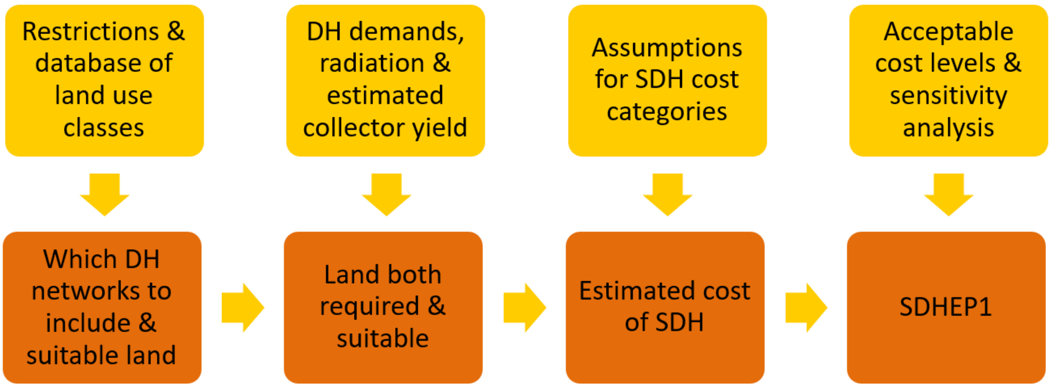


**Figure 30. Stepwise approach of the SDH analysis of European potentials.**

## 3.2 GIS Analysis of Land Availability

### 3.2.1 Approach

The approach of the spatial analysis is to estimate the available land needed to establish solar collector fields using geographical information system (GIS) software by combining

- location and heat demand of a wide range of European DH networks
- estimation on the urban area in which the DH network is located
- preconditions for which networks to focus on (and which ones not)
- a database of land use classes (identifying areas which could be allocated for SDH plants)
- data on solar radiation for every location
- rules to estimate the required area to cover a certain share of the heat demand

This analysis only includes the potential for large ground-mounted solar collector fields outside of cities though roof-mounted (and similar) collector fields could also represent a feasible solution.

### 3.2.2 Heat Roadmap Europe Collaboration

The Heat Roadmap Europe (HRE) project[9] is aiming at new policies and encouraging investments to decarbonise the heating and cooling sector. A part of the project focuses on mapping the potential correlations between available heat sources (e.g. excess heat) and existing heat demand using GIS. This includes also towns suited for introducing solar heating in their (existing) DH system.

In a collaboration between the HRE project and IEA SHC task 52, a conceptual and spatial methodology for estimating theoretical possibilities for large-scale solar thermal heat utilisation in urban areas has been developed. This spatial analysis as described in this section 3.2 would not have been possible without this collaboration. The efforts carried out in the framework of the HRE, regarding mapping of resources and DH networks, have made it possible to utilise comprehensive database material combined with geographical location of thousands of DH networks across Europe (see section 4.1). The countries included in this analysis are Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark,

[9] The Heat Roadmap Europe project is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 695989.

Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, the Netherlands, Poland, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom[10].

A detailed description on the mapping work done within the HRE project is available on the project website (www.heatroadmap.eu) [13]. Here it is also possible to access the online map containing multiple layers of resources and demands. The map is called the Pan-European Thermal Atlas (referred to as "Peta") and includes a layer indicating the analysed potential SDH systems[11].

This analysis on areas suitable for SDH focuses on towns where there are no options of using excess heat from industrial processes or waste incineration (see section 3.2.4). It should also be noticed that the analysis considers only ground mounted solar collector fields. However, also systems within the towns could in principle contribute to the accumulated solar heat produced and replace/diminish the area of the systems located outside the towns. Such opportunities are being investigated e.g. in the SDHp2m project[12] (www.solar-district-heating.eu) [14].

### 3.2.3 Combining Multiple Databases

To avoid double-counting potentials for cities with more than one DH system, the spatial analysis includes an evaluation of what is called urban morphological zones (UMZ) i.e. the urban area where the DH network(s) are located within. For a further description of these UMZs, see [13]. When referring to the list of DH networks where some of them are grouped together for the above-mentioned reason, the term "coherent DH networks" is used. By applying this method, it is possible to check a given distance from the town boarder instead of a certain radius from the DH plant location.

For these coherent DH networks, the yearly heat demand is estimated according to the method defined in the HRE project. The heat demand for each DH area is a function of building types, floor area, sub-sector and country. For towns where the DH demand is unknown, the yearly heat demand is estimated based on the number of inhabitants. For this assumption the average heat demand derived from the available dataset of DH systems and inhabitants is used. This results in a demand of 3 MWh/year per person.

Based on the land surface categorisation from the Corine Land Cover [15] and experience from the plant location of Danish systems where the typical location is on agricultural areas, a GIS software analysis is used to derive the availability of "suitable land" for each DH network.

### 3.2.4 Restricting the List of DH Networks

This analysis limits the potential for SDH to already existing DH networks. The demand of the DH networks included in this analysis are based on the HRE project using GIS data. The specific objective of the HRE project has been to identify the most obvious candidate SDH

[10] The countries included in the HRE project are the 14 ones representing the largest heat demands thereby covering more than 90 % of the total EU heat demand. These are Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, the Netherlands, Poland, Romania, Spain, Sweden and the United Kingdom thus leaving out Austria, Croatia, Denmark, Estonia, Latvia, Lithuania, Slovakia and Slovenia.

[11] The analysis and mapping do not take into account if one or more solar thermal systems have been established in practice.

[12] The SDHp2m project is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 691624.

cities, based on general qualifying conditions. Only the DH networks without opportunity to access excess heat are included in this analysis.

This limitation excludes a large number of the locations, where SDH could also be considered. Hence, this study aims at the "low-hanging fruits" for SDH. The thought behind this limitation is that it does not seem logical to establish a SDH system in places where there is simultaneously a need to cool down a similar or larger amount of excess heat. In these cases, it should at least be explored if it would make sense to tap into the excess heat already available. Examples of transmission lines from large excess heat sources in lengths of tens of kilometres exist around Europe. Hence, a distance[13] of 20 km could be considered reasonable distance to check for available excess heat and/or WtE facilities. However, though excess/waste heat may be available, there could be arguments against using it. Further analyses would be required to determine where it would make sense to utilise the excess heat already available and to which extent it would make sense to supplement such sources with solar heat. Hence, SDH might be a feasible solution also for some DH networks omitted from this study.

A main task has been to map available land areas near towns and cities with existing DH network. To identify relevant cities for SDH the following core criteria are applied:

- The city does not have an excess heat source[14] within 20 km
- The city does not have a WtE facility within 20 km
- Suitable land for solar collector installation is available in the city vicinity (200 and 1,000 m are used in the analysis)

First, the cities with a DH network, but without access to excess heat and WtE heat were identified. The GIS data were used to map the distances between potential excess heat sources or WtE plants to all DH networks recorded in EU28. If the distance for a potential heat source is shorter than 20 km from a given town, that town is excluded from the candidate list, regardless whether the heat source is utilised or not today, and irrespective of the temperature levels.

***Only existing DH networks where there is no WtE/excess heat nearby are included in the further analysis***

### 3.2.5 Defining Required Land Area and Solar Collector Area

To estimate how much land would be necessary for a desired SF, the corresponding solar collector area needs to be defined first. This is done by a simple conversion method estimating how much solar heat can be produced by an optimally oriented collector field depending on the solar radiation in the investigated location. A conversion is then applied to estimate the land area needed to install the collector field.

The area of (potentially) available land in the city vicinity is estimated according to Corine Land Cover (CLC) classes. Seven categories were selected to resemble land types suitable for solar collector installations, i.e. fairly flat, neither built nor covered by forests or waterways. Agricultural land and some natural areas were assumed to be suitable land use categories based on Danish experience, as shown in Table 1.

[13] Distances refer to the city boarder represented by the edge of the UMZ (see section 3.2.3).

[14] Only large-scale sources are included in this criterion (thermal power generation activities > 50 MW [13]).

The potential land areas are checked within a distance of 200 m and 1,000 m from the town border. For each distance the required solar collector and land area to provide 20 % and 40 % SF is calculated.

**Table 1. Selected Corine Land Use Classes [16] as representative of suitable land categories for large-scale solar collector installations, by code and label levels.**

| *CLC code* | *Overall land use class* | *Detailed land use class* |
|---|---|---|
| *12* | *Agricultural areas* | *Non-irrigated arable land* |
| *13* | *Agricultural areas* | *Permanently irrigated land* |
| *18* | *Agricultural areas* | *Pastures* |
| *21* | *Agricultural areas* | *Land principally occupied by agriculture* |
| *26* | *Forest and semi natural areas* | *Natural grasslands* |
| *27* | *Forest and semi natural areas* | *Moors and heathland* |
| *32* | *Forest and semi natural areas* | *Sparsely vegetated areas* |

The desired SF is based on analysis of solar thermal coverage of heat demand in Danish DH systems. This is then related to the solar radiation in the investigated location to provide a SF specified for each DH network. The steps of the calculation are the following.

The desired solar heat production ($Q_{solar}$) to cover a certain share (SF) of the annual DH demand ($Q_{DH}$) is found by

$$Q_{solar} = SF \cdot Q_{DH} \qquad \text{(kWh/yr)}$$

The solar collector area ($A_{c,SF}$) needed to deliver a certain amount of solar heat per year is calculated as

$$A_{c,SF} = \frac{Q_{solar}}{c_{hor-to-yield} \cdot G_{hor}} \qquad (m^2)$$

where

$c_{hor\text{-}to\text{-}yield}$: Conversion factor from solar radiation on horizontal to yield from solar collector system at optimum orientation (-)

$G_{hor}$: The yearly horizontal solar radiation (kWh/m²·yr)

The radiation data used is global solar radiation (on horizontal surfaces) while the estimated solar thermal production is based on optimum orientation of the collectors.

The global solar radiation, $G_{hor}$ for each DH area is based on the European Joint Research Center solar radiation data [17].

$c_{hor\text{-}to\text{-}yield}$ is a function of DH temperature levels, solar radiation, latitude, collector type, collector row spacing and other parameters. In this analysis, it is assumed that $c_{hor\text{-}to\text{-}yield}$ is 0.4 for all systems. This is based on the common calculation method for solar collector energy output as defined by IEA SHC [18].

The needed ground area ($A_{land,SF}$) is proportional the collector area:

$$A_{land,SF} = A_{c,SF} \cdot f_{land-to-col} \qquad (m^2)$$

where

$f_{land\text{-}to\text{-}col}$: Ground area to collector area ratio (-)

The ratio $f_{land-to-col}$ of optimised SDH systems depends on solar radiation, latitude, collector type, collector row spacing and other parameters. In this analysis, it is assumed that $f_{land-to-col}$ is 3.5 for all DH areas.[15] Thus, for 1 m² of collector area, 3.5 m² of land are needed.

The potential land area for a solar collector field at a given DH area ($A_{land,pot}$) is calculated as the minimum of two following parameters:

- The sum of identified suitable land of the selected Corine Land Use Classes ($A_{CLC}$) within the zone between the town boarder and a fixed distance outward.
- The needed ground area to deliver a specified SF ($A_{land,SF}$).

$$A_{land,pot} = \mathrm{MIN}(A_{CLC}, A_{land,SF}) \qquad (m^2)$$

As a result of the potential ground area, the possible collector field area for a given DH network ($A_{col,pos}$) is:

$$A_{c,pos} = \frac{A_{land,pot}}{f_{land-to-col}} \qquad (m^2)$$

The yearly net delivered solar heat to the DH network is calculated as:

$$Q_{solar} = A_{c,pos} \cdot c_{hor-to-yield} \cdot G_{hor} - Q_{TL,hl} - Q_{stor,hl} \text{ (kWh)}$$

where

$Q_{TL,hl}$: Yearly transmission pipe losses between collector field and DH network (kWh)
$Q_{stor,hl}$: Yearly storage losses from solar thermal energy storage (kWh)

The calculations of storage and transmission pipe heat losses are explained in section 3.3.2 and 3.3.3 respectively.

An example of the methodology for identifying suitable areas for solar collector fields is seen in Figure 31-Figure 34 for the Austrian town of Gleinstätten. The yellow region indicates the area supplied by DH, while the green region indicates the identified suitable land for a ground-mounted solar collector field. The town is almost completely surrounded by agricultural land, but west of the town a forest is excluded from the area considered suitable (as seen in Figure 34). East of the town a solar thermal system can be spotted (highlighted with a red circle in Figure 34).

[15] This can be considered a conservative estimation compared to the similar level for a ratio based on collector aperture area stated in the SDH fact sheet 2.3 [19].


**Figure 31. Map of Gleinstätten (AT). (Source Google Maps, 2017.)**

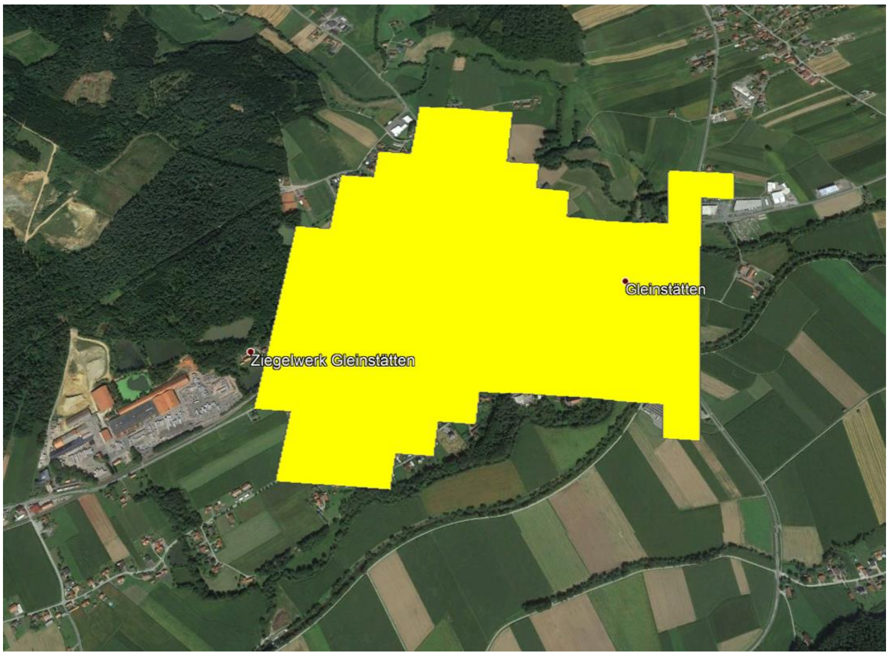


**Figure 32. Map of Gleinstätten (AT) with the analysed DH network area highlighted in yellow (approx. 1 by 1 km). (Source of background map: Google Maps, 2017.)**


**Figure 33. Map of the area around Gleinstätten (AT) checked for suitable areas indicated with two yellow lines (town boarder and 200 m distance respectively). (Source of background map: Google Maps, 2017.)**

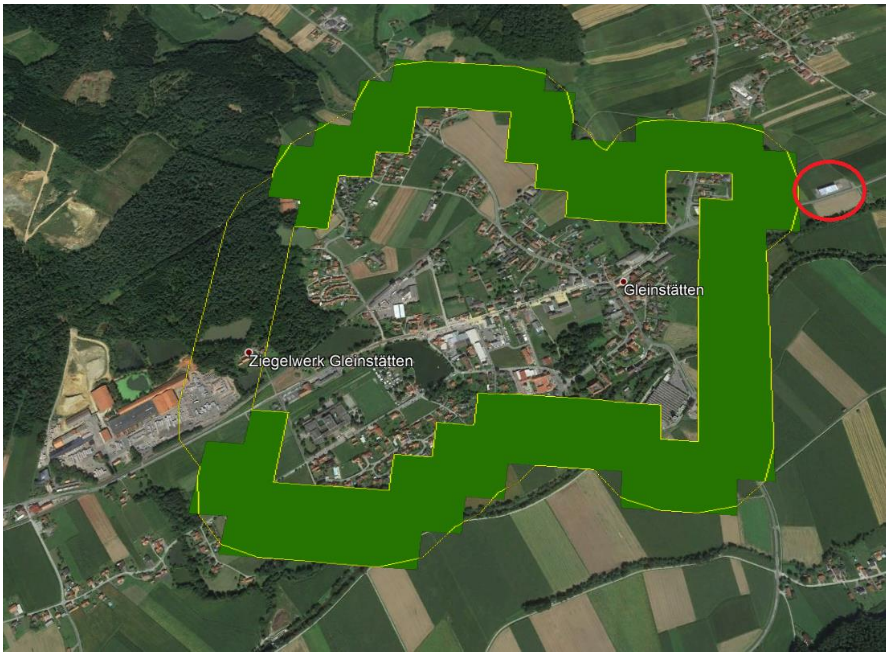


**Figure 34. Map of Gleinstätten (AT) highlighting identified potential areas in green. Realised solar heating system indicated with a red circle. (Source of background map: Google Maps, 2017.)**

### 3.2.6 Comparing Method with Realised Examples

The following figures demonstrate how the analysis can be used to identify potential SDH systems and compare the identified suitable land with the required land. The figures show a few Danish towns which recently installed SDH systems. In each of the first two cases, a small (for Danish standards) solar collector field with short term storage delivers a 20 % SF. The solar collector field is located along the border of the town. The collector field only covers a minor part of the area included in the 200 m vicinity border.


**Figure 35. Gedser (DK): Example of district heating network (yellow), agricultural land within 200 m vicinity (green), and a 20 % SF SDH system that was installed in 2016 (red).**

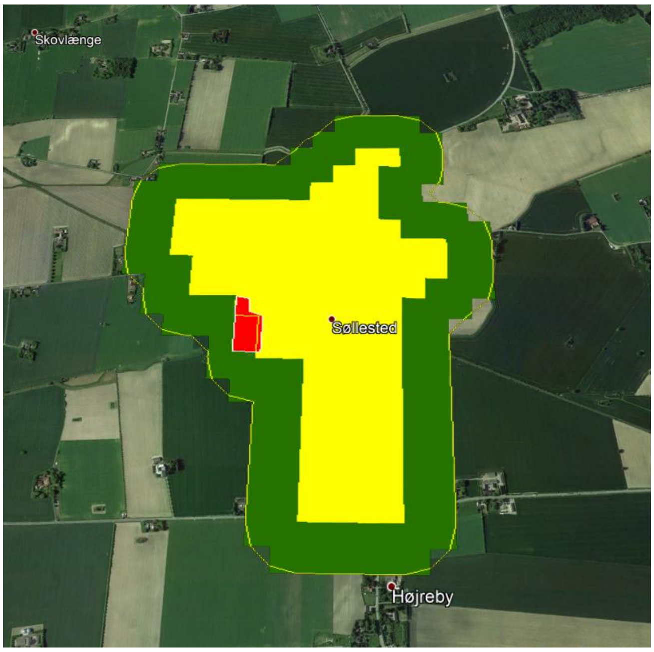


**Figure 36. Søllested (DK): Example of district heating network (yellow), agricultural land within 200 m vicinity (green), and a 20 % SF SDH system that was installed in 2016 (red).**

In the third case, a large solar collector field with a seasonal water pit storage was installed to deliver approximately 40 % SF. The installation was located 1 km from the town to find the optimal location for the pit storage, and not due to lack of space closer to the town. This can be seen from the large green areas within the 200 m and 1,000 m vicinity borders. Even a 40 % SF SDH system has a low space requirement compared to the suitable areas around a town like Dronninglund.

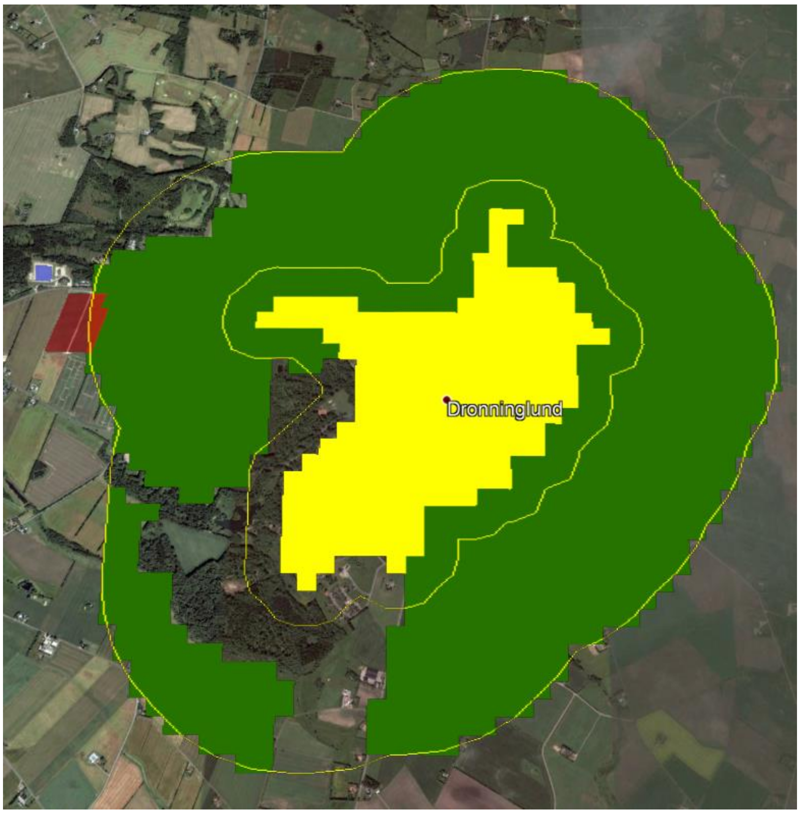


**Figure 37. Dronninglund (DK): Example of district heating network (yellow), agricultural land within 200 and 1,000 m vicinity (green), and a 40 % SF SDH system that was installed in 2014 comprising a collector field (red) and a water pit storage for seasonal storage (blue).**

The location of the solar collector field in the case of Dronninglund was chosen as it was, so that the seasonal storage could be located in an old gravel pit (highlighted in blue in Figure 37), otherwise the collectors could have been placed closer to the DH network.

## 3.3 Assumptions for the Economic Analysis

The cost of a solar thermal installation consists of several components. It is assumed that there is no need for major refurbishments in the existing DH systems to integrate the solar system.

Four investment categories are considered in this analysis:

1. Solar collector field including installation, main components etc.
2. Thermal energy storage
3. Transmission line to the town
4. Cost of land

### 3.3.1 Solar Collector Field

The cost of the collector field is divided in a variable (i.e. depending on collector area) and in a fixed part.

It is assumed that the following parameters are included in the cost of the solar collector system:

- Solar collector panels
- Mounting, installation and piping
- Main system components, such as heat exchanger and pumps

- Simple CRS-system (control, regulation and supervision)
- Water-glycol mixture and expansion/blow-out vessels
- Room for heat exchanger sub-station

A fixed cost of 50,000 € per plant is assumed independently of the size of the collector field. In practice, the required misc. installations will depend on the existing DH system[16].

The costs are not divided in specific sub-categories, because these are unlikely to be the same for all plants. Some DH plants will have a suitable building for the heat exchanger, pumps, control equipment, power supply, etc., whereas other systems might be needing extra investments.

The cost is given as a function of the solar collector area, $A_c$. For systems larger than 75,000 m² of collector area, it is assumed that the specific cost (€/m²) does not further decrease. The price function is estimated based on the Danish experience[17] (Figure 4).

$$\text{Price}\left[{}^{€}/_{\text{m}^2{}_{\text{gross}}}\right] = \begin{cases} 1{,}000 \cdot \text{A}_\text{c}{}^{-0.16} & , \quad 1{,}000\ \text{m}^2 \leq \text{A}_\text{c} < 75{,}000\ \text{m}^2 \\ 166 & , \quad \text{A}_\text{c} \geq 75{,}000\ \text{m}^2 \end{cases}$$

### 3.3.2 Thermal Energy Storage

The relative storage volume needed for a given system depends on the simultaneity between solar heat production and the demand. In the analysis it is assumed that there is no storage already installed, although this has not been the case in many examples in Denmark. The ratio between storage volume (V) and collector area ($A_C$) is assumed a function of the SF:

$$\text{V}/\text{A}_\text{C}\ [\text{m}^3/\text{m}^2] = \begin{cases} 0 & , \quad \text{SF} \leq 5\ \% \\ 0.2 & , \quad 5\ \% < \text{SF} < 30\ \% \\ 3 & , \quad \text{SF} \geq 30\ \% \end{cases}$$

The reason why not only 20 % and 40 % SFs are considered is that the size of the system may be limited by the available land area. Hence, even when 20 % or 40 % SFs are targeted, smaller systems covering smaller shares are also included. In these cases, the reduced potential is applied[18].

To cover up to 5 % SF it is assumed that the solar heat can always be delivered directly to the DH network, thus eliminating storage losses. This assumes that it is always possible to use the solar heat for heat consumption, to cover network thermal losses or to store the heat in the DH network by increasing the network temperature. To cover between 5 and 30 % SF a diurnal thermal energy storage is needed – while to cover more than 30 % SF a seasonal storage is assumed. In reality, the $V/A_c$-ratios are quite system dependent, as mentioned in section 2.2.9. The average $V/A_c$-ratio of 0.2 m³ of storage per square meter of solar collector is assumed in this analysis in case of SFs between 5 % and 30 %. The typical range is between 0.1 and 0.5 m³/m², often depending on the existing storage before the installation of the solar collector field. The storage heat loss for systems with

[16] E.g. whether a small building for heat exchanger and pumps is required next to the collector field or it can be placed at the DH plant.

[17] There is a difference compared to the Subtask C report [20], but that represents a total system whereas in this report collector field, storage, transmission line and land costs are separated costs.

[18] As explained in the calculation method of section 3.2.5.

SF up to 30 % is assumed to be 2 % of the yearly gross solar gain thus resulting in actual SFs slightly lower than the targeted one.

The impact of the storage investment cost is more important in the calculations for high SFs. An important role is also played by the assumption on the $V/A_c$-ratio. Hence, the actual load profile of a DH network becomes increasingly important for the economic estimations. A conservative assumption of 3 m³ storage per square meter of collector is made for the seasonal storages installed in SDH systems with SF higher than 30 %.

In practice, seasonal storage losses of around 10 % have been recorded, while other examples show losses higher than 20 %. How the storage is used and sized affects the losses. Hence, it is not easy to provide a single number for seasonal storage losses. In this study, a heat loss of 20 % of the solar yield is assumed for systems with seasonal storage. Consequently, an estimated solar heat production of 50 % of the annual DH demand covers approximately 40 % of the DH demand.

Two thermal energy storage technologies are considered in this analysis: steel tank and water pit storage. For systems with a storage volume below 40,000 m³ a steel tank (or a pair of steel tanks) is considered, while for storage volumes above 40,000 m³, water pit storages are assumed.

The cost functions for installation of the two storage types are given by the following equations.

- Steel tank thermal energy storage (TTES):

$$\text{Price}\ \left[{}^{€}/_{\text{m}^3}\right] = \begin{cases} 550 & , \quad V_{\text{TTES}} \leq 300 \\ 5{,}300 \cdot V_{\text{TTES}}^{-0.43} & , \quad 300 < V_{\text{TTES}} < 8{,}000 \\ 110 & , \quad V_{\text{TTES}} \geq 8{,}000 \end{cases}$$

- Water pit storage (PTES):

$$\text{Price}\ \left[{}^{€}/_{\text{m}^3}\right] = \begin{cases} 150 & , \quad V_{\text{PTES}} \leq 1{,}500 \\ 2{,}300 \cdot V_{\text{PTES}}^{-0.37} & , \quad 1{,}500 < V_{\text{PTES}} < 200{,}000 \\ 25 & , \quad V_{\text{PTES}} \geq 200{,}000 \end{cases}$$

The volume of 40,000 m³ is not the crossing between curves derived from the above-mentioned cost functions. The value is chosen from a practical point of view.

The cost of the thermal energy storages per unit volume is shown in Figure 38. It is seen that the storage cost is higher for 30,000 m³ than for 50,000 m³, due to the embedded constraint for the limit between steel tanks and pit storage.

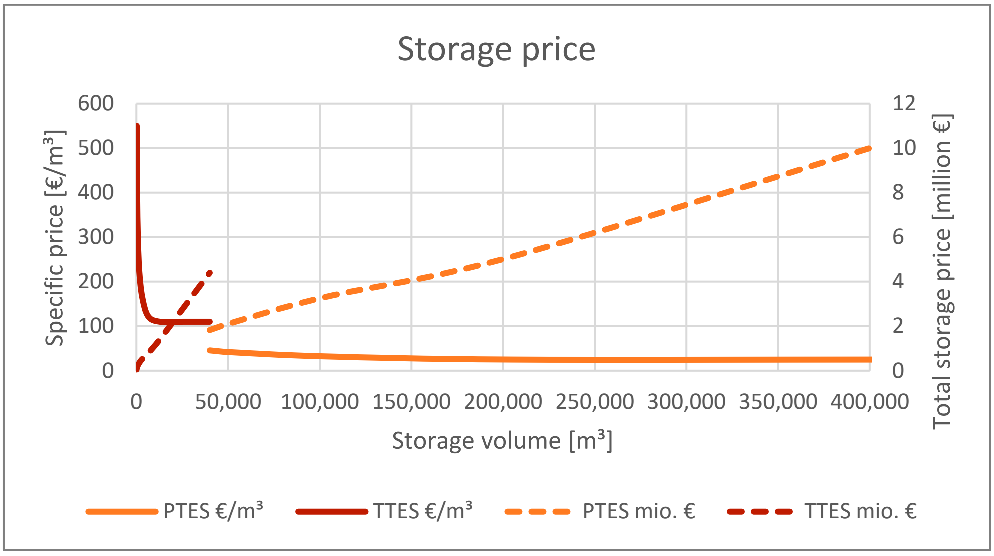


**Figure 38. Between 8,000 and 40,000 m³ the storage is assumed to be steel tanks at a fixed price of 110 €/m³. Above 40,000 m³, where pit storage is introduced, the price drops significantly.**

Whereas the thermally insulated steel tank is a well-known technology across the world, which can be installed any location, a pit storage requires a more careful planning and more land area.

### 3.3.3 Transmission Line to District Heating Network

The analysis is carried out for a transmission line length of 200 or 1,000 m. When investigating suitable areas for the collector field at 200 m (or 1,000 m) from the town, the cost of a transmission line of 200 m (or 1,000 m) is used in the cost calculations. In practice the available land may be found between these distances.

It will normally be necessary to connect the SDH supply to a main DH network pipe or to the DH plant. The extra costs associated with this could be partly compensated by the fact that the first meters (e.g. 50 m) of connection pipe from the solar collector field to the DH plant could be included in the cost of the collector field. Additionally, the assumed costs stated below could be considered conservative, at least compared to Danish examples.

The transmission pipe cost is a function of the length and the diameter. The diameter is a function of the maximum solar thermal output, which can be calculated assuming a peak performance of 700 W/m² [18] for the solar collectors.

The diameter $D_{TL}$ is calculated based on the formula:

$$D_{TL}\ [mm] = 92.17 \cdot P_{solar,max}{}^{0.38}$$

where $P_{solar,max}$ is the maximum thermal power output from the solar collector field.

The maximum flow rate is calculated as:

$$\dot{V} = P_{solar,max} \frac{T_f - T_r}{\rho \cdot c_p} \cdot 3{,}600\ [m^3/h]$$

where $T_f$ and $T_r$ are the forward and return temperature from/to the solar collector field to/from the transmission line respectively. ρ is the density and $c_p$ is the heat capacity of the fluid in the transmission pipe.

The required pumping power ($P_{pump}$) is calculated as:

$$P_{pump} = \frac{\dot{V}}{3,600} \cdot \frac{\Delta p}{1,000} 2 \cdot L_{TL} \text{ [kW]}$$

where Δp is the pressure drop gradient and $L_{TL}$ is the length of the transmission pipe.

The electricity required for transmission line pumping is calculated as:

$$Q_{el,pump} = n_{full,load} \frac{P_{pump}}{\eta_{pump}} \text{ [kWh/a]}$$

where $n_{full,load}$ is the number of full load hours of the transmission pipe per year and $\eta_{pump}$ is the pump efficiency.

The transmission line investment is based on the diameter of the pipe.

$$\text{Price } [€/_{m}] = 138 + 3.57 \cdot D_{TL}(1 - f_{discount})$$

where $f_{discount}$ is the discount compared to the list prices of manufactures. In this case $f_{discount}$ is set to 30 %.

For example, if a solar collector field has a collector area of 10,000 m², the maximum heat production is approximately 7 MW. Based on the above-mentioned assumptions, the calculated diameter $D_{TL}$ is about 200 mm.

The overall cost for a 200 mm pipe is then 620 €/m, while the heat losses are around 6 MWh/year for a 20 % SF SDH plant with a 200 m transmission line. Hence, the losses are small compared to around 4,000 MWh/year of produced solar heat.

**Table 2. Example of transmission line values for a given collector area.**

| *Parameter* | *Unit* | *Example 1* | *Example 2* |
|---|---|---|---|
| *Length of transmission line, $L_{TL}$* | *m* | *200* | *1,000* |
| *Collector field area, $A_c$* | *m²* | *10,000* | *10,000* |
| *Max. solar yield, $P_{solar,max}$* | *MW* | *7* | *7* |
| *Inner diameter of transmission line, $D_{TL}$* | *mm* | *193* | *193* |
| *Specific price for transmission line* | *€/m* | *620* | *620* |
| *Heat loss, $Q_{TL}$ diurnal (20 % SF target)* | *MWh/a* | *6* | *32* |
| *Heat loss, $Q_{TL}$ seasonal (40 % SF target)* | *MWh/a* | *14* | *70* |

The number of full load hours for the SDH plant is estimated in 700 hours/year for calculating the electricity consumption of the transmission pump[19]. To calculate the electricity needed for the transmission pump, a pressure drop of 100 Pa/m and 60 % pump efficiency ($\eta_{pump}$) is assumed for the 700 full load hours.

To calculate the transmission heat losses ($Q_{TH,hl}$), the number of hours of operation is set to 2,000 and 4,380 hours for system without and with seasonal storage respectively[20]. The value of 2,000 hours is based on the typical number of hours of operation for a solar thermal plant, while 4,380 hours (half a year) is estimated based on the fact that roughly half of the DH heat demand is covered by solar thermal.

[19] Rough estimation corresponding to a solar heat production of 490 kWh/m² divided by 0.7 kW/m² peak thermal power.

[20] The hours for the transmission pipe heat loss calculation differs from the pumping full load hour number since the pipe will be warm throughout the day though the collector field may not be performing at 100 %.

$$Q_{TL,hl}\left[\frac{MWh}{yr}\right]=0.476\cdot\left(\frac{D_{TL}}{1,000}\right)^{0.372}\pi\,\frac{D_{TL}}{1,000}\,(\Delta T_f+\Delta T_r)\cdot\frac{n_{TL,loss}\cdot L_{TL}}{10^6}$$

where $\Delta T_f$ and $\Delta T_r$ are the temperature difference between forward temperature and ground temperature, and between return temperature and ground temperature respectively. $n_{TL,loss}$ is the number of hours of operation of the transmission line; 2,000 or 4,380 depending on whether the storage is diurnal or seasonal.

The temperatures used for the analysis are:

- Solar system forward temperature, $T_f$: 80 °C
- Solar system return temperature, $T_r$: 40 °C
- Ground temperature, $T_{soil}$: 9 °C

### 3.3.4 Cost of Land

The cost of land is found for each country based on country statistics (Figure 39). The cost depends on the economy/wealth of the country, but it also depending strongly on other factors, e.g. types of farming, available farming land, etc. The land areas considered in this analysis, at a distance between 200 and 1,000 m from the perimeter of a town, are obviously not the cheapest. Nevertheless, the cost of land is not very significant compared to the total costs of the solar installation.

The average cost of land was found for most of the considered countries, based on prices for arable land reported by Eurostat [22]. The statistics refer to 2014. For 4 countries (Austria, Belgium, Germany and Italy) the latest data were not available. Hence, these values were estimated based on data from similar countries (Austria) or projected based on data from previous years (remaining countries). Within the same country there may be significant variations as seen for Germany by the Statistisches Bundesamt (Destatis) [23] where costs between the "Länder" are compared. The impact of this is investigated in the sensitivity analysis (section 4.3).

The value of the farm land after the end of the SDH system lifetime is not included in the analysis – i.e. it is assumed that the value of land is 0 at the end of the system's lifetime. This is of course not true in practice. Thus, the cost of land included as part of the payment per MWh of solar heat could actually be considered a rental cost. The cost of land is calculated by applying the solar thermal system lifetime (assumed to be 25 years) and the general interest rate (3 %[21]). For a land cost of 20,000 €/ha this would correspond to an annualised cost of 1,149 €/year per hectare. Compared to other cost categories of a SDH system, this represent a minor share except for the highest land costs seen in Figure 39. However, it should be noted that the differences in solar radiation has a direct impact on the required land area. For example, the low land cost in Finland is somewhat counterbalanced by the fact that here the solar radiation is lower than in most of the other countries.

[21] See section 3.3.5 Financial Parameters.

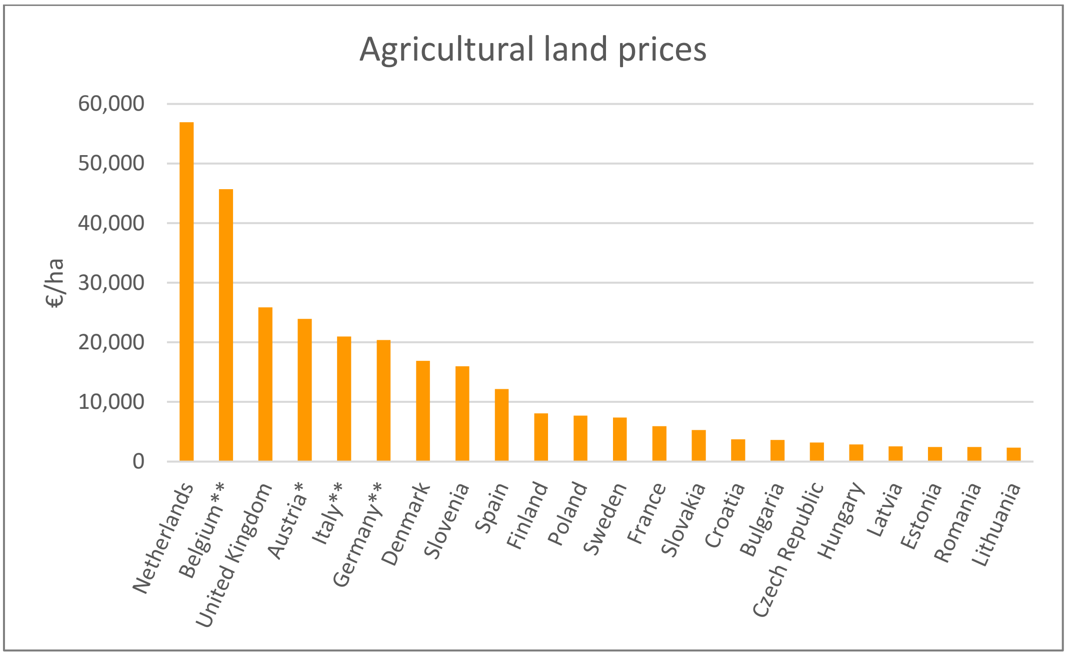


**Figure 39. Cost of land based on Eurostat data (2014). * No Eurostat data available – land price estimated based on an average of Germany and Luxembourg values. ** No data available for 2014 – land price projected based on data for 2005-2012.**

### 3.3.5 Financial Parameters and Technical Lifetimes

The need for pumping power for the solar installation (excluding transmission) is assumed to be 3 $kWh_{el}/MWh_{solar}$. Operation and maintenance (O&M) costs for SDH systems are in general a minor cost. In the analysis the cost of electricity for the pumps is assumed to be 0.12 €/kWh and represents the main cost connected to the operation of the SDH system (assuming the workers of the DH plant can manage its daily operation along with the DH plant). Since SDH systems have a high capital cost of investment compared to the O&M costs, the conditions for financing the investment have a large influence on the overall cost of solar heat. Hence, cheap loan options are key for the breakthrough of SDH. The interest rate has been fluctuating in the last years, and the financing possibilities vary from country to country depending on national and local framework.

For calculating the capital costs, an interest rate of 3 % p.a. is used. From the Euro area bank interest rate statistics in December 2017 [24] for non-financial corporations, it seems likely that 3 % (or less) would be obtainable for most areas.

The technical lifetime of the solar installation is assumed to be 25 years, while 20 years is assumed for the thermal energy storage. The value of any investment is assumed to be 0 after the end of the lifetime, although the technical lifetime of existing SDH systems in Denmark has been estimated to be at least 30 years [25]. Hence, the applied lifetime of 25 years is a conservative estimate. This point also applies to the transmission line which have likely a longer lifetime than 25 years.

This lifetime is used both as a payback period for the loan corresponding to the total investment (except for the storage) and for calculating the expected accumulated solar heat produced. This is then used together with the other costs stated in this section (3.3) to calculate the cost of the solar heat in the form of €/MWh. This parameter is considered a key indicator for the potential of realising a SDH system and is therefore the main focus in section 4.2.

# 4 Results of SDHEP1

In this chapter the results of the analysis of European SDH potentials are presented. Note that the analysis represents similar conditions as in the present Danish SDH market, so it does not represent the full potential for SDH in either Europe as a whole or in the individual countries. The analysis aims at “low-hanging fruits” in the form of identifying existing DH networks without obvious alternatives, for which a solar heating system could be considered possible, applicable and feasible.

## 4.1 Spatial Analysis of Land Availability and Potential Solar Yield

### 4.1.1 Existing DH Networks Without Excess Heat/Waste Incineration Nearby

In total 2,482 DH networks are included in the “candidate list” (i.e. used in the further analysis) after introducing the restrictions of no WtE/excess heat nearby (see section 3.2.4). The result of the described “filtering” is that most towns are still included (the *number of DH networks* is relatively high) but most of the *total heat demand* is excluded – see Table 3.

766 of the towns in the candidate list did not contain data for yearly heat demand. The DH demands of these systems are estimated according to average demand per inhabitant from the systems *with* available data. As stated in section 3.2.3 a demand of 3 MWh/year per person is used for these networks.

**Table 3. DH networks considered vs. included in the further analysis.**

| | ***Potential SDH networks*** | ***Sum of annual DH Demand*** |
|---|---|---|
| *DH networks localised in total* | *3280* | *340 TWh** |
| *DH systems after excluding networks with/near WtE and/or excess heat* | *2480 (76%)* | *71 TWh (21%)*<br>*→ 105 TWh*** |

*Notes:*

** This number represents the data available on DH demands for 2316 out of 3280 DH networks (70 %).*

*** The available data on remaining DH networks is 71 TWh (for 1716 coherent DH networks), but this value is calibrated to 105 TWh by estimating DH demand for towns without demand data based on number of inhabitants.*

Figure 40 shows how the number of DH included initially is reduced by the restrictions stated in section 3.2.4. Comparing this with the reduction in heat demands, it is revealed that typically smaller towns are included in the candidate list. Most of the existing DH networks could consider investigating WtE/excess heat options as part of their planning for future low-carbon heating options. It could be taken into account when investigating various options for decarbonising their heating sectors.

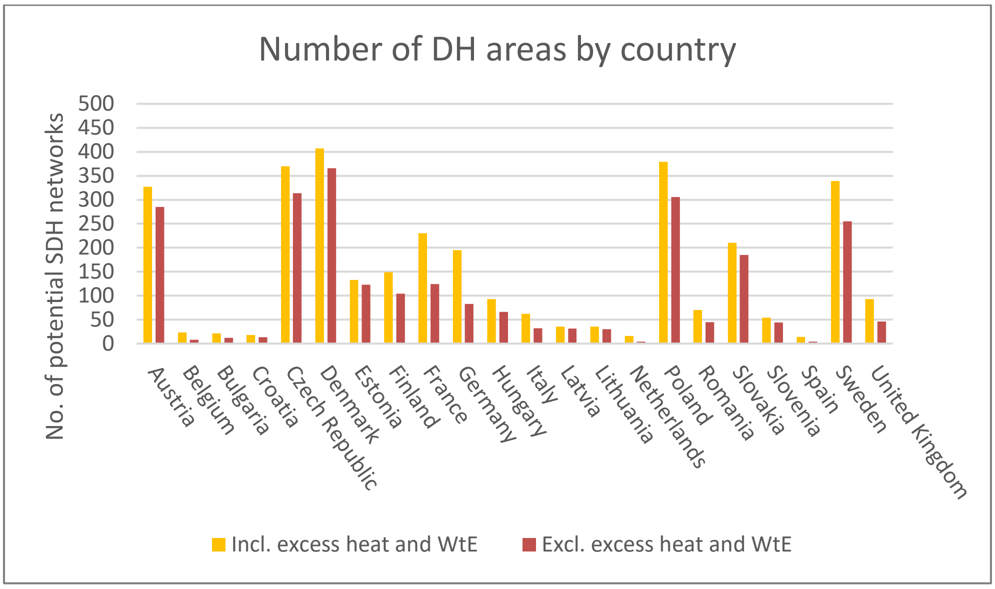


**Figure 40. No. of DH systems before and after the filtering of networks close to WtE/excess heat options. The red ones are included in the further analysis.**

***Disqualifying DH with nearby WtE or excess heat means that most big cities and the majority of existing DH demand are omitted from the further analysis***

Three main points can be highlighted from this part of the analysis:

- Mainly smaller DH networks do not have excess heat/WtE nearby.
- Denmark has the highest number of DH plants, but it is followed closely by Poland, Czech Rep., Austria and Sweden. Most of these could consider SDH.
- Larger DH utilities should investigate excess heat first, but could consider SDH
    - to supplement the excess heat source (depending on available quantities, supply and demand profile, and storage options)
    - to expand their network and cover a larger area
    - to avoid relying on the excess heat source (e.g. an industry which may be shut down in the coming years)

### 4.1.2 Required Land Area vs. Suitable Land Area

For the DH systems included in the candidate list, the analysis on the availability of land areas within 200 m (or 1,000 m) shows that the majority of DH networks has the opportunity for find land for the collector field nearby.

The land area required to reach a SF of 20 % in each country corresponds 100 % Figure 41. The figure shows the share of this area which in the spatial analysis was indicated as suitable for SDH (based on the preconditions described in section 3.2.5).

The share ranges between 87 % and 100 %. The lowest share characterises Finland, which has large forestry areas (compared to for example Denmark), which are not considered suitable land area in the analysis.

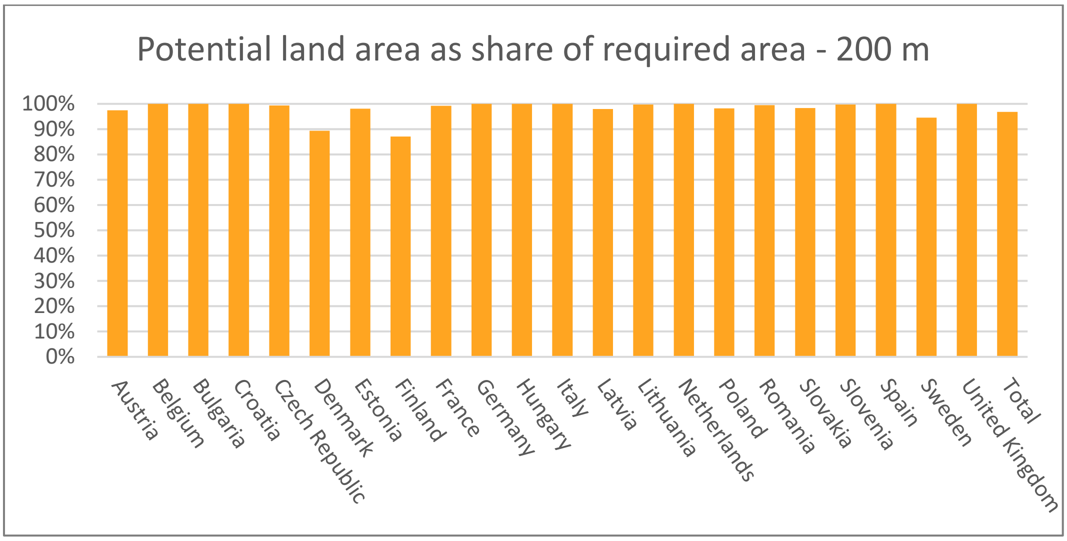


**Figure 41. Indication of how the potential is slightly diminished due to limited suitable areas within a distance of 200 m (aiming at 20 % SF).**

Figure 42 shows the same type of data as Figure 41, but with a transmission line of 1,000 m. It is seen that 100 % of the required area is found for almost all countries.

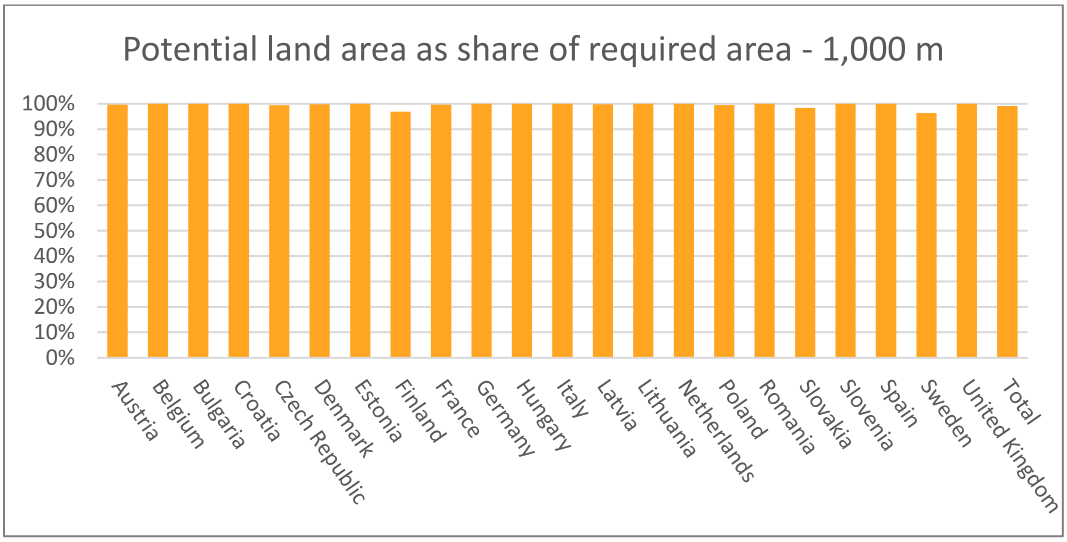


**Figure 42. Indication of how the potential is slightly diminished due to limited suitable areas within a distance of 1,000 m (aiming at 20 % SF).**

Table 4 summarises the land availability of suitable land for all investigated countries described for each scenario (targeting 20 % and 40 % SF respectively at distances of 200 m and 1,000 m from the DH network).

Although some of these areas may be unusable, the results indicate that for the individual DH networks it may be possible to locate several different options for a collector field location. As the change from 200 to 1,000 m distance from the DH network does not represent a major increase in the identified gross potentials[22], the 200 m distance seems to be sufficient for most of the investigated systems to find suitable areas. Therefore, the further analysis focuses on the 200 m distance for the investigated SDH plants. Where

[22] The term "gross potentials" reflect that the analysis of the feasibility is not included here.

nothing else is mentioned, the presented results refer to a 200 m transmission line scenario and a target of 20 % SF.

**Table 4: The remaining potential SDH systems based on the GIS analysis of available suitable land.**

| | ***Number of potential SDH networks*** | | ***Area enough to deliver targeted SF*** | |
|---|---|---|---|---|
| *Transmission line length →* | *200 m* | *1,000 m* | *200 m* | *1,000 m* |
| *20 % SF target* | *2376 (96%)* | *2414 (97%)* | *97 % of aim* | *99 % of aim* |
| *40 % SF target* | *2351 (95%)* | *2408 (97%)* | *95 % of aim* | *99 % of aim* |

An average of the ratio between suitable land area and required area for each DH network reveals ratios of 74 and 184 for 40 % and 20 % SF target respectively. This indicates that in most cases it should be possible to locate enough suitable area for a targeted SF – even if some of the identified suitable area would in practice not be available for some reason.

***The availability of suitable land is in general not a significant limiting factor when it comes to the potential for the investigated DH networks***

Figure 43 shows a summary by country of the suitable land areas required to reach a SF of 20 % in each individual DH network.

For example, it is seen that the many DH networks in Poland result in a large cumulated area, which could potentially be used to install solar collector fields.

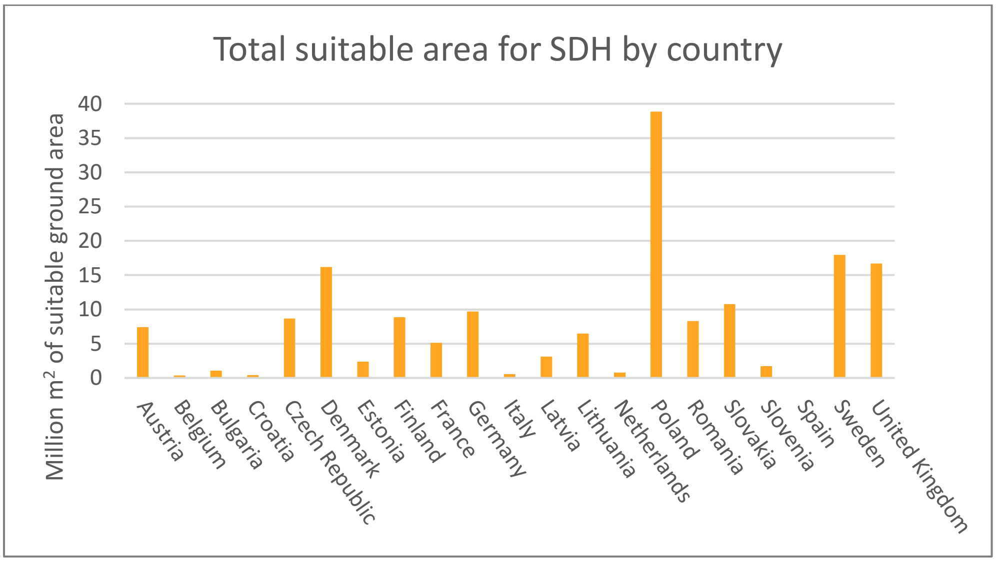


**Figure 43. Accumulated suitable and required ground area for collector fields by country. The areas are identified to be both required to target 20 % SF of the DH networks and suitable when considering land use.**

The technical and even economical potential for SDH is significantly higher than what is identified by this analysis, because some DH areas are excluded, even if they may not utilise the available excess heat sources located nearby. Additionally, the assumption of 0.2-1.0 km as the maximum distance between solar collector field and DH network may exclude several towns/cities, where a longer transmission pipe could be still feasible. However, in most cases the results show that a distance of 200 m from the town perimeter is sufficient and that the availability of suitable land areas is not a limiting factor in most cases. It should be noted that the actual possibility of purchasing/renting the identified land areas has not been verified. This availability is likely to be subject to political prioritisation, owners' personal plans and general demand for the given land type/location. As previously mentioned, the aim of the study is to identify possible SDH solutions and not to provide a complete technical potential covering all aspects and hypothetic possibilities for SDH.

Figure 44 shows the distribution of land use classes of the identified potential SDH areas (weighted average of all suitable areas). It is seen that most of the identified land suited for SDH is in CLC 12, which refers to "non-irrigated arable land".

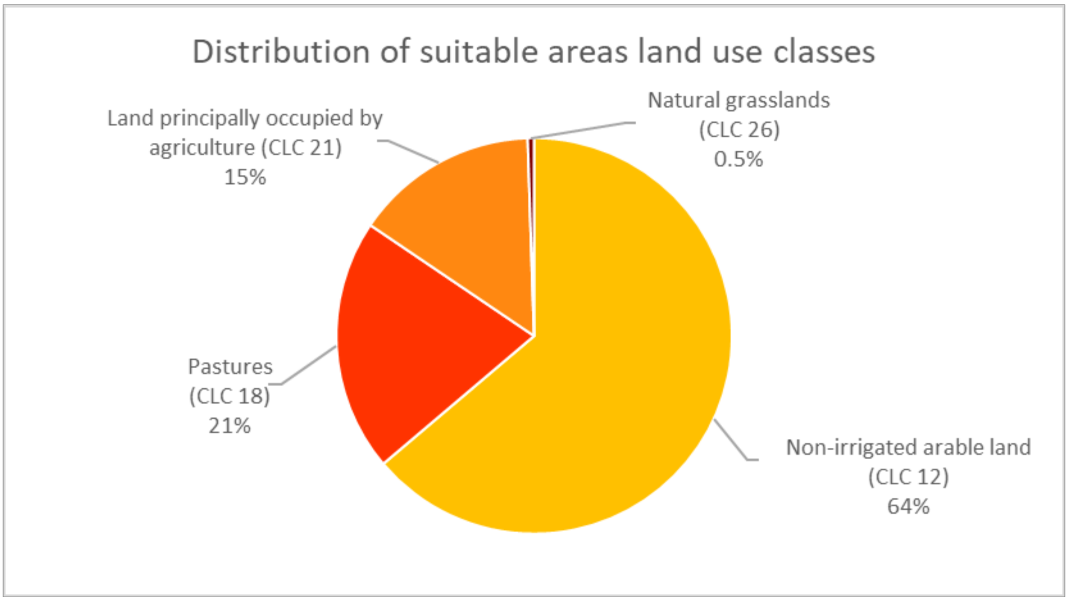


**Figure 44. Distribution of the land use classes for the identified total suitable areas for SDH.**

### 4.1.3 Land Use Considerations

Land is a resource itself. It is important to consider how to use it in the most appropriate way. With an urgent need to speed up the green transition of the energy sector [26], the focus is often turned toward biomass. However, when analysing future energy system alternatives, it is important to consider what the end goal is, and which pathways can lead there. While some countries may appear to have plenty of biomass, this could be/become a scarce resource [27], when considering the demand that a strongly decarbonised future would entail. Hence, there is an incentive to save fuels (in general) and cover the demand with an abundant energy source such as solar energy. Besides, the energy output per square meter of land is higher for solar thermal than for biomass.

## 4.2 Feasibility of SDH

### 4.2.1 Cost Distribution of SDH

Figure 45 shows the share of each cost category. This is based on the individual calculation for each of the DH networks, based on the assumptions described in section 3.3. It is seen that the collector field represents by far the main investment. The storage represents around 1/10 of the total cost, when targeting a SF of 20 %. Land costs and transmission line (200 m) represent minor shares of the total investment.

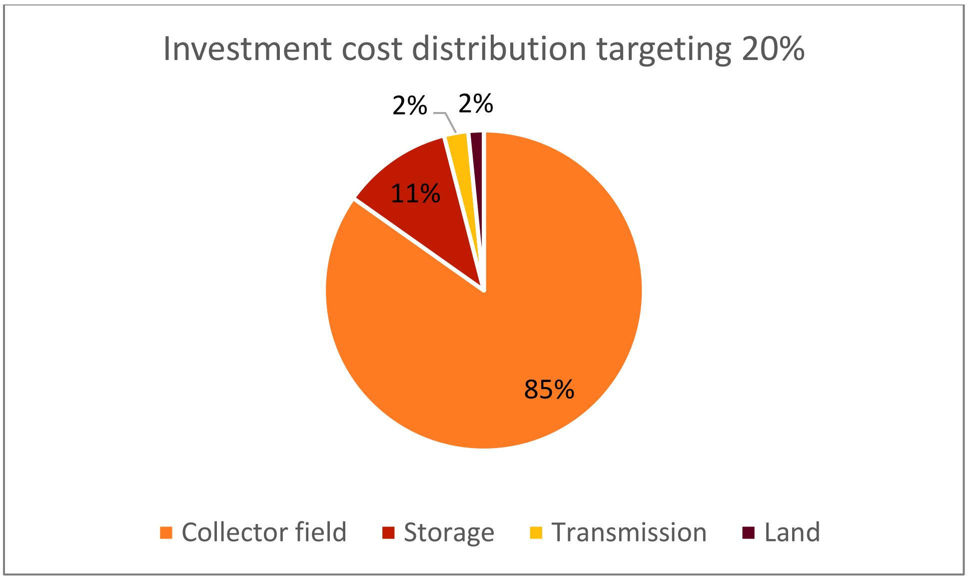


**Figure 45. Average cost distribution for the identified SDH potentials targeting a SF of 20 %, i.e. comparing the different cost categories.**

A similar cost distribution is found for SDH networks targeting 40 % SF (Figure 46).

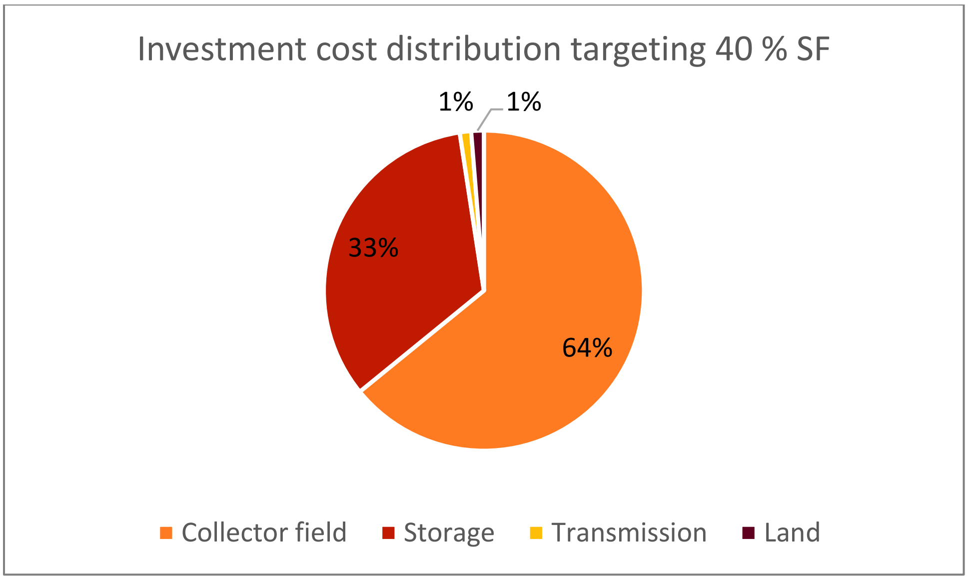


**Figure 46. Average cost distribution for the identified SDH potentials targeting a SF of 40 %.**

Comparing the two diagrams with the corresponding ones for a 1,000 m transmission line (see Annex III – Average cost distribution for the identified SDH potentials at 1,000 m), it is seen that in the latter cases the transmission costs represent 11 % and 5 % of the total cost for 20 % and 40 % SF respectively (mainly subtracted from the Collector field cost shares).

The calculated solar heat costs for all the DH networks of all countries are shown in Figure 47 as function of the DH heat demand. A detail of the diagram, focusing on the systems with the lower DH heat demands, is found in Annex IV – Solar Heat Cost of Each Identified Potential SDH System.

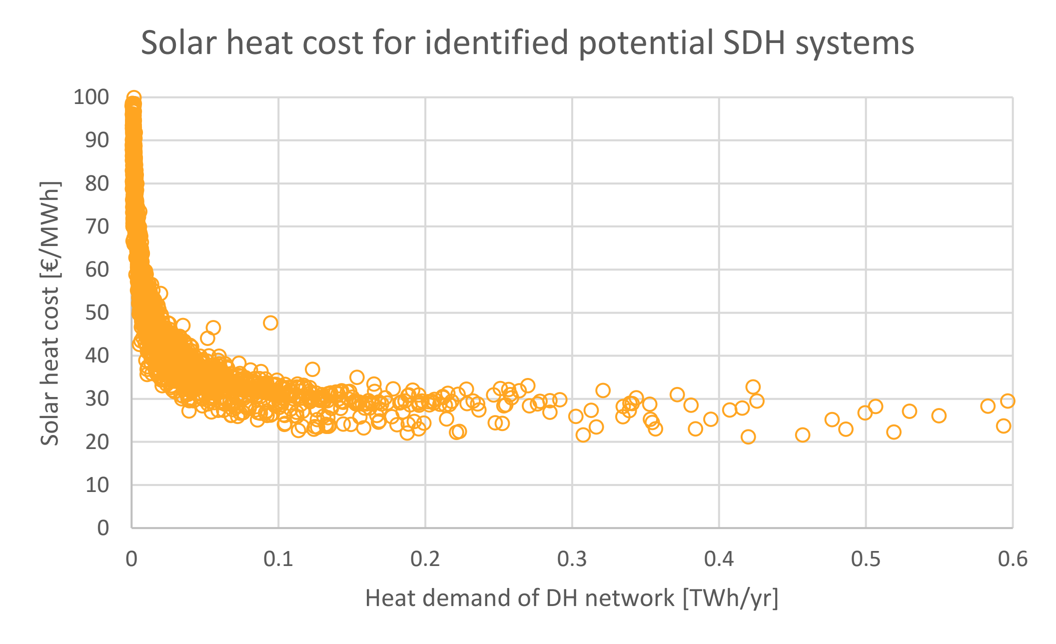


**Figure 47. Calculated solar heat cost of each of the identified potential SDH systems included in SDHEP1 (with a 20 % SF target).**

### 4.2.2 Overall Feasibility Analysis Results

The purpose of the feasibility analysis is to follow up on the "gross potentials" identified previously (based on area availability), by raising the question which of these SDH systems (or rather solar heat quantities) would be possible to realise at a reasonable price level.

The answer is presented as plots showing how much of the identified potential is left out due to too high solar heat price. This is done by raising the limit (maximum heat price) in steps and showing how the identified potential increases. Conversely, as the limit is lowered, more and more SDH systems are excluded, thus reducing the total solar heat potential. A summary of the results for all investigated potential SDH systems is given in Figure 48. The figure shows the share of the potential as function of the upper limit of the solar heat cost. It can be seen that most of the identified potential (> 90 %) for a SF target of 20 % can be implemented without exceeding a solar heat cost of 40 €/MWh.

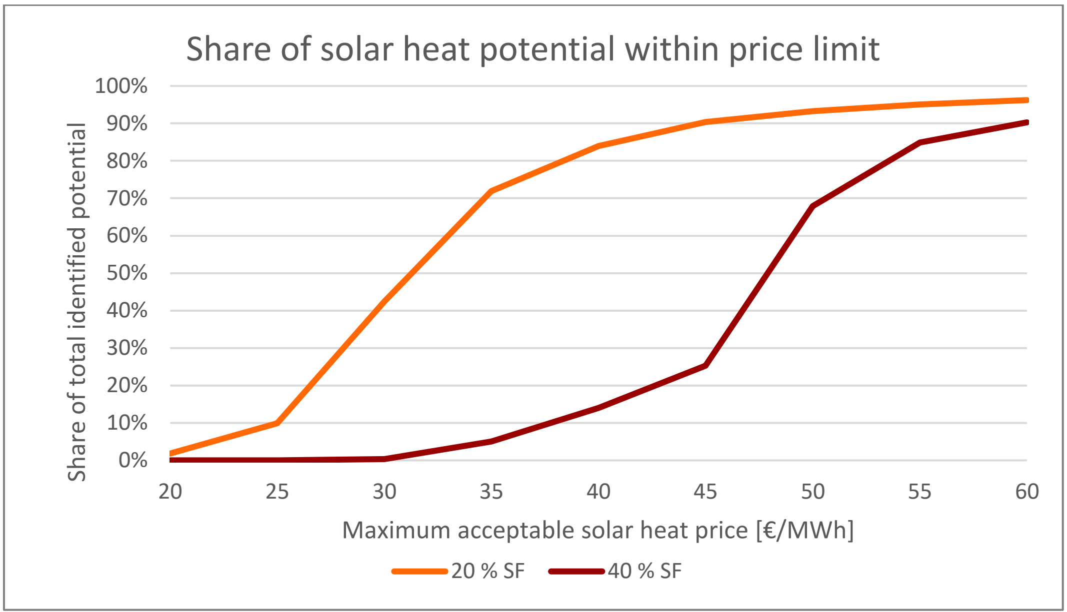


**Figure 48. Setting a maximum price for the solar heat price reduces the identified potential. The figure shows, for increasing price limits, the share of the total identified solar heat production potential which can be realised within the given upper price limit (horizontal axis).**

Figure 49 shows the cumulated identified potential of solar heat production. It is seen that the curve referring to 20 % SF target does not exceed 20,000 GWh/yr. This indicates that almost the entire identified potential can be realised with a solar heat cost in the range 20-50 €/MWh. For a SF of 40 %, it is not possible to achieve the entire identified potential for a solar heat cost lower than 60 €/MWh. The same can be seen in Figure 48 where the 40 % SF curve only reaches approximately 85 % at 60 €/MWh.

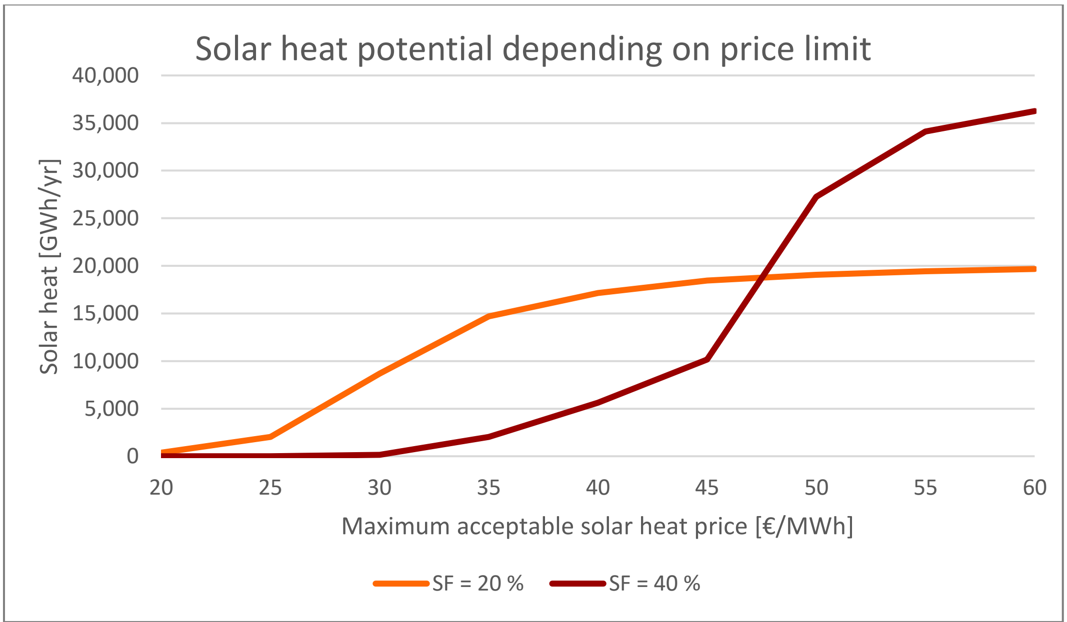


**Figure 49. Identified solar heat production potential targeting 20 % and 40 % SF respectively depending on solar heat price limit.**

A figure similar to Figure 49, but including the corresponding curves for a transmission line of 1,000 m is seen in Annex V – Solar Heat Potential Depending on Solar Heat Price

Limit and SF. This shows the impact in the case that available land is found farther away than 200 m from the town perimeter or the connection pipes to the main DH network are longer than 200 m. Note that the distance and associated costs are fixed, although there may be available land at a distance shorter than the 200 m/1,000 m assumed.

Figure 49 shows that the curves cross at a maximum solar heat cost of 47-48 €/MWh, which indicates that with this given limit a similar identified solar heat potential could be achieved in two different ways. However, the figure does not show that the total costs of these two pathways will be different, as there would be more low-cost SDH opportunities for the SF target of 20 %. Figure 50 shows the average solar heat cost of the systems included for each step in heat price limit. Focusing for example at 48 €/MWh on the horizontal axis of Figure 50, it is seen that the average heat price for a 20 % SF is lower than that for a 40 %. Since the identified solar heat quantities are similar (as seen in Figure 49), the 20 % SF option for achieving this solar heat production (approx. 19,000 GWh per year) is cheaper. However, for larger SF targets, combinations should/could be pursued.

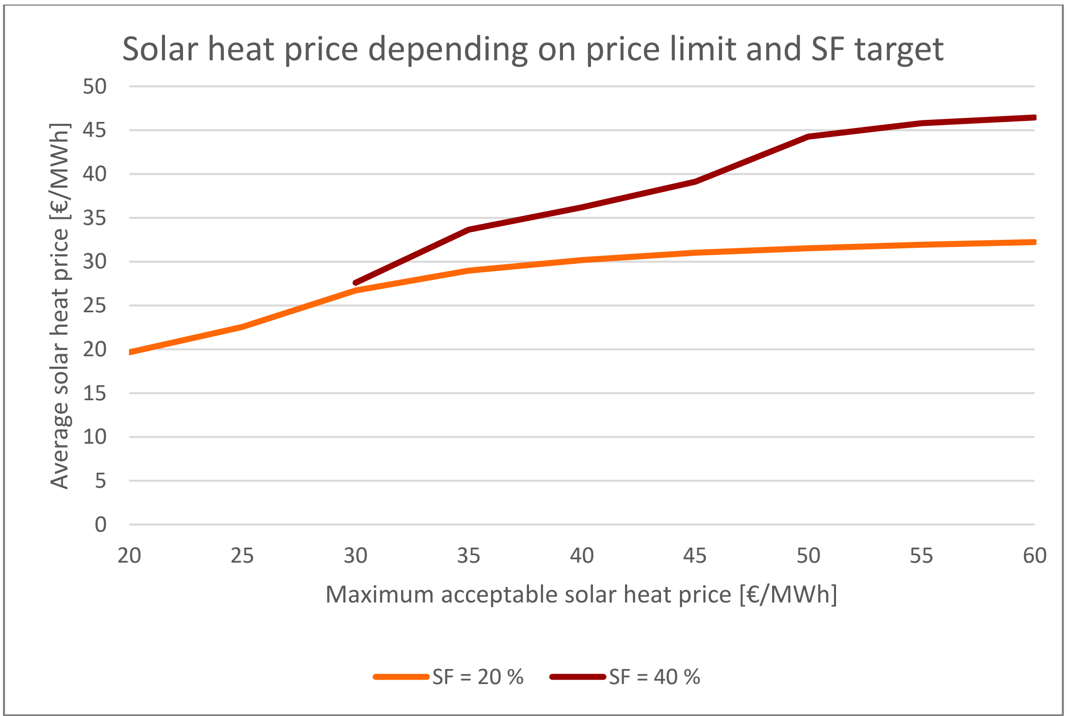


**Figure 50. Average solar heat cost of the systems included up to a given heat price limit (primary axis).**

Figure 51 represents the solar collector area required to reach the solar heat production of Figure 49.

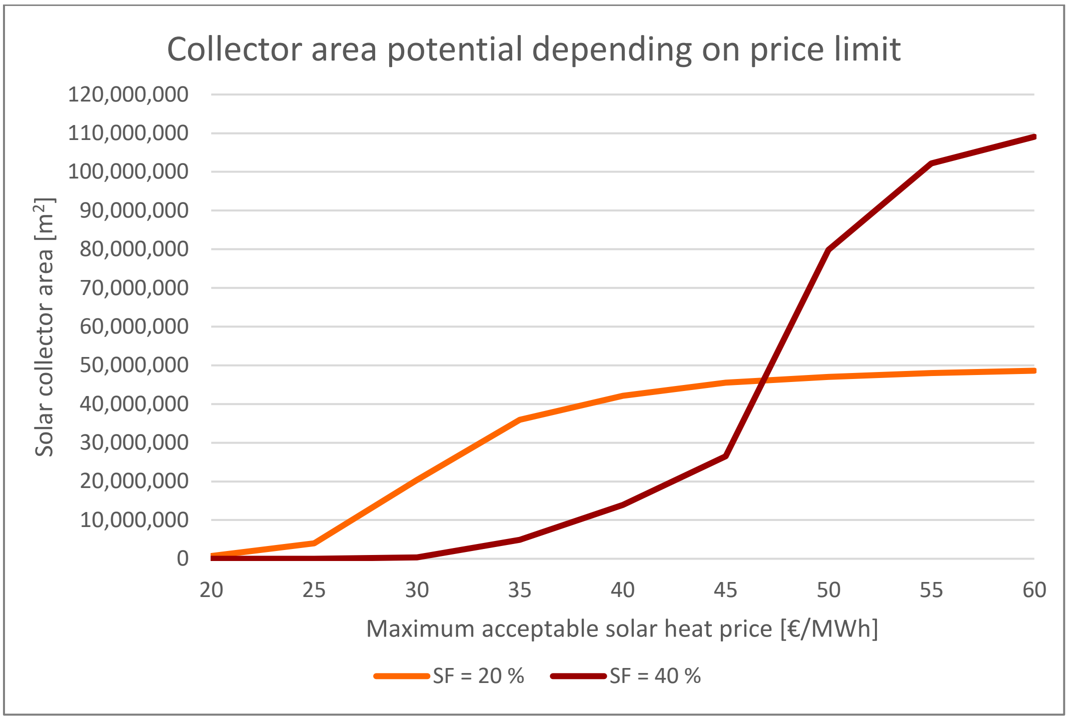


**Figure 51. Identified solar collector gross area potential depending on solar heat price limit.**

This indicates that there is a significant potential for low-cost SDH, even though this analysis only investigates part of the technical potential.

### 4.2.3 Country-Specific Feasibility Analysis

The estimated solar heat cost of each SDH system in each of the investigated countries is plotted as function of the annual DH heat demand in Annex VI – Solar Heat Cost vs. DH Demand by Country.

The identified potentials targeting 20 % SF can be seen for each country in Figure 52, assuming an upper limit for acceptable solar heat cost of 50 €/MWh. Especially in Poland there seem to be a significant potential for SDH (in terms of quantities). However, current legislative restrictions in Poland can prove a barrier for this by limiting the opportunity to utilise land with high soil quality for other purposes than agricultural.

Similar diagrams are found in Annex VII – Identified potential solar heat production for a limit of 30 and 40 €/MWh. Although Denmark is in the upper end of the scale, there does not seem to be spatial and economic reasons why other countries could not also see a development of large-scale SDH.

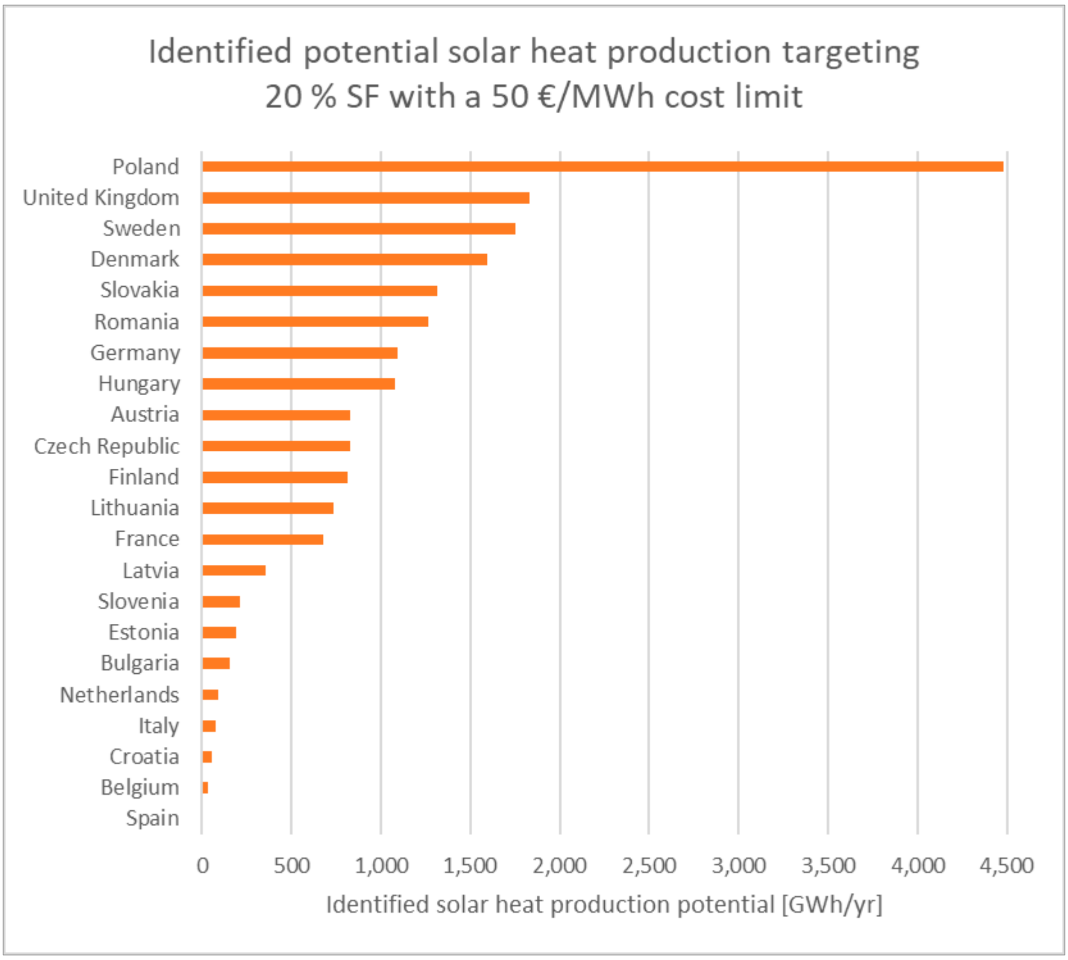


**Figure 52. Potential annual solar heat production per country for a maximum solar heat cost of 50 €/MWh.**

The influence of the solar heat cost limit on the potential of SDH can be seen for each country in Figure 53. The results show that for most countries the majority of the identified potentials are estimated to be possible to establish at costs as low as 35 € per MWh of solar heat.

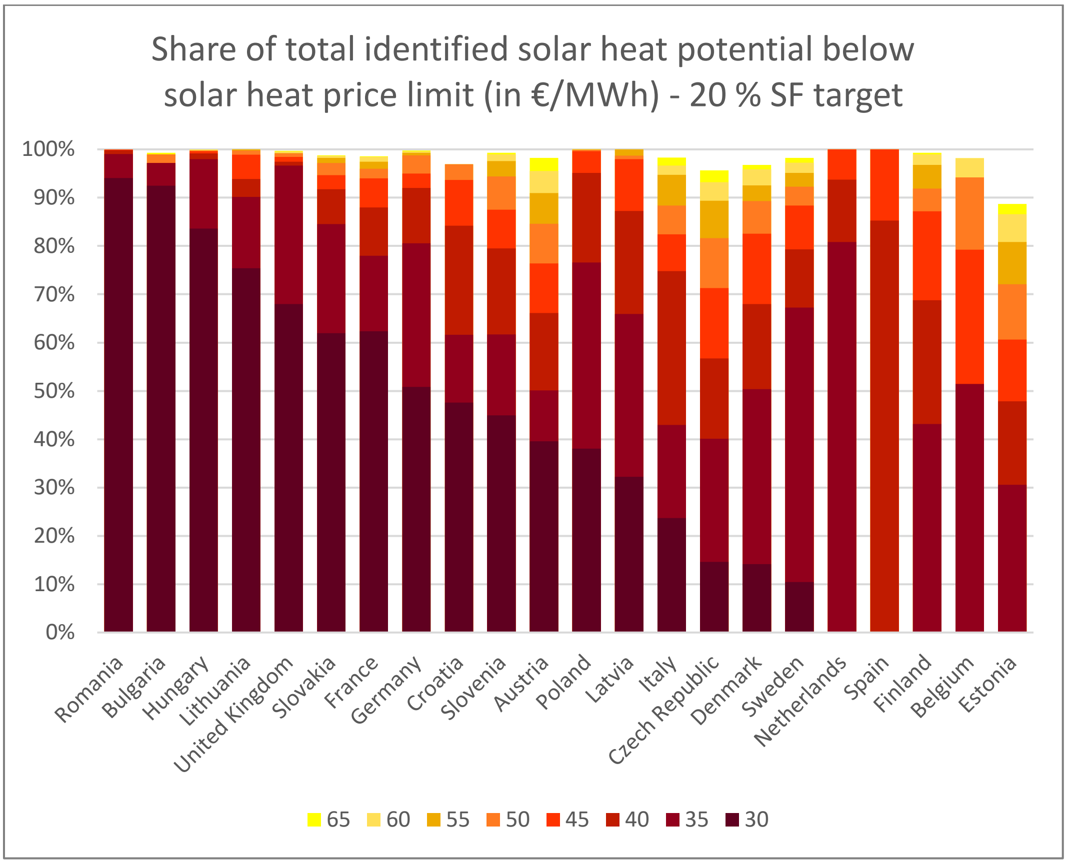


**Figure 53. Share of total identified solar heat potential depending on maximum solar heat price (legend in €/MWh) for the analysis targeting 20 % SF.**

A diagram similar to Figure 53 in a larger version and another for 40 % SF are found in Annex VIII – Share of Total Solar Heat Potential Depending on Price. The same annex also contains similar diagrams assuming a transmission line length of 1,000 m.

Similar to Figure 52, which represents only one solar heat cost limit, the diagrams in Annex IX – Identified SDH Potentials by Country and Price Limit show the influence of the solar heat cost limit on the identified potentials for each country. Two examples are shown in Figure 54 representing the case of Romania and Sweden targeting 20 % SF. It is seen that for Romania most of the potential can be obtained as low-cost solar heat (similar to what is indicated in the far-left column in Figure 53). The fact that the potential does not increase for increasing solar heat cost limits indicates that there are no more opportunities to exploit SDH, even if there was the willingness to pay more. Conversely, Sweden has a low potential for solar heat cost limits lower than 35 €/MWh, while the potential increases and becomes even larger than for Romania if the cost limit is higher.

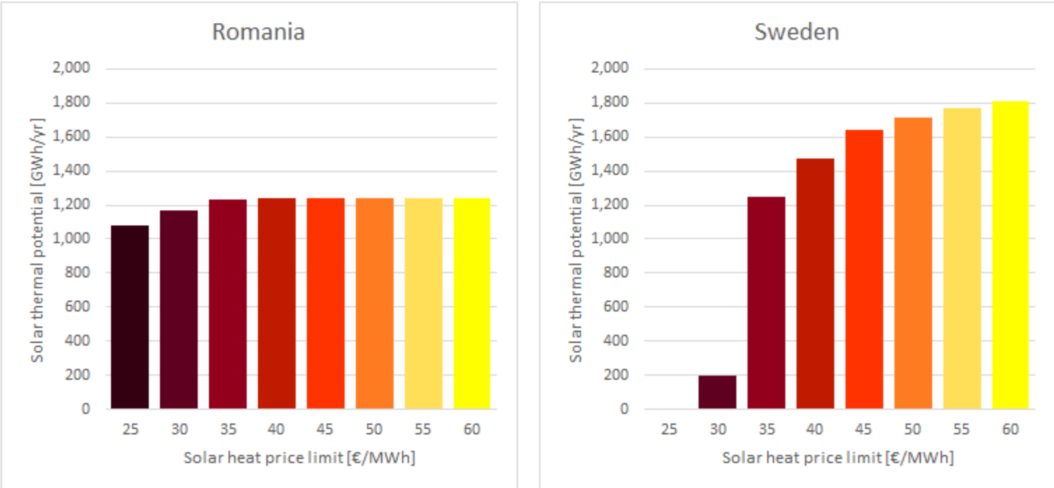


**Figure 54. Examples of identified solar heat potentials targeting a SF of 20 %.**

## 4.3 Sensitivity Analysis

### 4.3.1 Solar Collector Yield per Square Meter

To assess the impact of conversion coefficient $c_{hor\text{-}to\text{-}yield}$ (ratio between the solar heat production per square meter of collector and the solar radiation on a horizontal surface), this coefficient is varied and given the values of -20 %, -10 %, +10 % and +20 %. The results of this analysis are presented in Figure 55 for a SF target of 20 %.

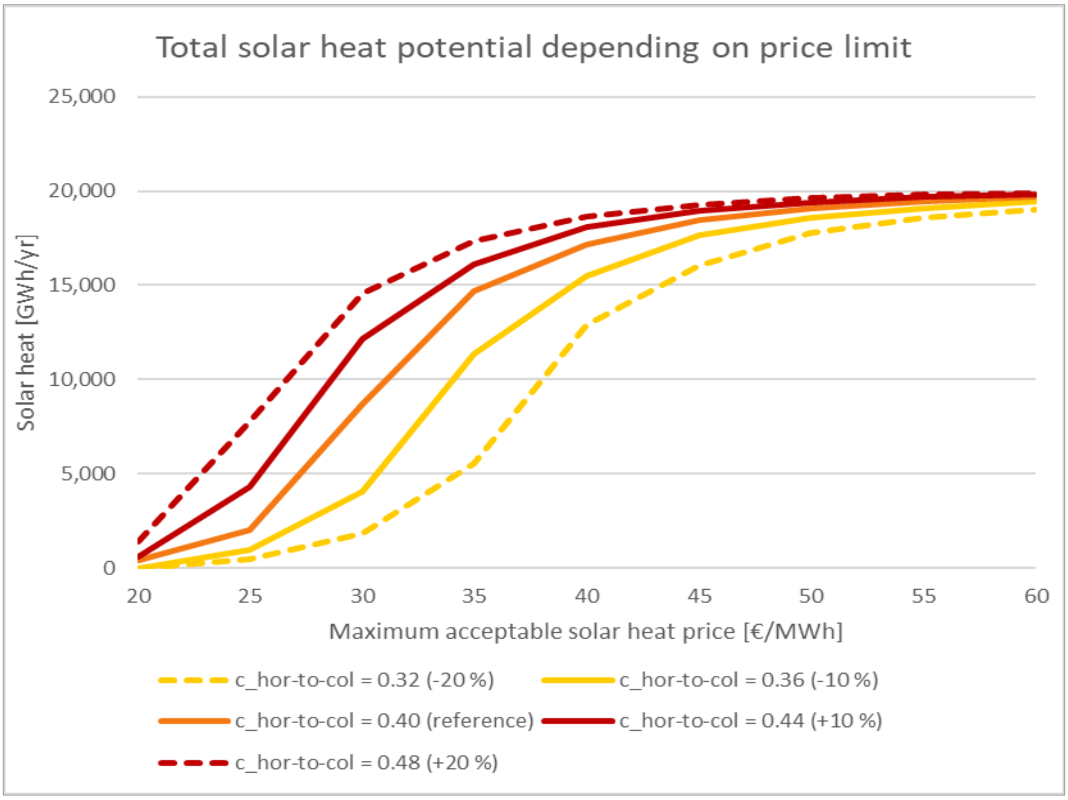


**Figure 55. Total identified solar heat production potential depending on solar heat price limit for various conversion factors for the estimation of the collector yield.**

### 4.3.2 Cost Assumptions

To assess the effect of the investment cost on the solar heat price, a sensitivity analysis is carried out and its results are shown in Figure 56 and Figure 57 for 20 % and 40 % SF respectively.

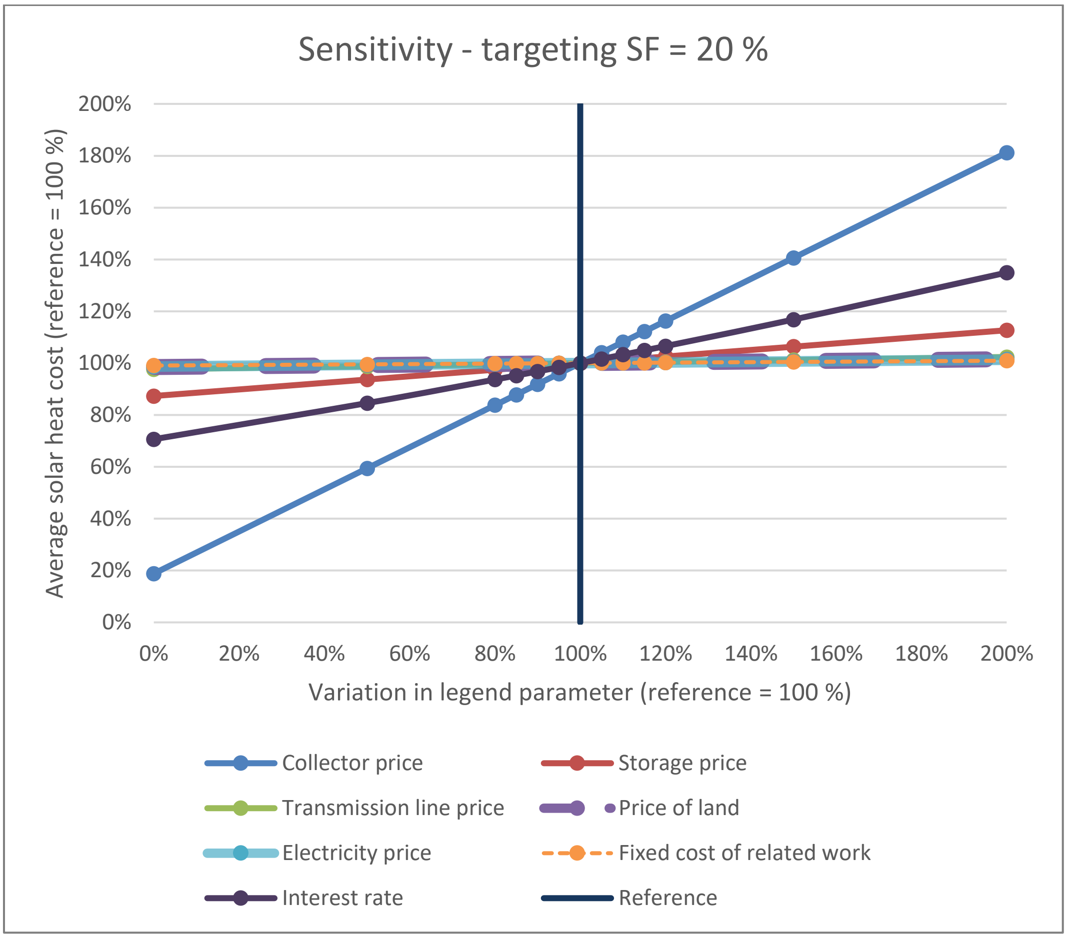


**Figure 56. Sensitivity of overall average solar heat cost for various parametric changes in the analysis targeting 20 % SF. Transmission line is hidden behind the other lines lying around 100 %.**

It is seen that the collector field cost has the stronger impact on the solar heat price. Another key parameter is the interest rate, which highlights the importance of having good financing options to achieve economically feasible SDH. Transmission line, electricity price, cost of land and "related work" (other costs) have a minor impact (transmission line is hidden behind the other lines lying around 100 %). This trend is also seen for the 40 % SF target in Figure 57.

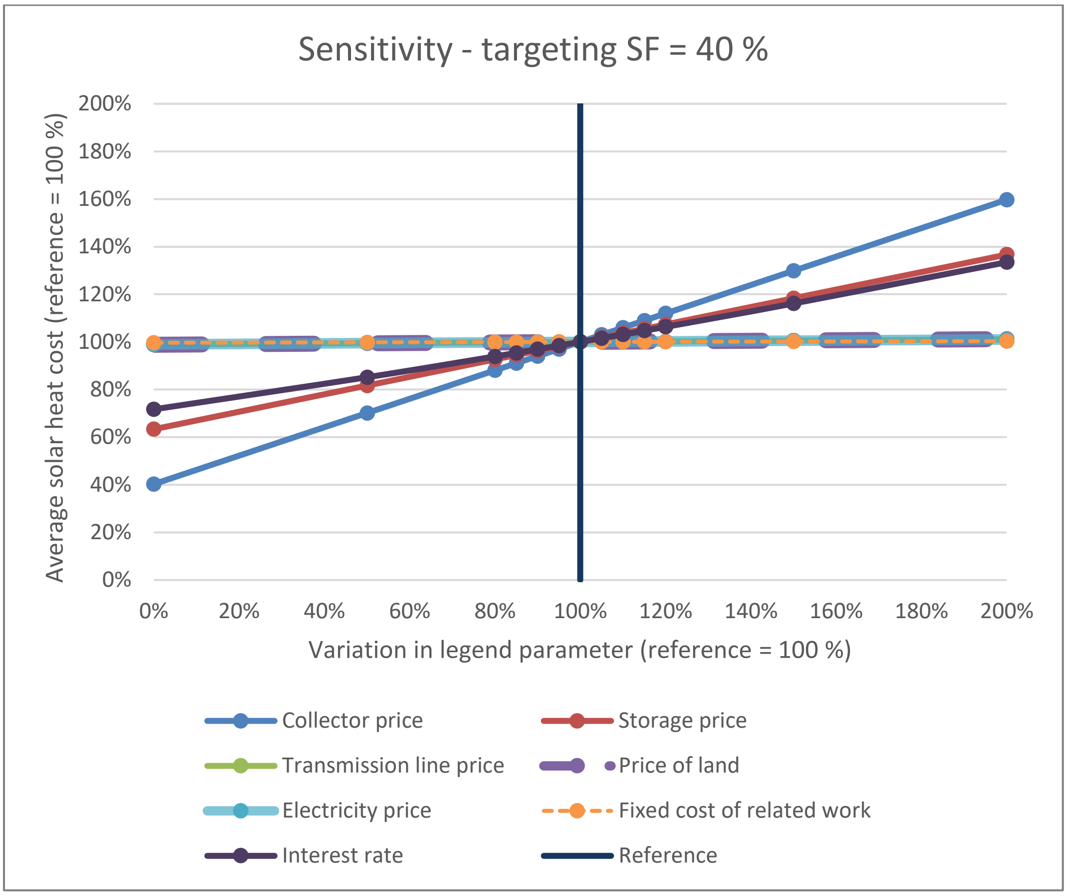


**Figure 57. Sensitivity of overall average solar heat cost for various parametric changes in the analysis targeting 40 % SF.**

For the larger SF, the impact of the storage investment is more important. It should be noted, however, that in the analysis the storages are not expected to be used for other purposes while in practice they could potentially improve the overall DH system performance (depending on the associated DH system).

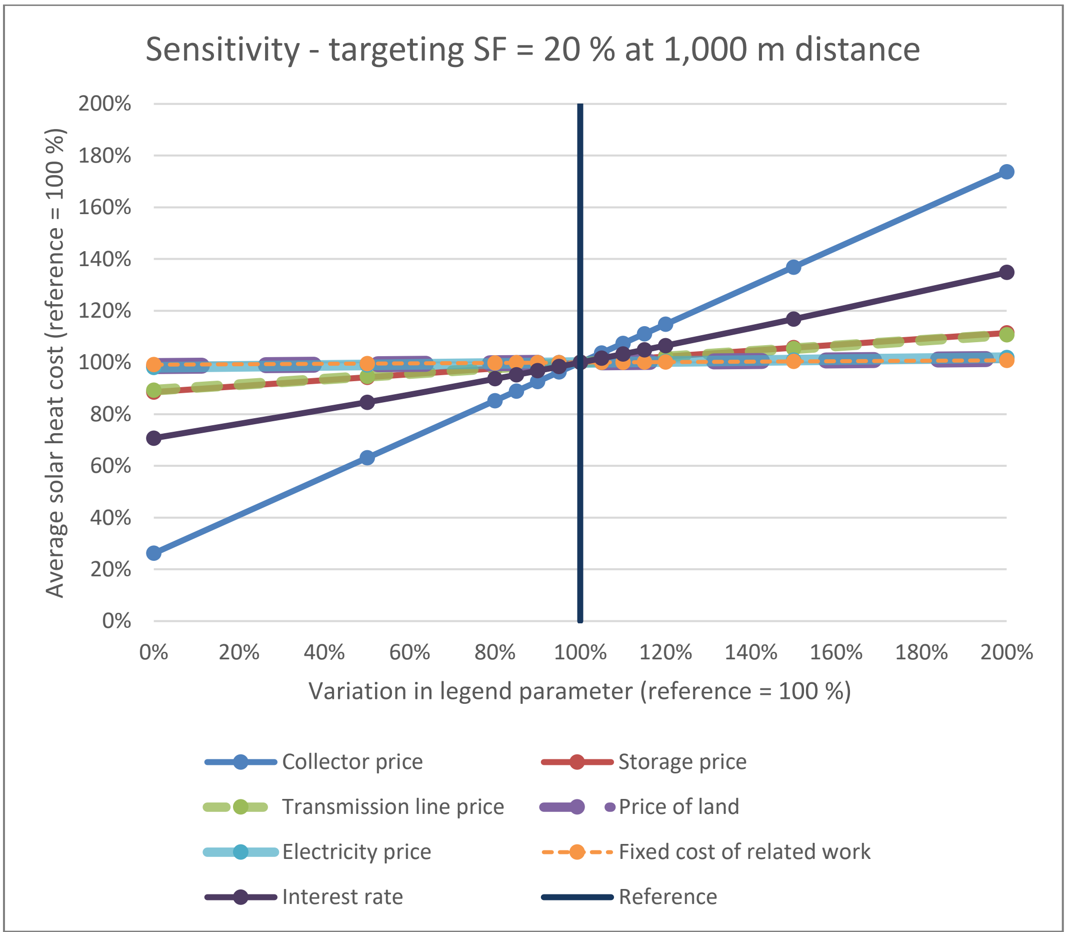


**Figure 58. Sensitivity of overall average solar heat cost for various parametric changes in the analysis targeting 20 % SF with a transmission line length of 1,000 m.**

For the corresponding sensitivity analysis applied for 20 % SF with a transmission line of 1,000 m, the curve referring to "Transmission line" overlaps with the curve referring to "Storage". Regarding the uncertainties about the land cost mentioned in section 3.3.4, it is seen that the land cost has anyway a lower impact than the length of the transmission line.

To illustrate the impact of the collector field cost assumptions on the identified solar heat potentials for a certain maximum solar heat cost, the collector field investment cost has been varied between -50 % and +50 % for both the 20 % and 40 % SF targets[23]. The results are shown in Figure 59 and Figure 60 respectively. In case the SDH systems could be located close to the DH plant with a suitable (short term) storage already in place[24], the investment cost reductions would lie between the Reference and -25 % curves in Figure 59.

[23] Using 200 m as transmission line length.

[24] Though these points are not used as assumptions in SDHEP1, this is often the case in the Danish systems.

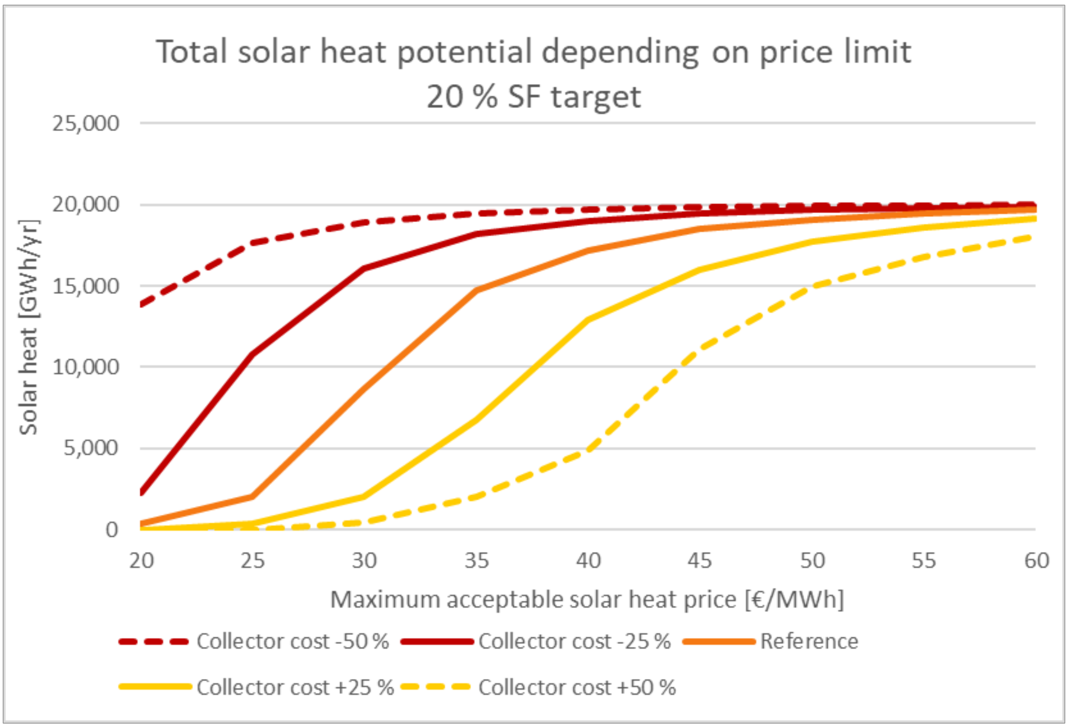


**Figure 59. Total solar heat potential as function of the solar heat price limit for the 20 % SF target.**

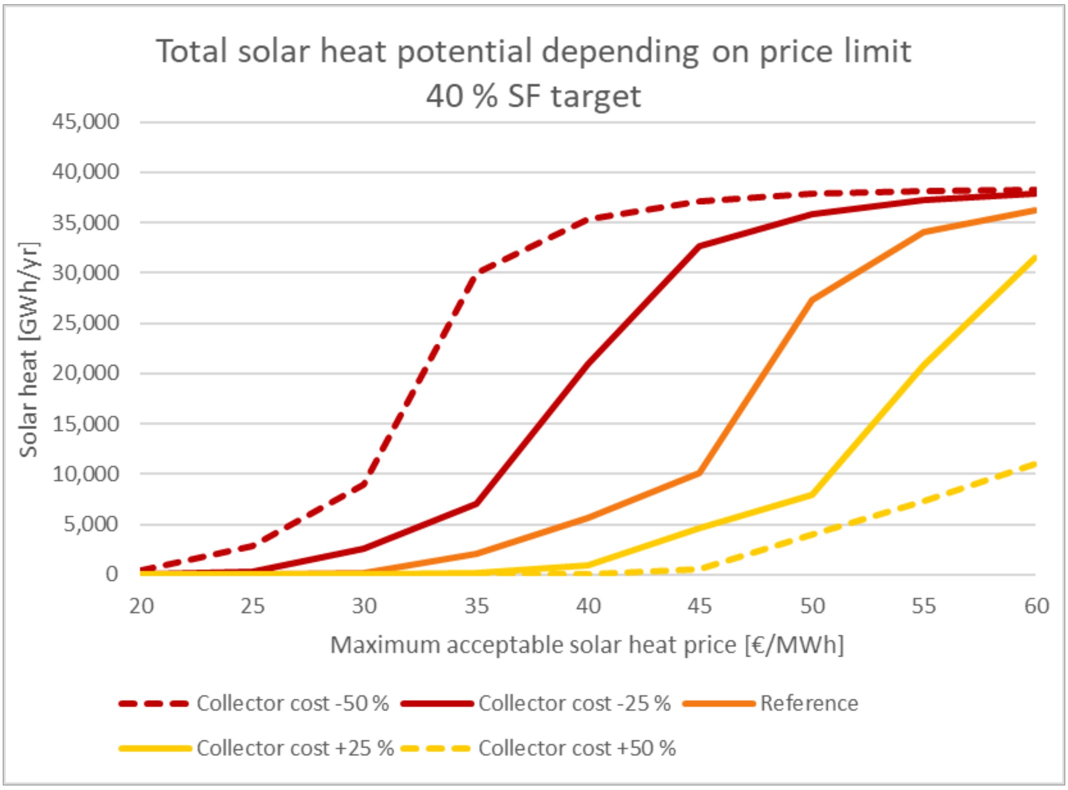


**Figure 60. Total solar heat potential as function of the solar heat price limit for the 40 % SF target.**

## 4.4 Estimation on $CO_2$ Reduction Potentials

To give a rough estimation of the $CO_2$ reduction potential which could be achieved through the implementation of SDH, a calculation is carried out assuming that solar heat production reduces the use of natural gas in natural gas boilers, and that all the SDH systems in the analysis with an estimated solar heat cost no higher than 50 €/MWh are realised.

The gas boiler operation is assumed to have a 100 % efficiency, a heating value of 11 $kWh/Nm^3$ and $CO_2$ emissions corresponding to 2.3 kg $CO_2/Nm^3$.

The resulting total $CO_2$ reduction potentials under these assumptions are between 100 and 180 million tonnes of $CO_2$ over the 25-year lifetime of the SDH systems (representing the analysis targeting 20 % and 40 % SF respectively).

In practice what is replaced would be a mix of fuels. In this perspective the emissions from $CO_2$ neutral fuels (biomass) could be a topic for further investigation and discussion, when considering global $CO_2$ targets. Arguments for replacing carbon neutral fuels (biomass) could also be limited biomass resources and/or emissions of local particles and of $NO_x$. Another argument for combining solar and biomass-based DH can be the possibility for maintenance of the biomass boilers during the summer, when the solar collectors can cover the entire demand.

# 5 Conclusion and Recommendations

Referring to the questions raised in the introduction regarding the characteristics of the Danish SDH systems and if it would be possible to see a similar development in other countries, the following conclusions can be drawn:

The analysis reveals widespread possibilities for the deployment of large-scale SDH by using agricultural land for the collector fields and supplying the heat by means of a transmission line to the nearby town. Suitable land areas in the vicinity of the investigated towns are available in most cases and within a reasonable distance.

***The analysis indicates that a roll-out of large-scale SDH is possible and economically feasible in most countries – there seem to be plenty of space***

The resulting costs of the SDH systems, including transmission line, land and storage, show that this solution could be realised in a feasible way in most of the investigated DH networks. The economy of scale of the collector fields in general outweigh the additional costs to connect the collector field to the network, thus resulting in a reasonable solar heat price. Low interest rates (combined with accepting long-term payback times) have however also a key importance for the feasibility. At the same time, diminishing any favourable conditions for fossil fuel-based supply can represent an indirect incentive to convert to renewable energy sources and thereby improve the feasibility of replacing larger shares of fossil fuel-based DH supply with solar heat. Besides this, organised sharing of experiences can ensure that the SDH technology becomes widely known, mistakes are avoided, and the system performances are optimised.

***Sizing up the solar collector field can be an effective way to reach a low cost per m$^2$ of collector, which is key to achieve feasible SDH***

While the Danish conditions have resulted in a significant development in the market for large-scale SDH, the analysis indicate that the typical SDH system is so far applied only to smaller towns. To continue a development towards increasingly larger SDH systems, new configurations of using storages for multiple purposes (heat sources) besides solar heat could show the way for cost-effective SDH also for larger cities. In these cases, the transmission lines could potentially be longer than those identified in this SDHEP1 analysis.

***Before ruling out SDH due to space limitations, consider locations for the collector field further away than usually thought to be relevant***

It should be noted that the analysis does not represent the full technical potential for SDH. The assumption of excluding DH networks with or near opportunities of WtE and/or excess heat causes a significant reduction of the potential DH demand which could be covered also partially with solar heat. In fact, 24 % of the DH *networks,* corresponding to 79 % of the DH *demand,* are excluded. Similarly, the analysis does not consider the opportunity of establishing new DH networks, including solar thermal as (partial) heat supply. Hence, the results should not be considered an upper limit for SDH, but rather as identified options to target already now.

***Many options for feasible SDH are identified, which encourages to exploit this potential***

Countries with a limited number of existing DH networks show obviously a low identified potential in the analysis. As DH represents an option to supply heat to districts, towns or cities, SDH can represent a viable option for decarbonising the heating sector for many consumers at the same time. In this way, solar thermal can facilitate the green transition in existing networks or by providing an argument for establishing new DH. In short, SDH can be a good "ambassador" for DH, and DH can be a good argument for establishing large-scale solar thermal systems.

***Expansion of DH could facilitate the deployment of solar thermal in general***

In general, it can be seen from this study, that high SF solutions result in higher solar heat costs compared to lower SFs. However, when aiming at a future renewable energy-based heating sector, fossil fuels should be disregarded, thus forcing a higher ambition level for the share of non-fossil-based heat supply. At the same time, intelligent and more complex combinations of solar thermal, seasonal storages and other heat production units (e.g. including interaction between the heating and electricity sector) can represent an opportunity for economically feasible and fully decarbonised DH systems with high SFs.

***Solar thermal and seasonal storages in intelligent combinations with other production options can improve feasibility of fully decarbonised DH systems***

# 6 Future Perspective

As described above, only the potential for ground mounted large-scale solar thermal systems outside the urban areas are investigated, and only in connection to existing DH systems, leaving out e.g. building integrated solar plants and solar potential related to future DH systems. Further investigations could include one or more of the following points:

- Including DH networks with WtE and/or excess heat available nearby to analyse a broader range of the technical SDH potential.
- Assessing the share of heat which could be covered with excess heat for each DH system to evaluate if there would be uncovered demand, which could be met with solar heat. (This could also form the basis of feasible expansion of the DH network.) The combination could perhaps benefit from the same large-scale storage.
- Including areas which are regarded as potentially feasible future DH areas, e.g. based on the results in the Heat Roadmap Europe project [13].
- Expanding suitable areas to include roofs of existing buildings within the towns.
- Including more details on local boundary conditions, e.g. on legislative framework, cost of alternative heat supply etc.
- Screening of areas in variable distances from the DH network determined by heat demand (i.e. bigger SDH area means potentially longer transmission pipe). This could be considered together with an estimation of the cost of tapping into excess heat sources at various distances.

# 7 Abbreviations

## 7.1 List of Abbreviations

| | |
|---|---|
| CHP | Combined heat and power |
| $CO_2$ | Carbon dioxide |
| CSR | Control, regulation and supervision |
| DH | District heating |
| GIS | Geographical information system |
| HRE | Heat Roadmap Europe |
| IEA SHC | International Energy Agency's Solar Heating and Cooling programme |
| JRC | Joint Research Center |
| LCOH | Levelised cost of heat |
| $NO_x$ | Nitrogen oxides |
| PTES | Pit thermal energy storage |
| SDH | Solar district heating |
| SDHEP1 | Solar district heating – European Potentials analysis version 1 |
| SF | Solar fraction |
| TTES | Tank thermal energy storage |
| WtE | Waste to energy (waste incineration) |
| yr | Year |

## 7.2 Nomenclature Used in Equations

| | |
|---|---|
| $A_c$ | Solar collector gross area |
| $A_{land}$ | Ground area |
| $c_p$ | Specific heat |
| $c_{hor\text{-}to\text{-}yield}$ | Conversion factor to calculate $Q_{solar}$ from on $G_{hor}$ |
| $D_{TL}$ | Diameter of transmission line |
| $f_{discount}$ | Discount compared to the list prices of manufactures |
| $f_{land\text{-}to\text{-}col}$ | Ground area to collector area ratio |
| $G_{hor}$ | Yearly horizontal solar radiation |
| $L_{TL}$ | Length of the transmission line |
| $n_{full,load}$ | Number of full load hours |
| $n_{TL,loss}$ | Number of hours of operation of the transmission line to calculate losses |
| $P_{pump}$ | Pumping power |
| $P_{solar,max}$ | Maximum thermal power output from the solar collector field |
| $Q_{DH}$ | Annual district heating demand |
| $Q_{el,pump}$ | Annual electricity consumption of the transmission line pump |
| $Q_{solar}$ | Annual solar heat production |
| $Q_{stor,hl}$ | Annual heat losses from heat storage related to solar heat |
| $Q_{TL,hl}$ | Annual heat losses from transmission line |
| $T_f$ | Supply temperature of the transmission line |
| $T_{soil}$ | Temperature of the ground surrounding the transmission line |

| | |
|---|---|
| $T_r$ | Return temperature of the transmission line |
| $V$ | Volume of thermal energy storage |
| $\dot{V}$ | Maximum flow rate in the transmission line |
| $\Delta p$ | Pressure drop |
| $\Delta T_f$ | Temperature difference between DH forward temperature and ground temperature |
| $\Delta T_r$ | Temperature difference between DH return temperature and ground temperature |
| $\eta_{pump}$ | Pump efficiency |
| $\rho$ | Density |

# 8 Acknowledgement

The Danish participation in the IEA SHC Task 52, Solar Heat and Energy Economics in Urban Environments was supported by the Energy Technology Development and Demonstration Program of the Danish Energy Agency under grant number 64013-0533.

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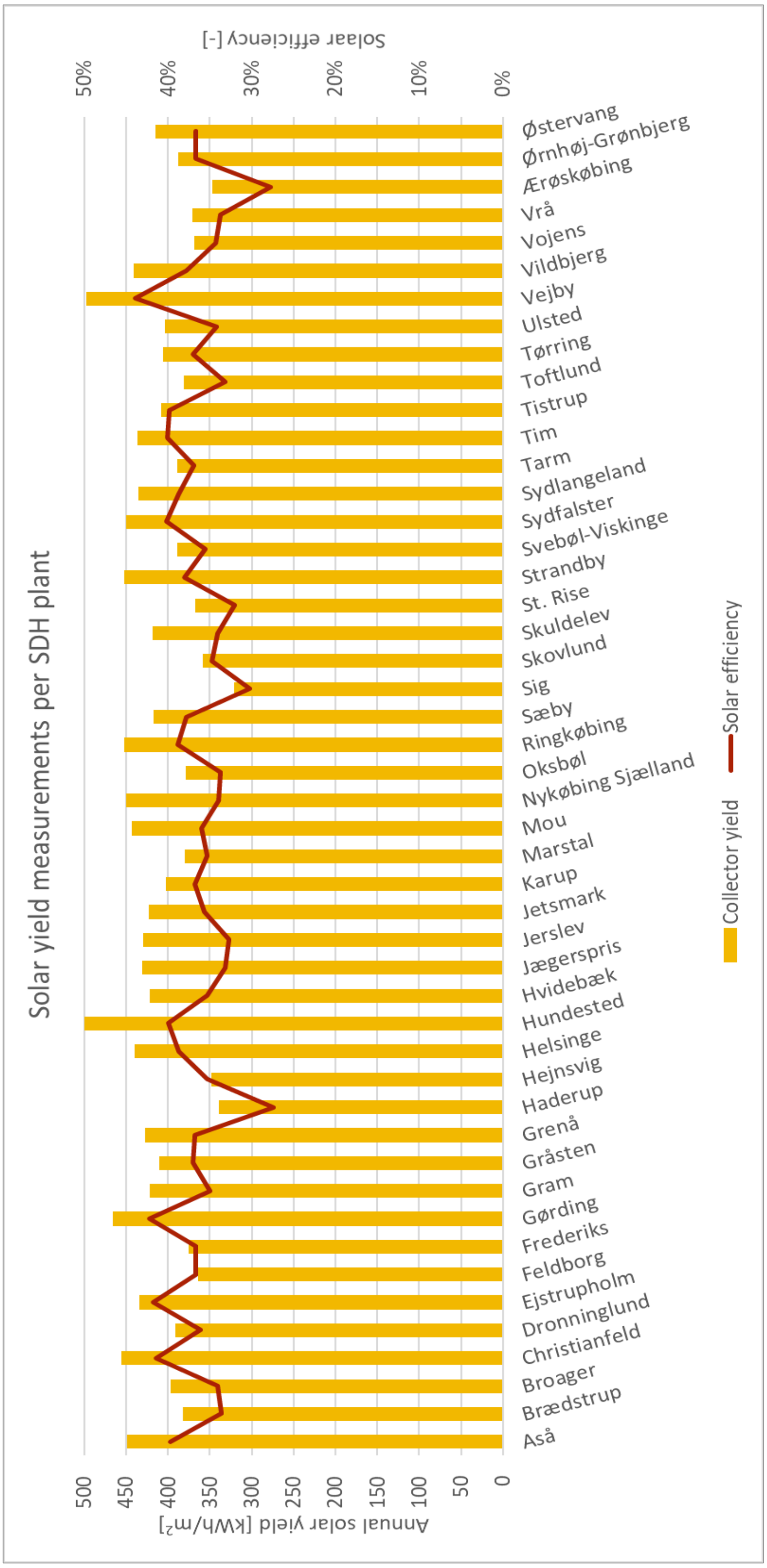
# Annexes

The following annexes are included:

- Annex I – Annual SDH Yield and Efficiency
- Annex II – Heat demand density and location of SDH systems in Denmark
- Annex III – Average cost distribution for the identified SDH potentials at 1,000 m
- Annex IV – Solar Heat Cost of Each Identified Potential SDH System
- Annex V – Solar Heat Potential Depending on Solar Heat Price Limit and SF
- Annex VI – Solar Heat Cost vs. DH Demand by Country
- Annex VII – Identified Potential Solar Heat Production
- Annex VIII – Share of Total Solar Heat Potential Depending on Price Limit
- Annex IX – Identified SDH Potentials by Country and Price Limit
    - Part A: Solar Fraction Target of 20 %
    - Part B: Solar Fraction Target of 40 %

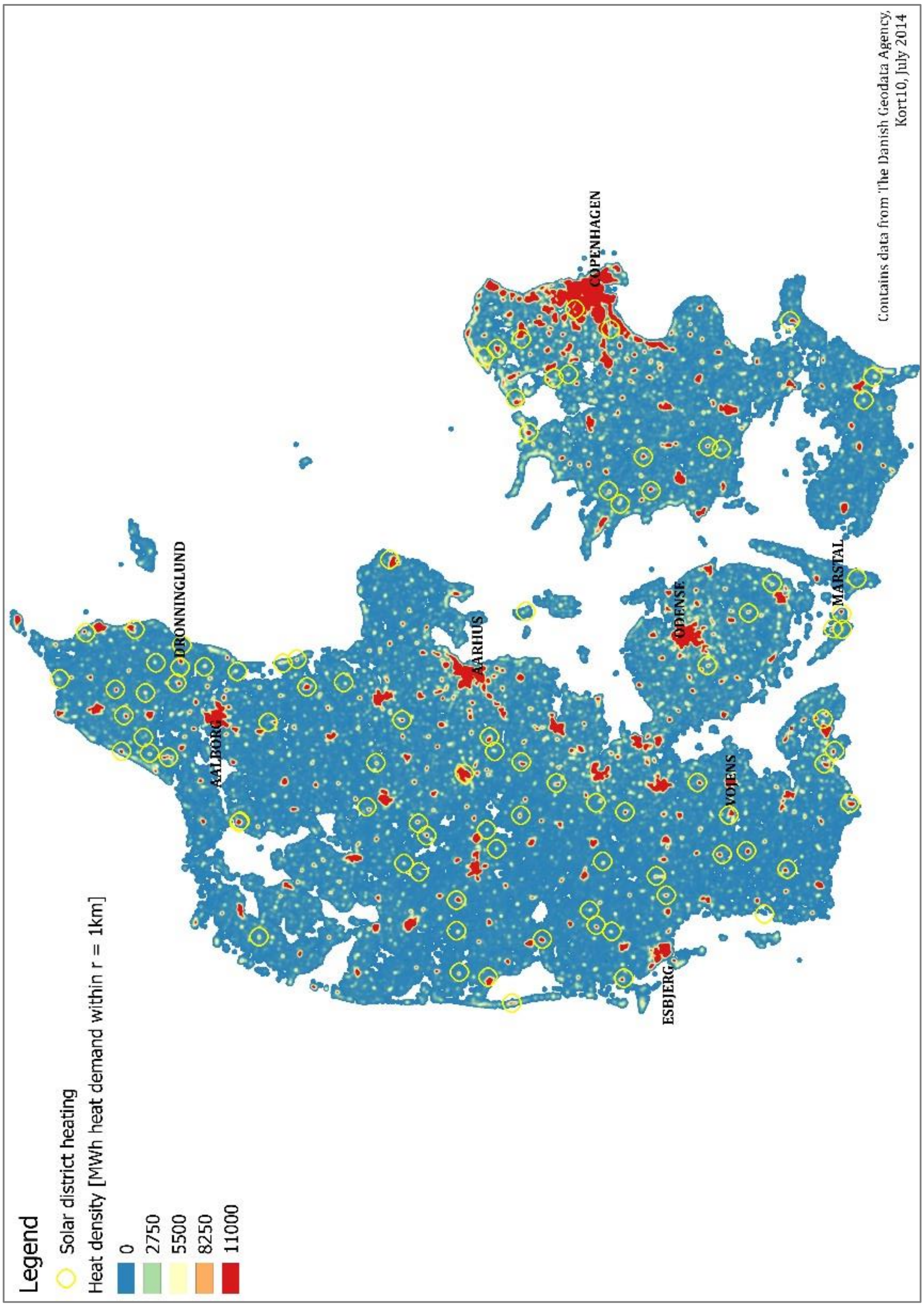
## Annex I – Annual SDH Yield and Efficiency

The efficiency represents the share of solar irradiation converted into heat supplied from the solar collector field.



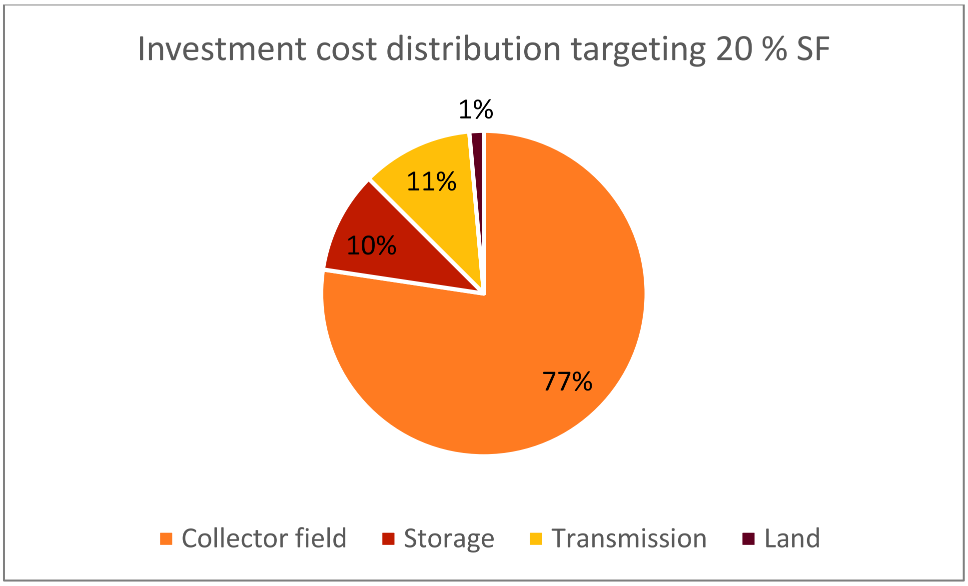
## Annex II – Heat demand density and location of SDH systems in Denmark

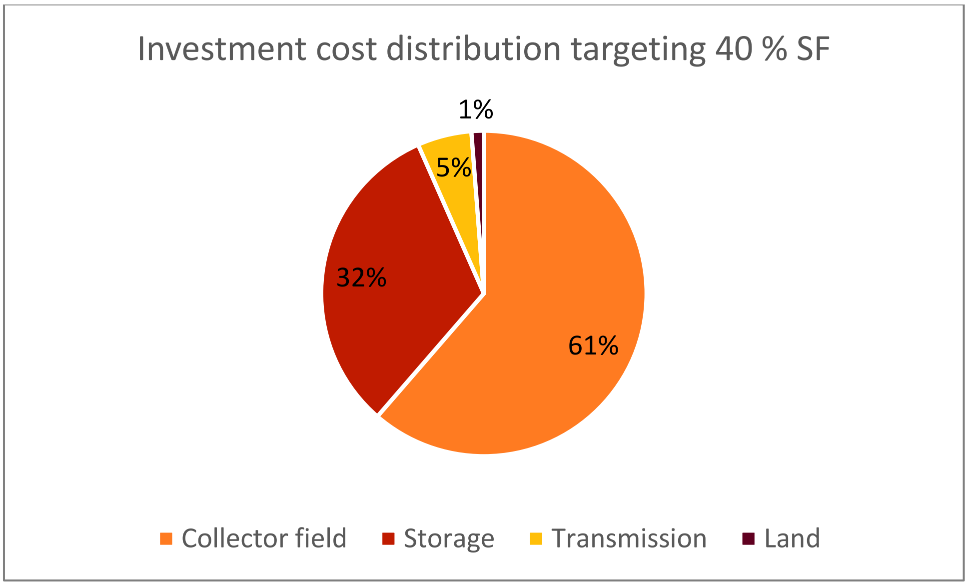
The map shows the location of Danish SDH plants (min. 1,000 m²) together with the heat demand density in terms of annual heat demand in MWh within a radius of 1 km. Bornholm is excluded since there is presently no SDH systems.



## Annex III – Average cost distribution for the identified SDH potentials at 1,000 m

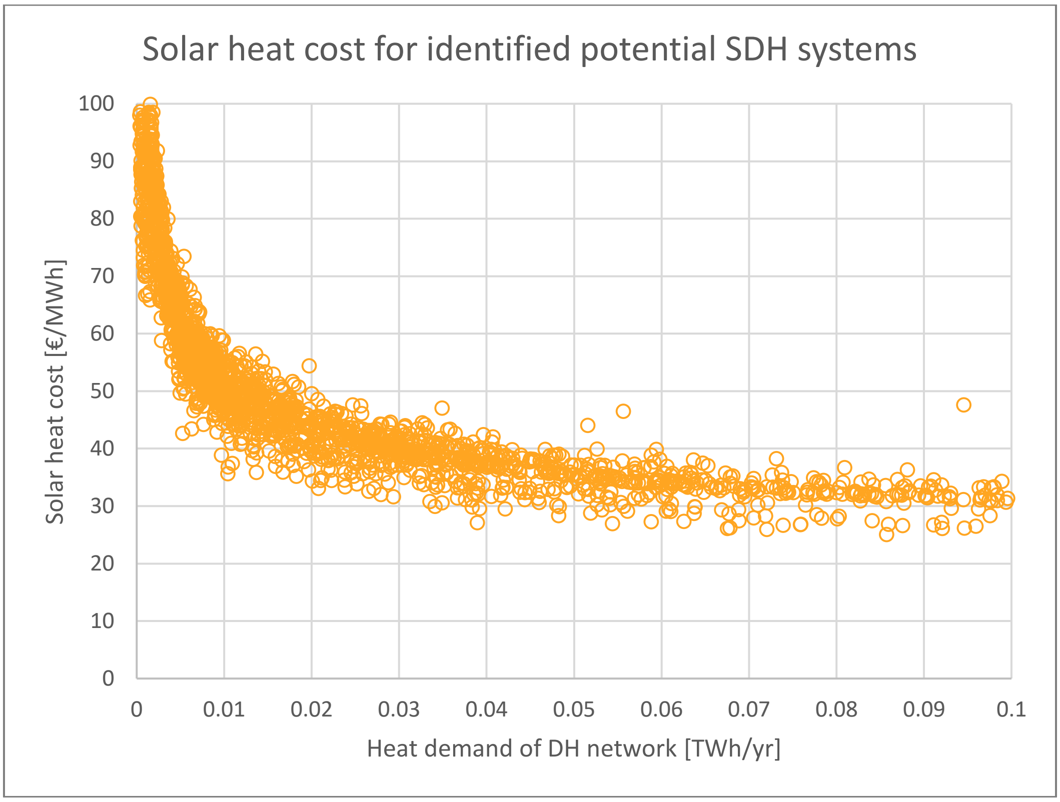
Cost shares figures corresponding to Figure 45 and Figure 46 with a (fixed) transmission line length of 1,000 m targeting 20 % and 40 % solar fraction respectively.



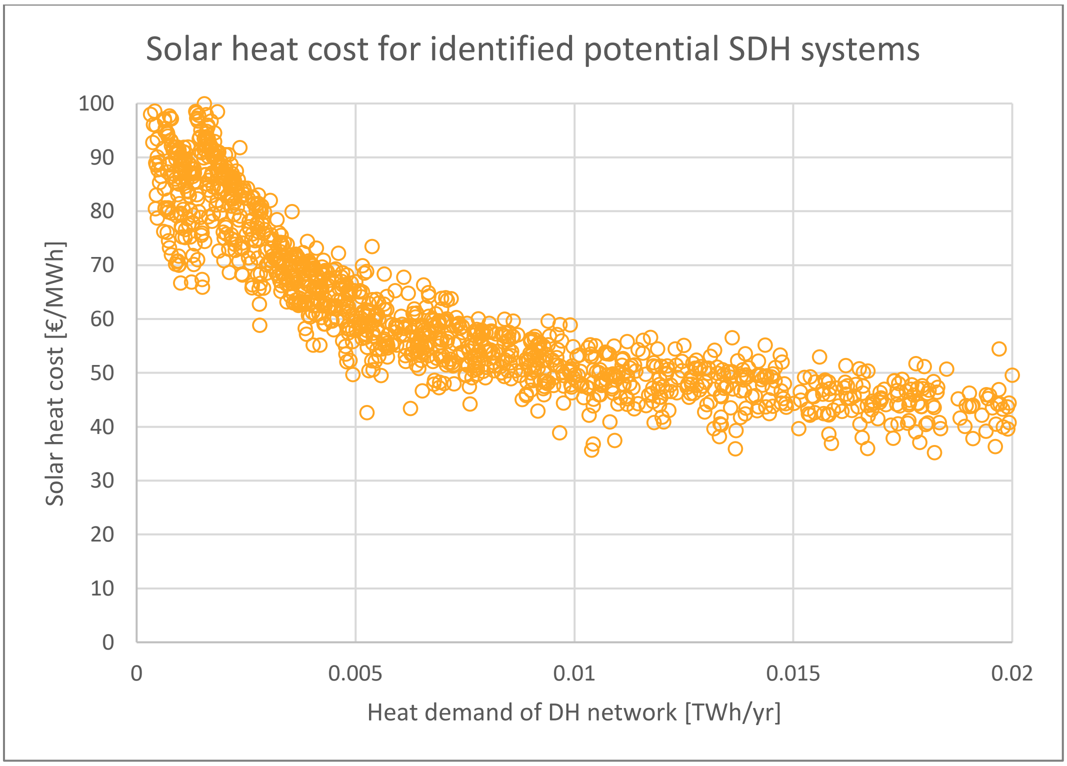



## Annex IV – Solar Heat Cost of Each Identified Potential SDH System

Zoom of Figure 47 showing DH network demands of 0-100 GWh/yr:

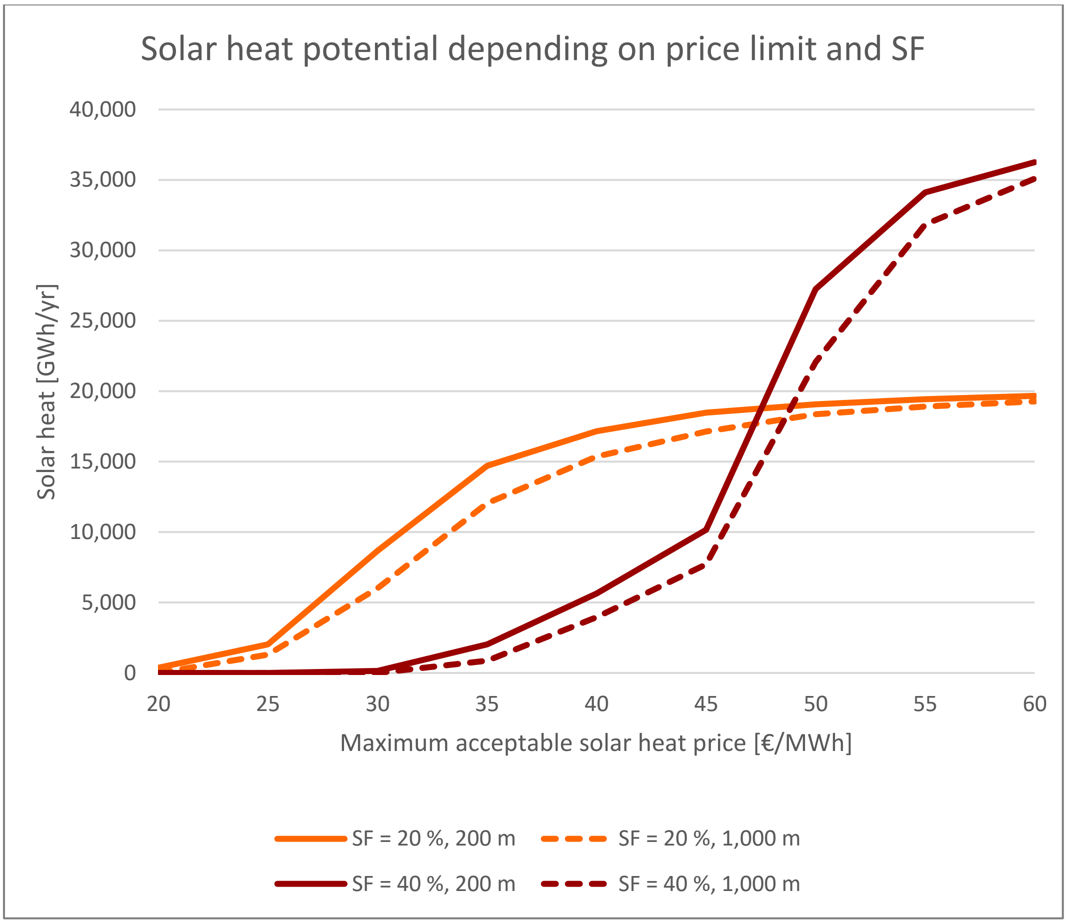



Zoom of Figure 47 showing DH network demands of 0-20 GWh/yr:



## Annex V – Solar Heat Potential Depending on Solar Heat Price Limit and SF

Comparison between identified solar heat production potential targeting 20 % and 40 % solar fraction for 200 m and 1,000 m transmission line length respectively.

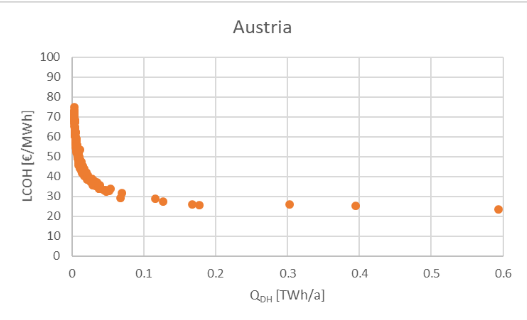


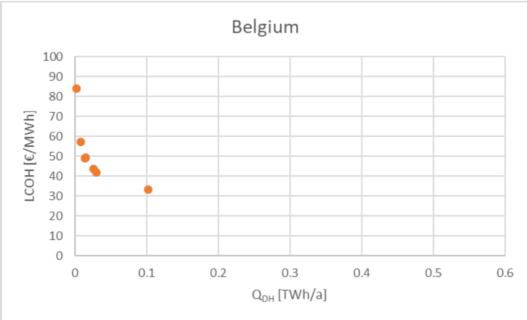
## Annex VI – Solar Heat Cost vs. DH Demand by Country

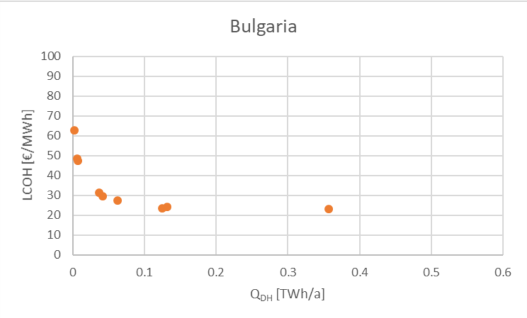
This annex includes figures showing the potential SDH plants for each individual country based on this analysis. The plants are plotted as calculated solar heat price (Levelised Cost of Heat) as function of the yearly heat demand of the district heating network.

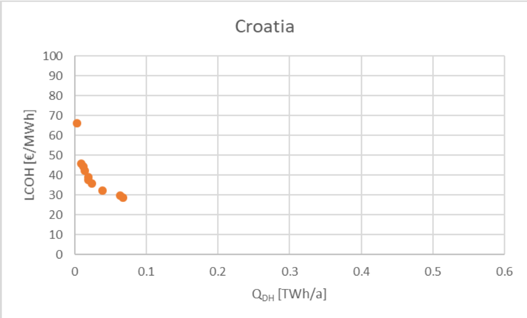
The plotted scenario is including:

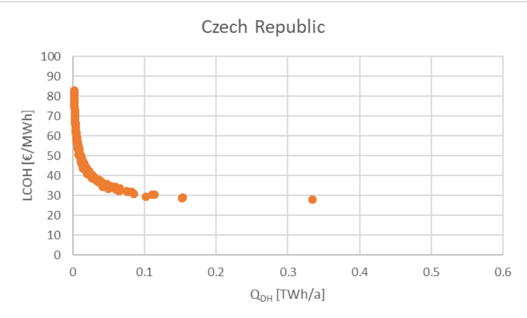
- 200 m transmission line, and
- aiming for 20 % solar fraction

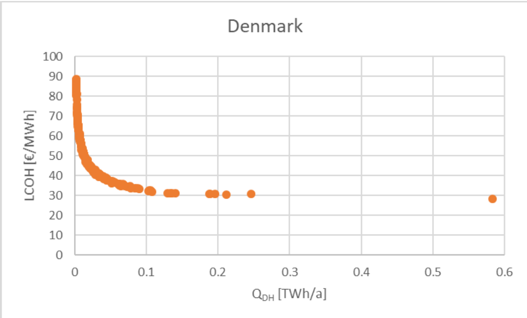


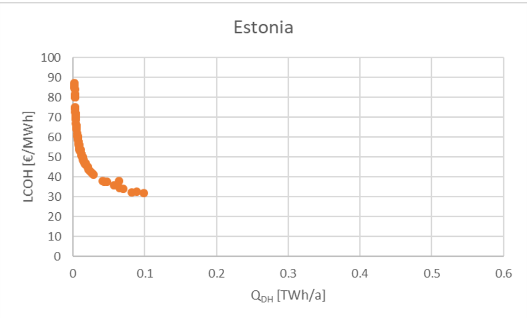



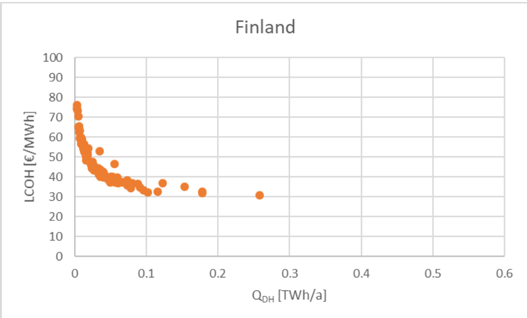



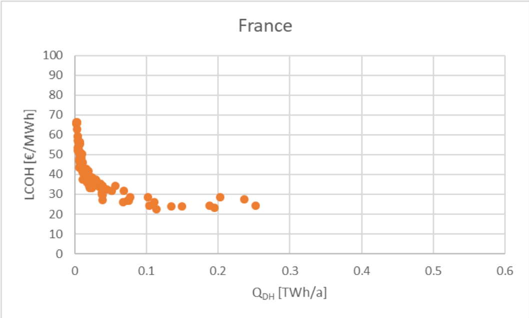



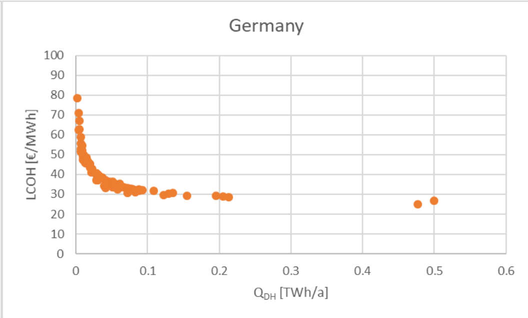



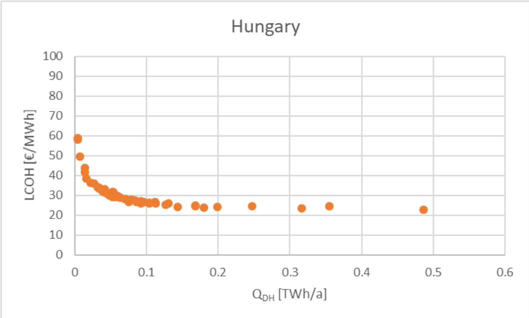



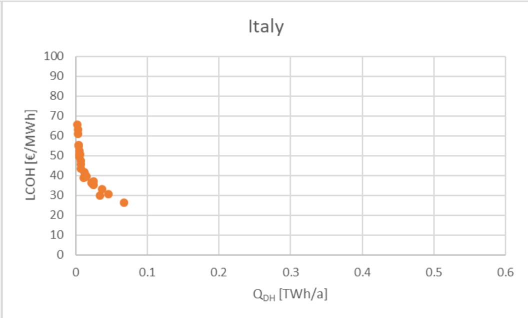



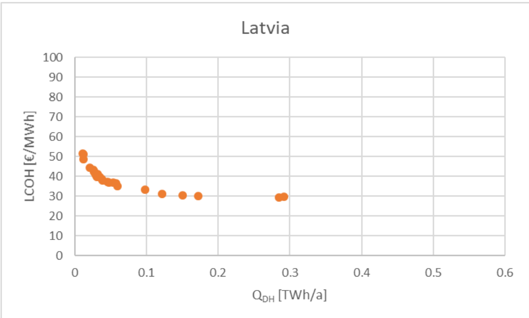



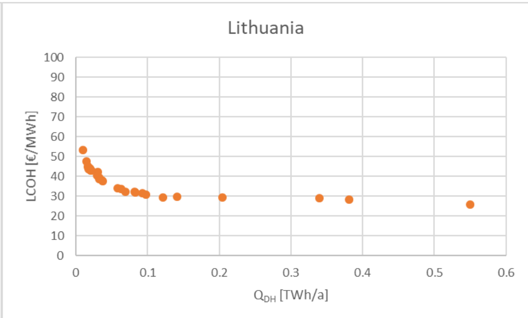

France
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

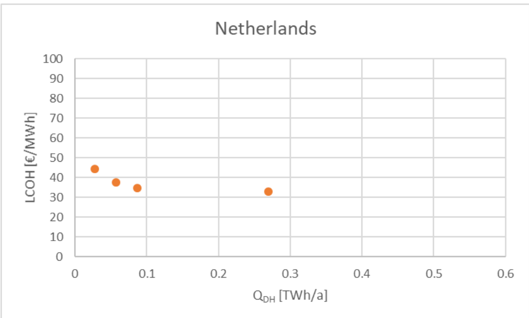

Germany
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

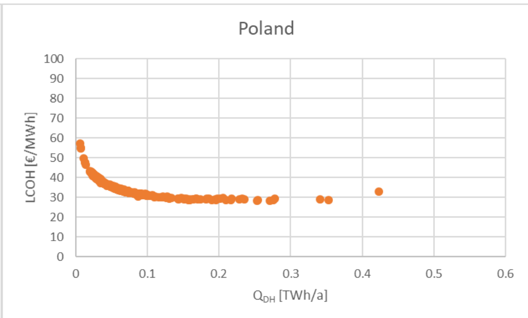

Hungary
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

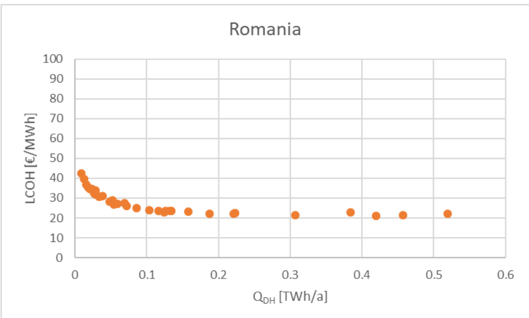

Italy
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

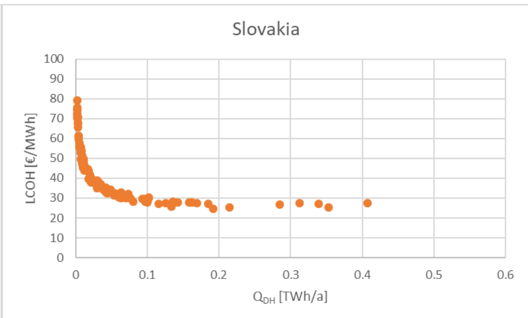

Latvia
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

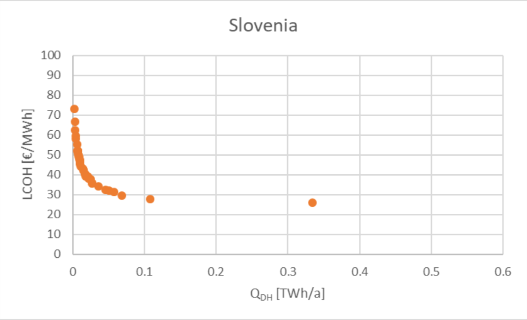

Lithuania
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

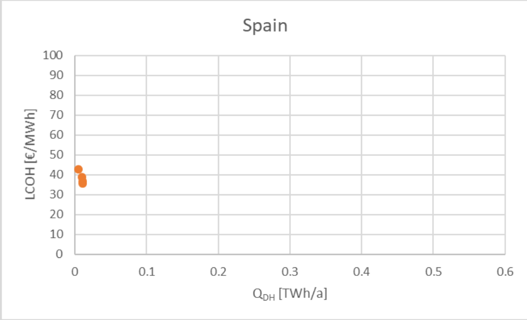

Netherlands
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

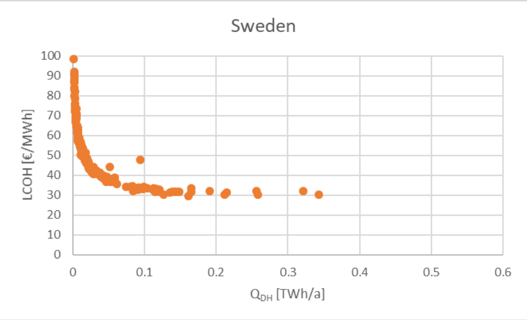

Poland
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]

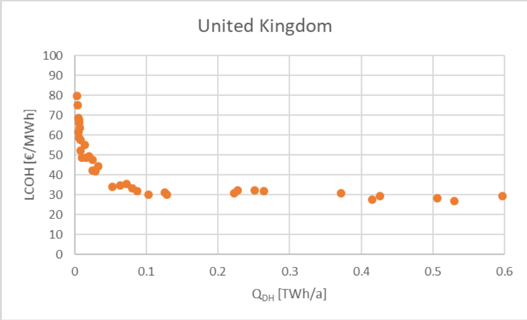

Romania
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]


Slovakia
LCOH [€/MWh]
0 10 20 30 40 50 60 70 80 90 100
0 0.1 0.2 0.3 0.4 0.5 0.6
$Q_{DH}$ [TWh/a]


Slovenia
LCOH [€/MWh]
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
QDH [TWh/a]

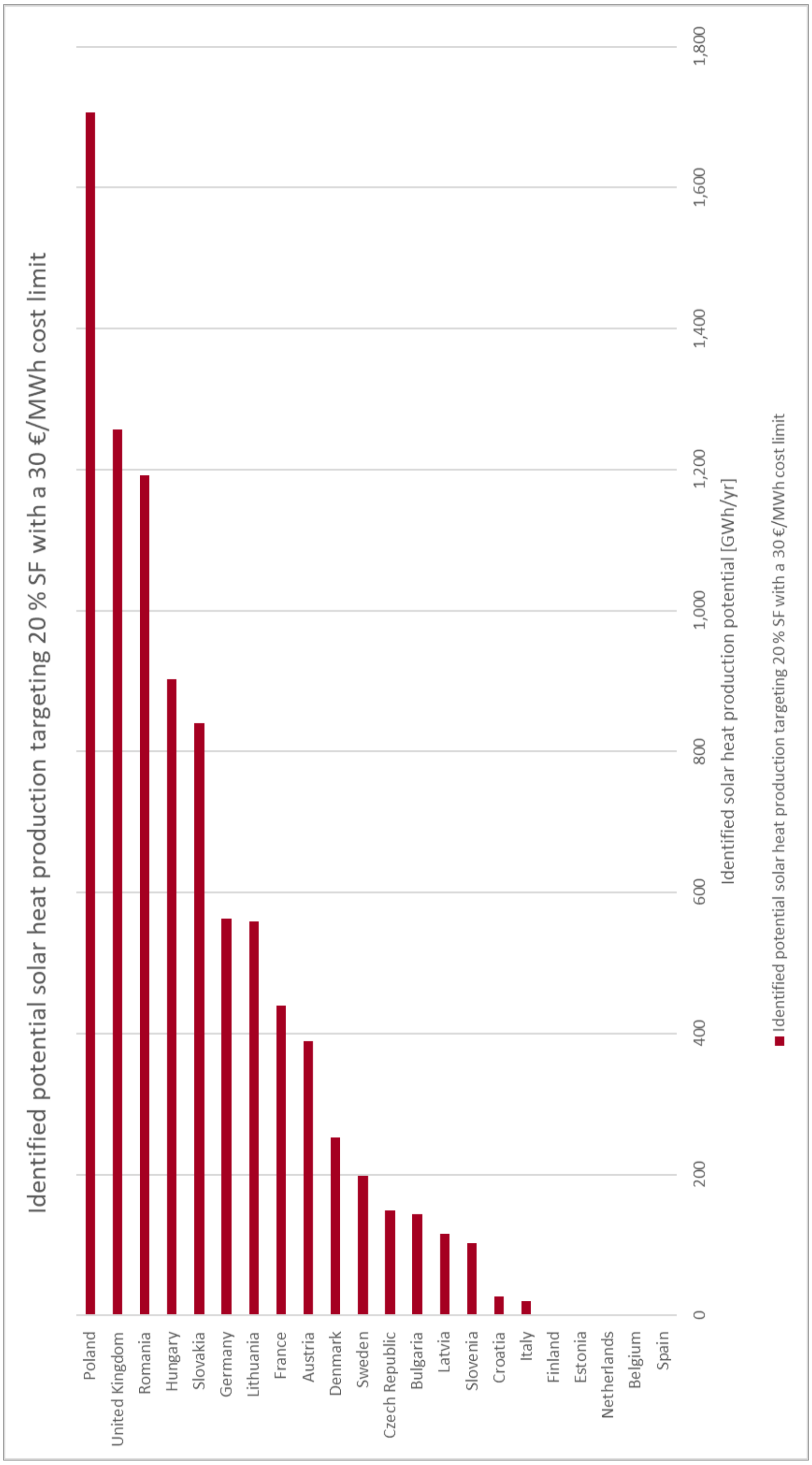

Spain
LCOH [€/MWh]
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
QDH [TWh/a]

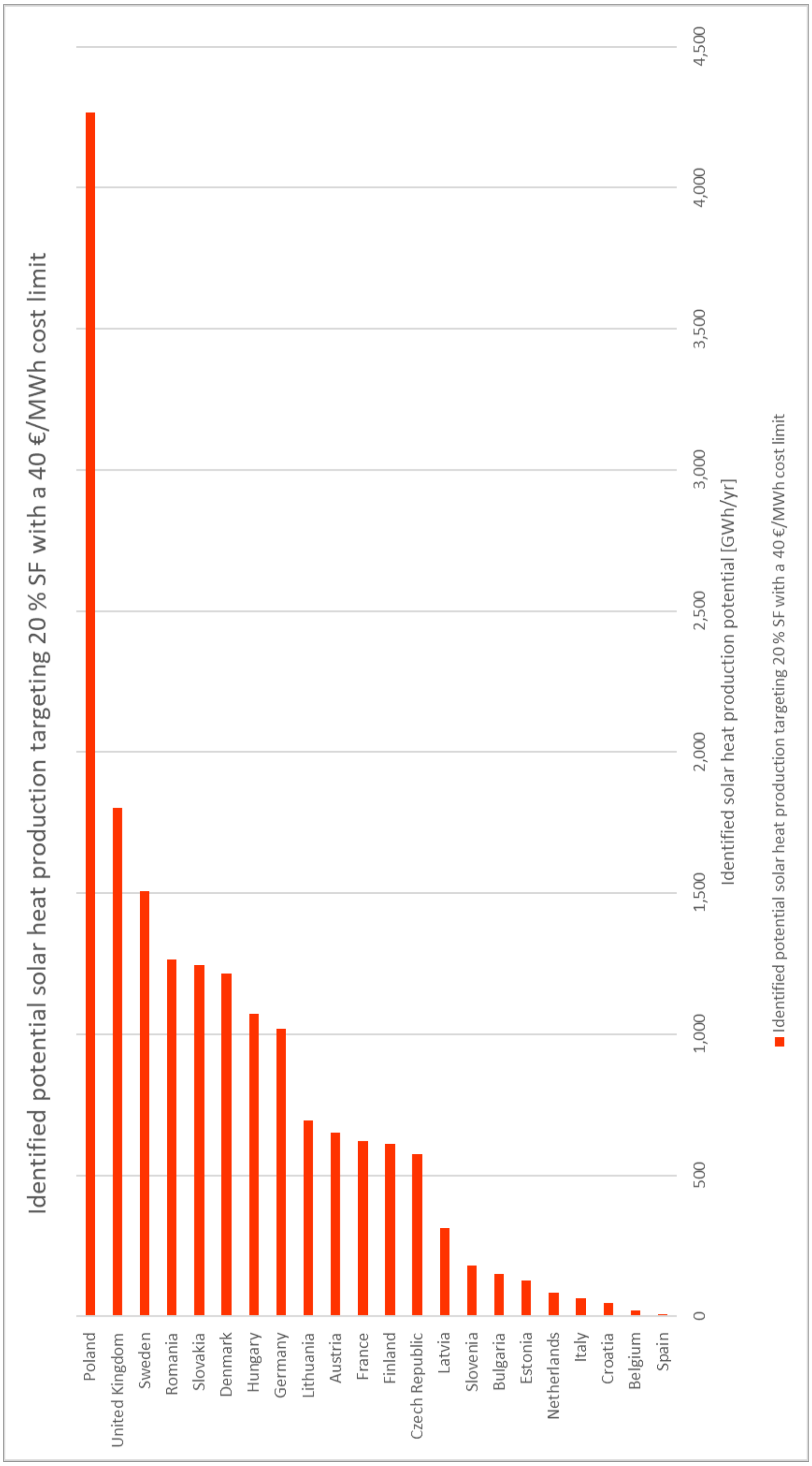

Sweden
LCOH [€/MWh]
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
QDH [TWh/a]

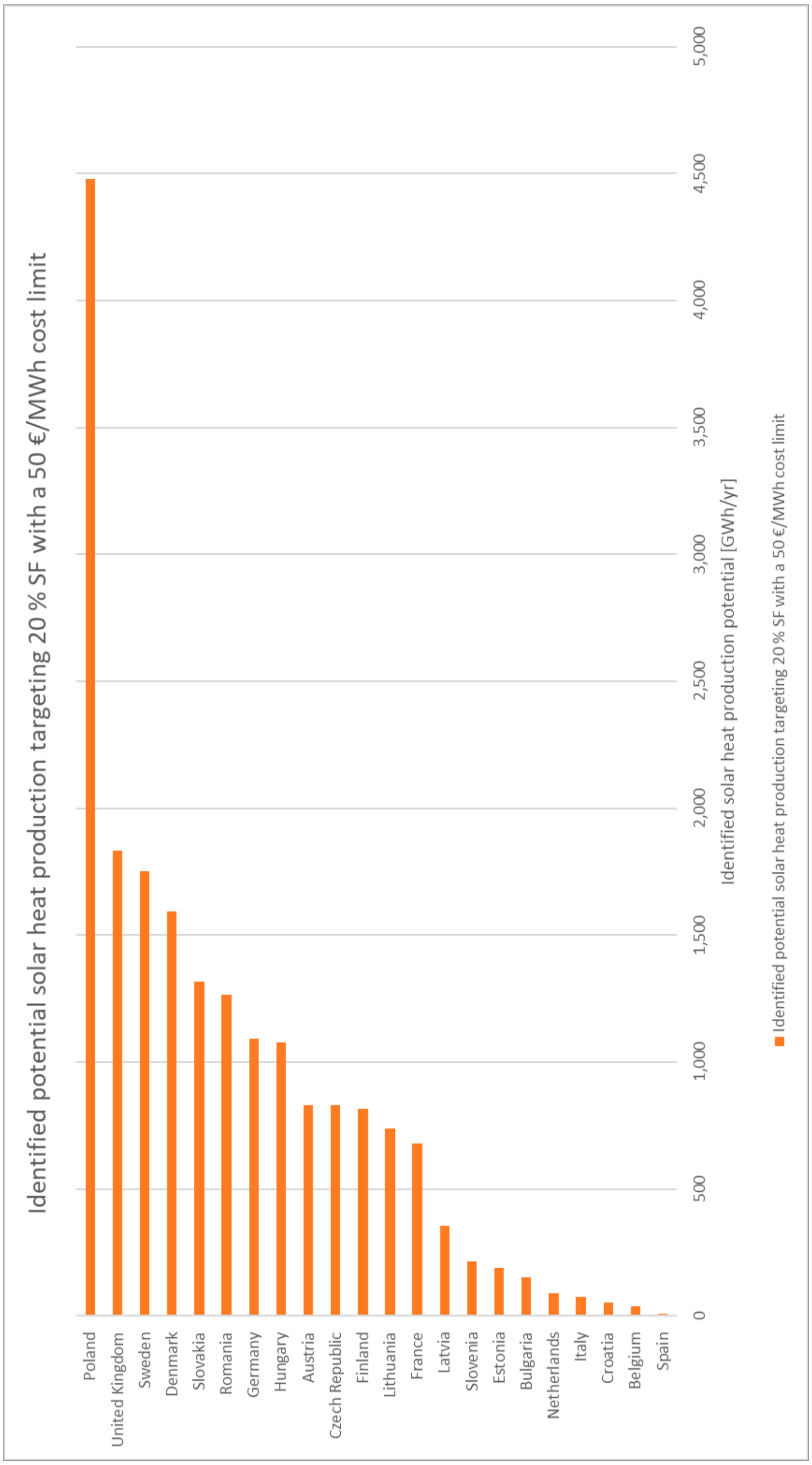

United Kingdom
LCOH [€/MWh]
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
QDH [TWh/a]

## Annex VII – Identified potential solar heat production

The figures indicate results of the analysis targeting 20 % solar fraction with a cost limit of 30, 40 and 50 €/MWh respectively.

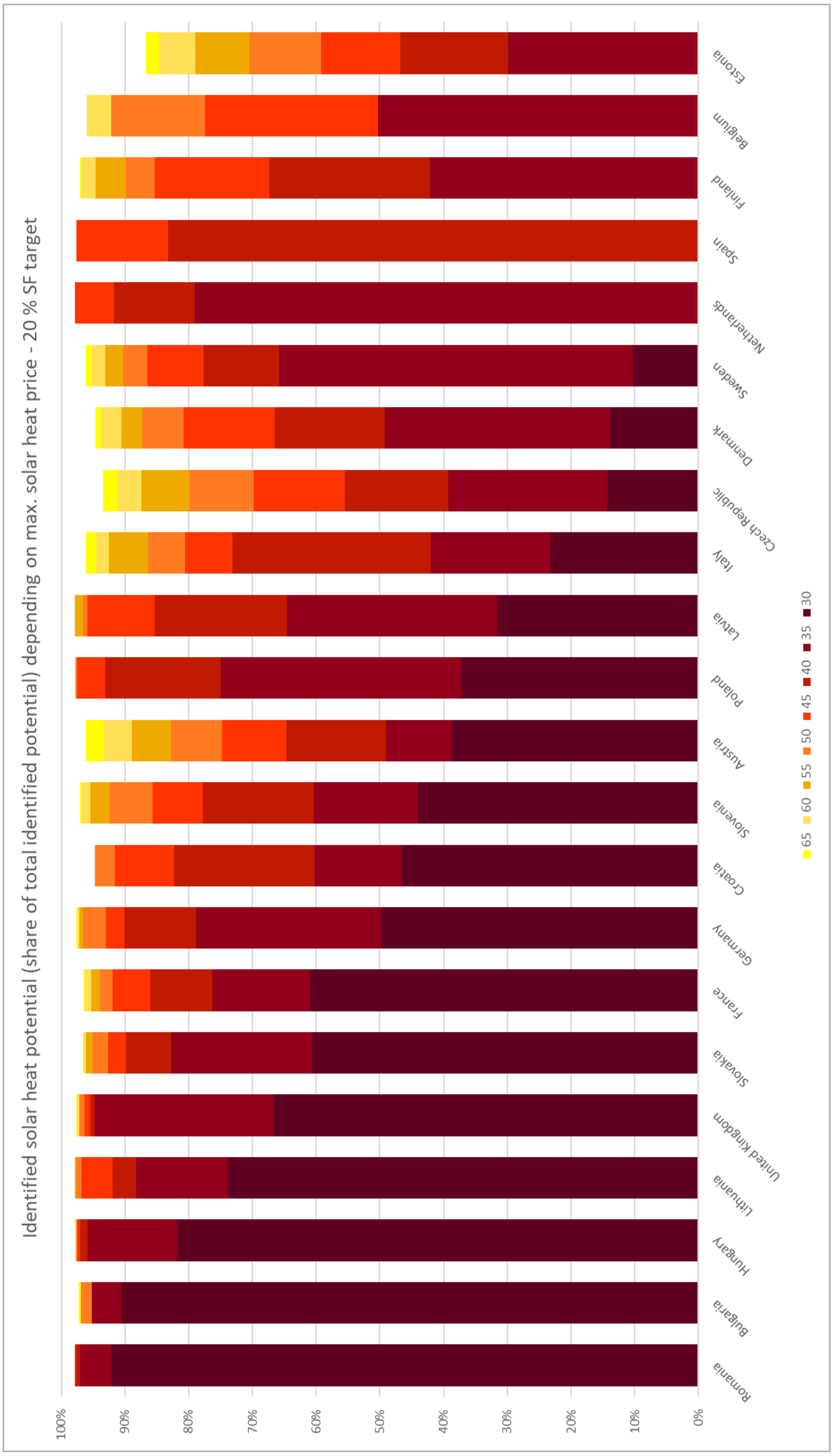



Identified potential solar heat production targeting 20 % SF with a 40 €/MWh cost limit
Identified solar heat production potential [GWh/yr]
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
Poland
United Kingdom
Sweden
Romania
Slovakia
Denmark
Hungary
Germany
Lithuania
Austria
France
Finland
Czech Republic
Latvia
Slovenia
Bulgaria
Estonia
Netherlands
Italy
Croatia
Belgium
Spain
Identified potential solar heat production targeting 20 % SF with a 40 €/MWh cost limit


Identified potential solar heat production targeting 20 % SF with a 50 €/MWh cost limit
Poland
United Kingdom
Sweden
Denmark
Slovakia
Romania
Germany
Hungary
Austria
Czech Republic
Finland
Lithuania
France
Latvia
Slovenia
Estonia
Bulgaria
Netherlands
Italy
Croatia
Belgium
Spain
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Identified solar heat production potential [GWh/yr]
Identified potential solar heat production targeting 20 % SF with a 50 €/MWh cost limit

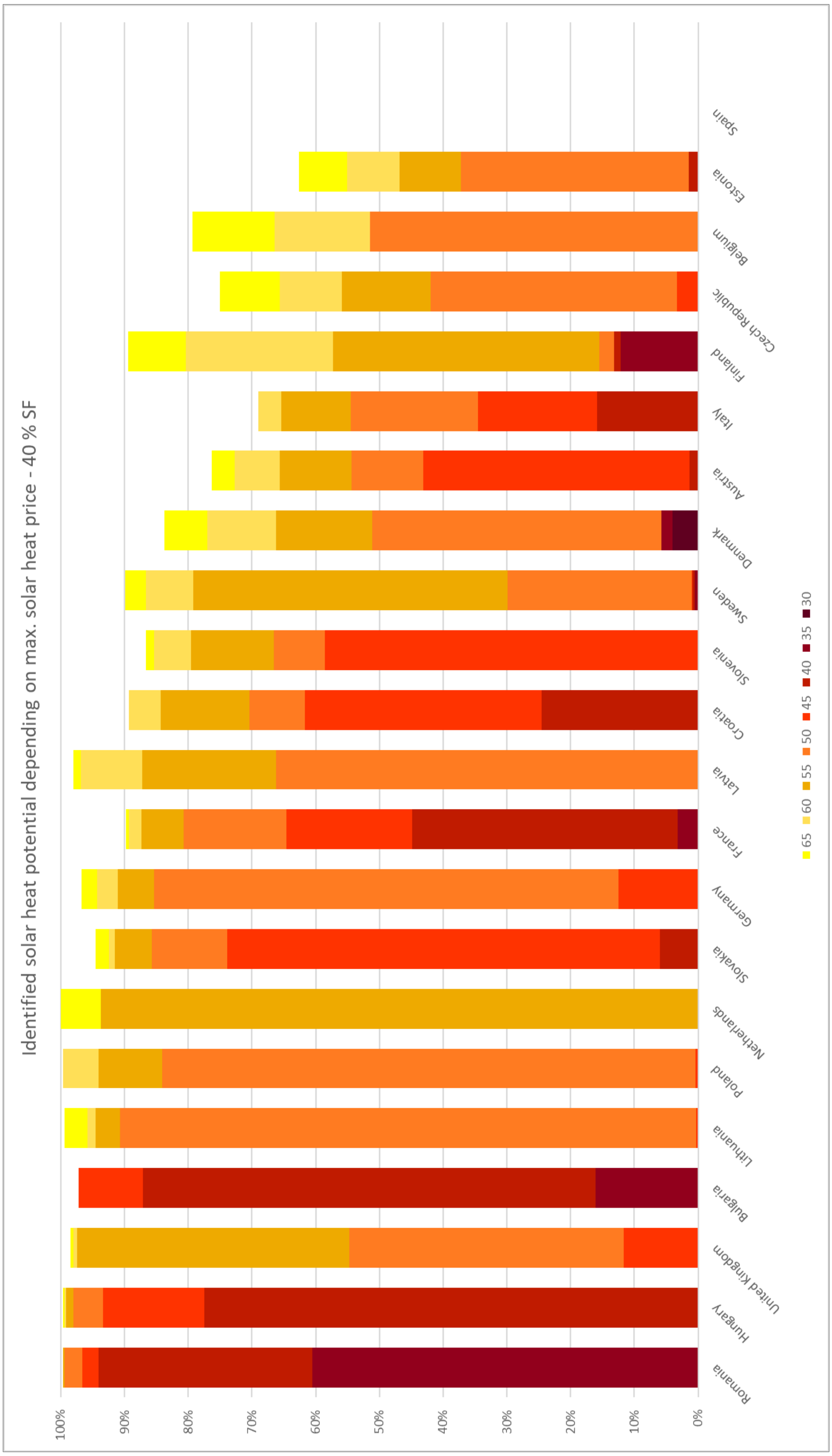
## Annex VIII – Share of Total Solar Heat Potential Depending on Price Limit

The figure below indicates the identified solar heat potential for the 20 % SF target and 200 m transmission line length. The legend indicates various solar heat price limits in €/MWh.

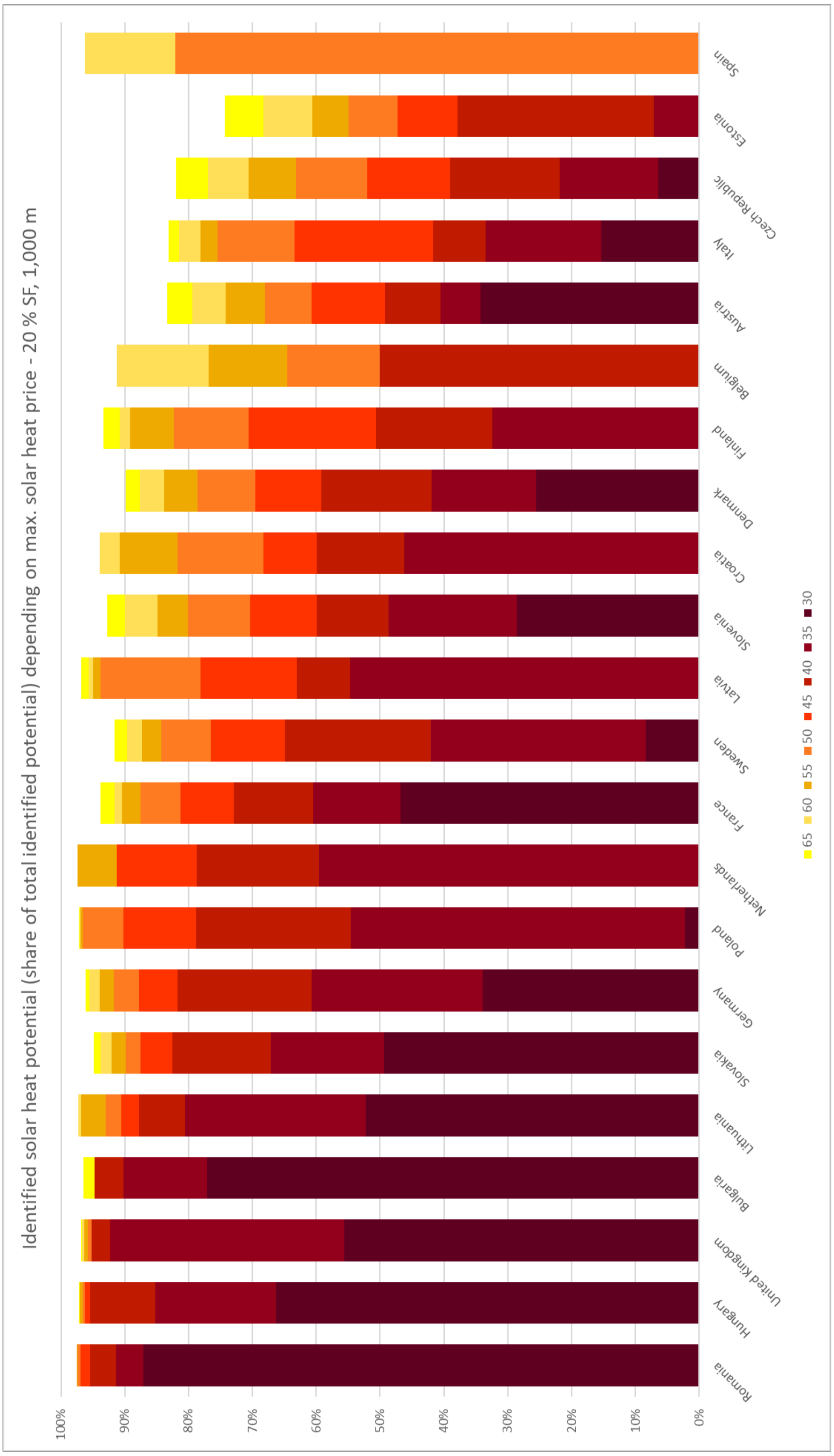


Identified solar heat potential for the 40 % SF target and 200 m transmission line length. The legend indicates various solar heat price limits in €/MWh.

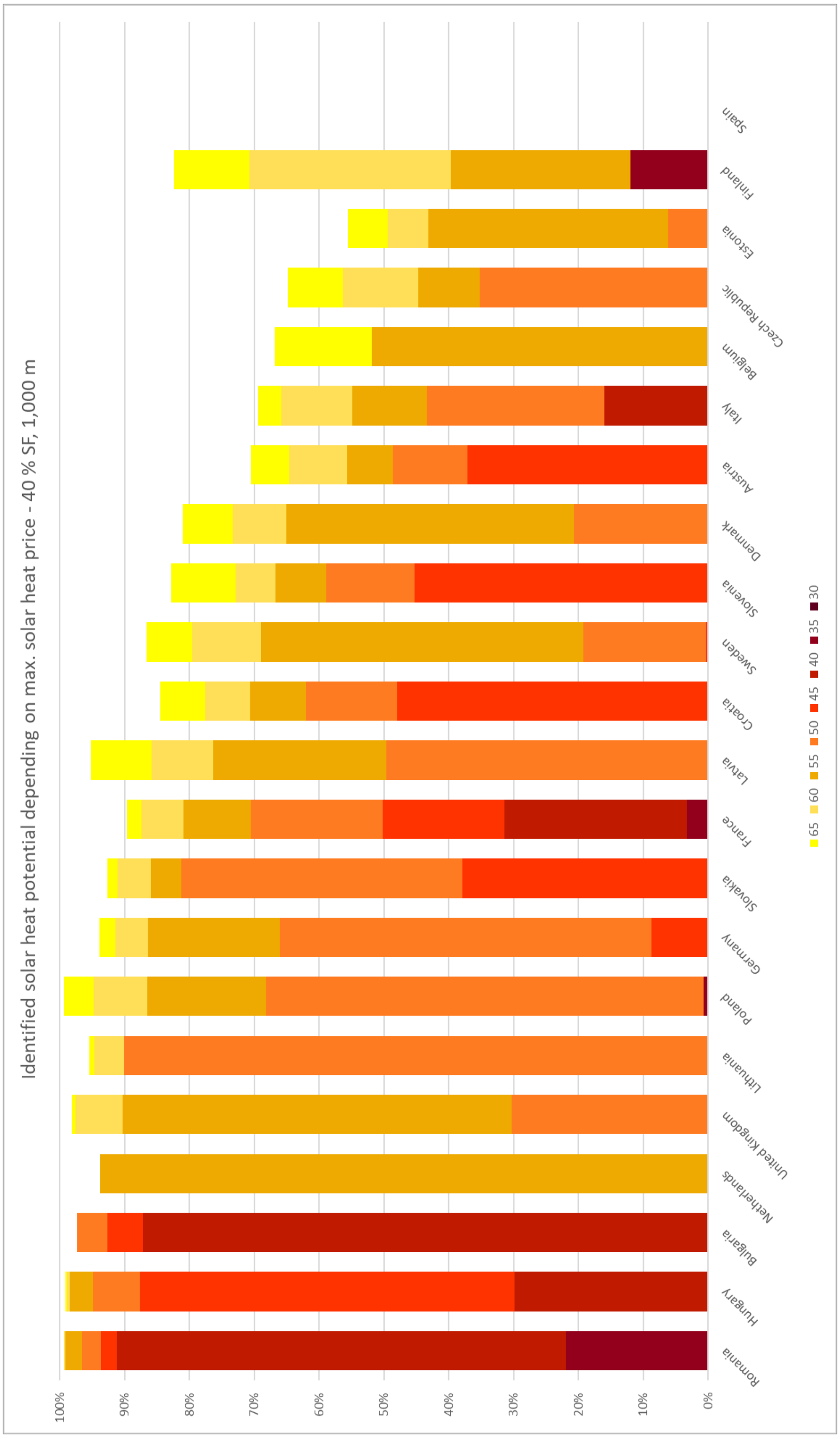
Note that the order changes to illustrate an overall trend indicating most feasible on the left and less feasible on the right.



Identified solar heat potential for the 20 % SF target and 1,000 m transmission line length. The legend indicates various solar heat price limits in €/MWh.



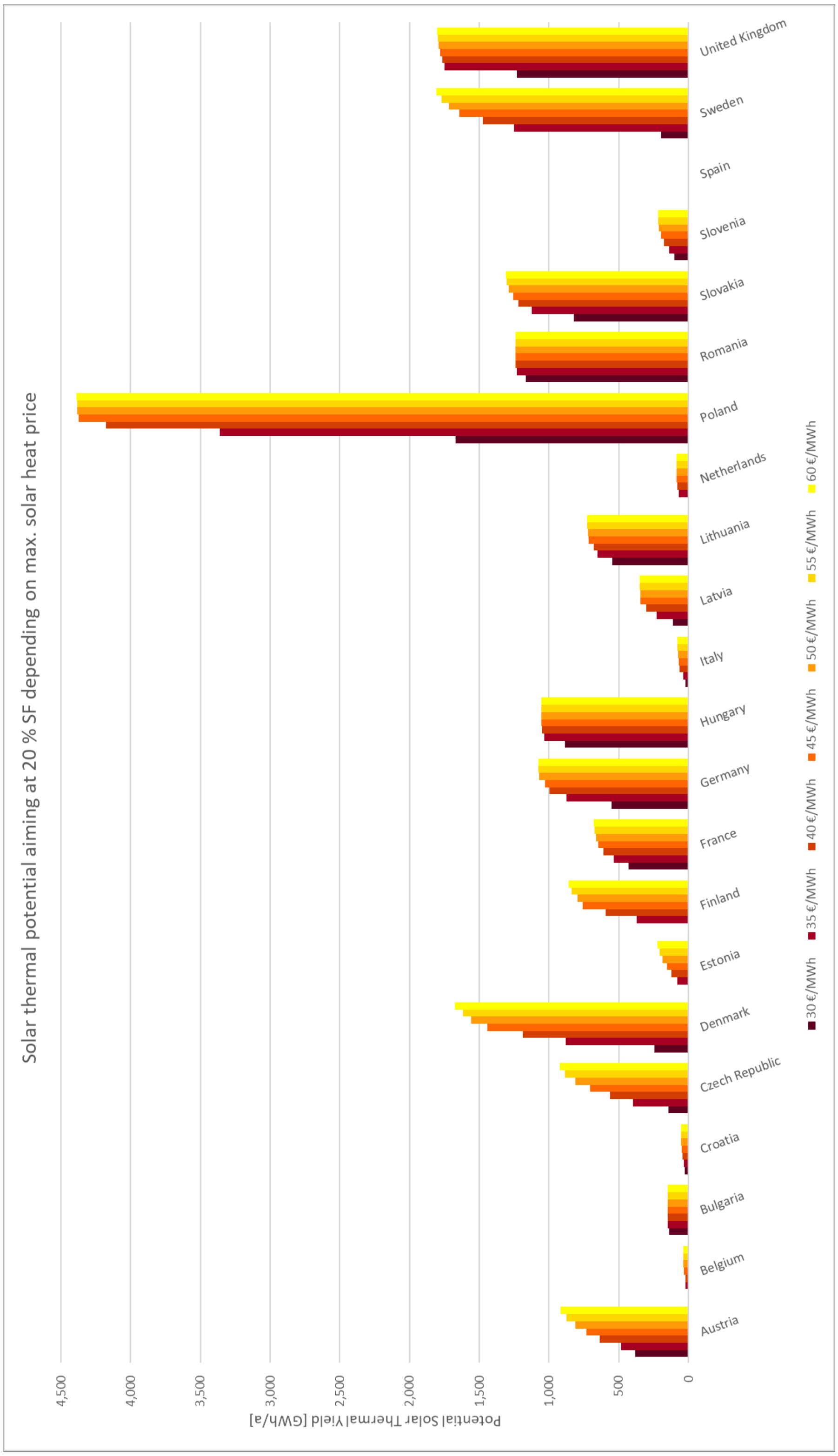
Identified solar heat potential for the 40 % SF target and 1,000 m transmission line length. The legend indicates various solar heat price limits in €/MWh.

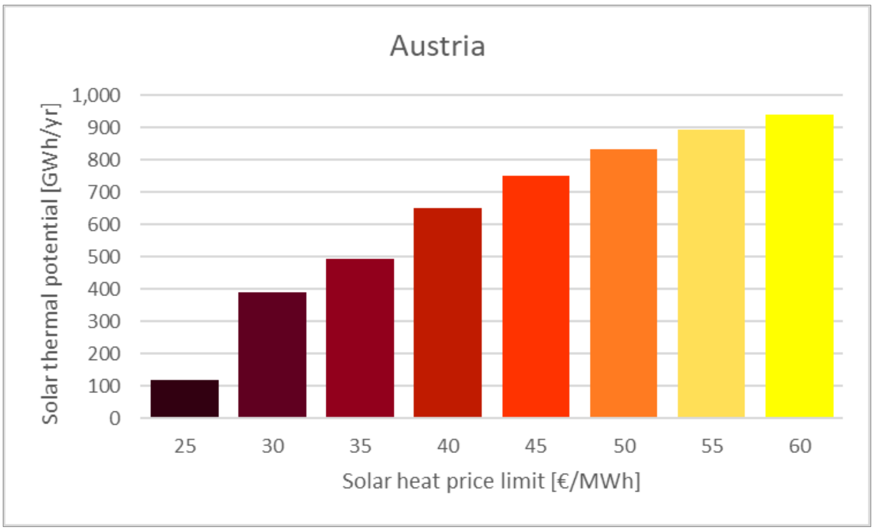


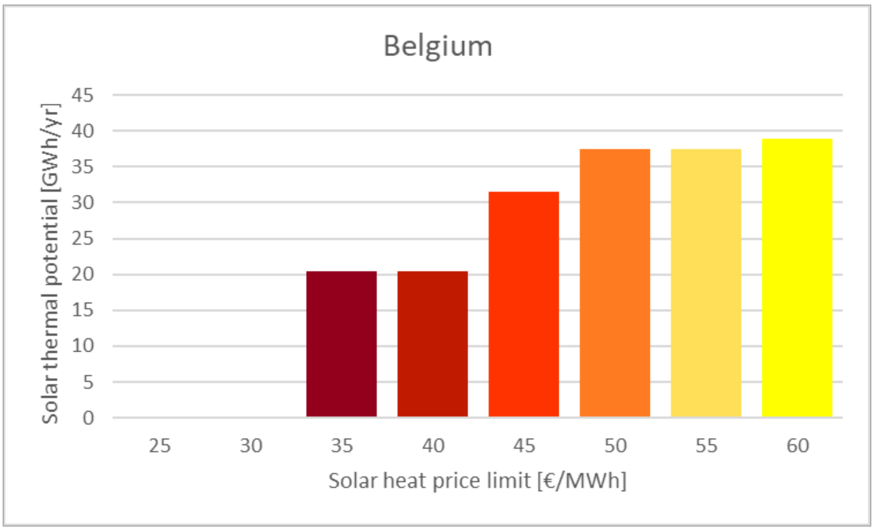
## Annex IX – Identified SDH Potentials by Country and Price Limit

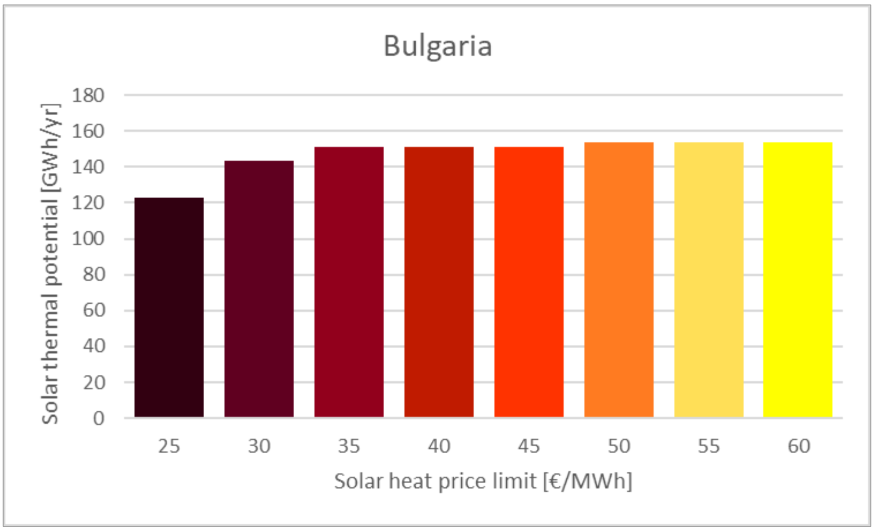
Below is seen the different identified potential solar heat productions by country depending on which solar heat price is defined as an upper limit. Charts for each country are following the one including all. (Notice the differences in secondary axis-levels.)

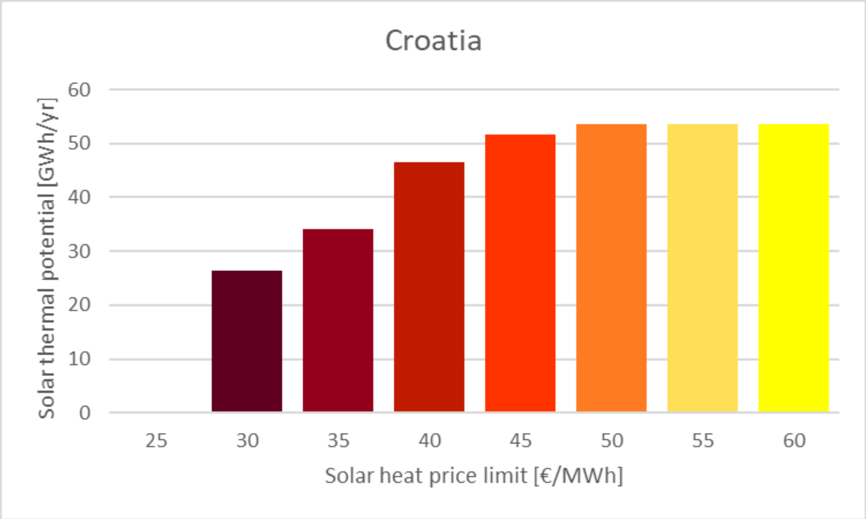
### Part A: Solar Fraction Target of 20 %

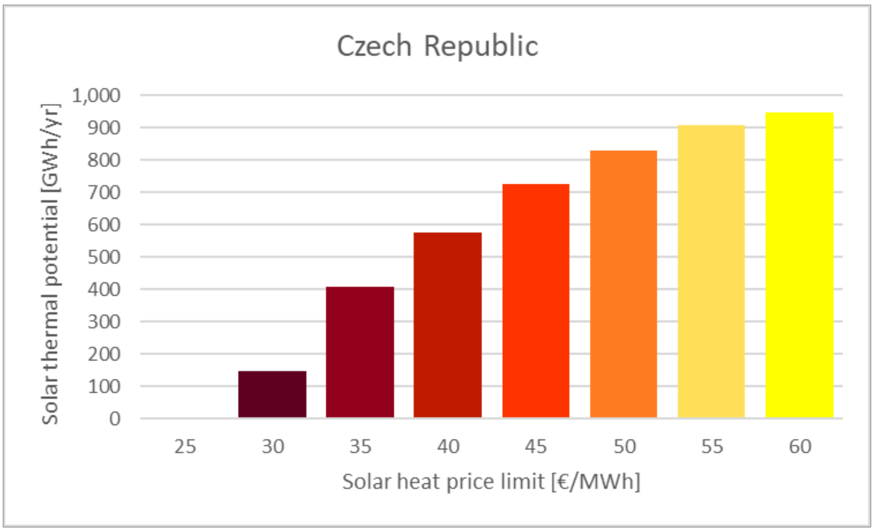


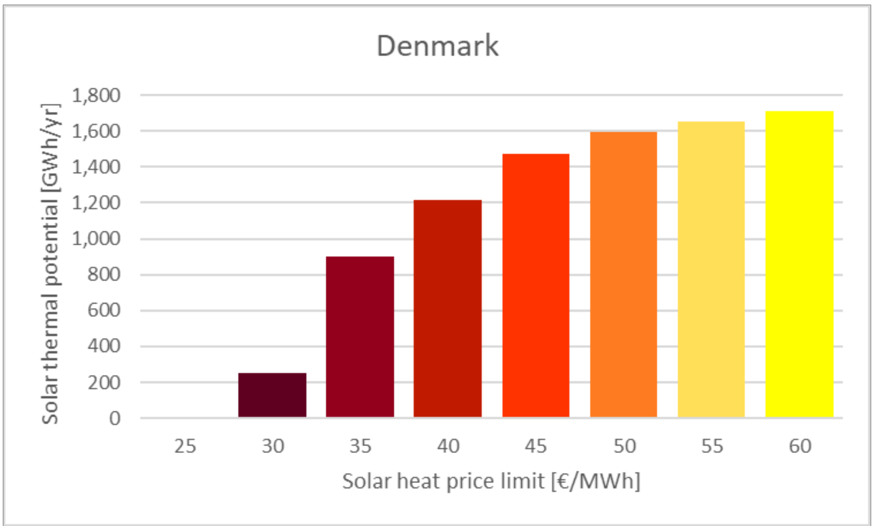

Austria
Solar thermal potential [GWh/yr]
1,000
900
800
700
600
500
400
300
200
100
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

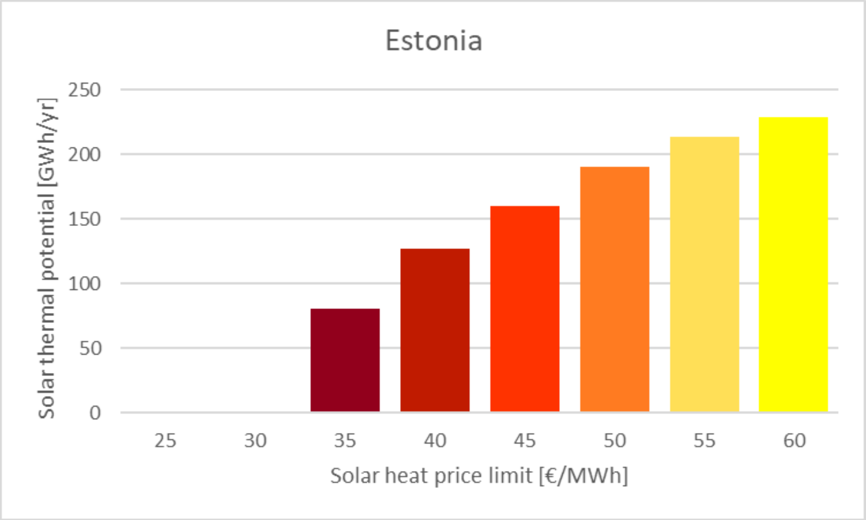

Belgium
Solar thermal potential [GWh/yr]
45
40
35
30
25
20
15
10
5
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

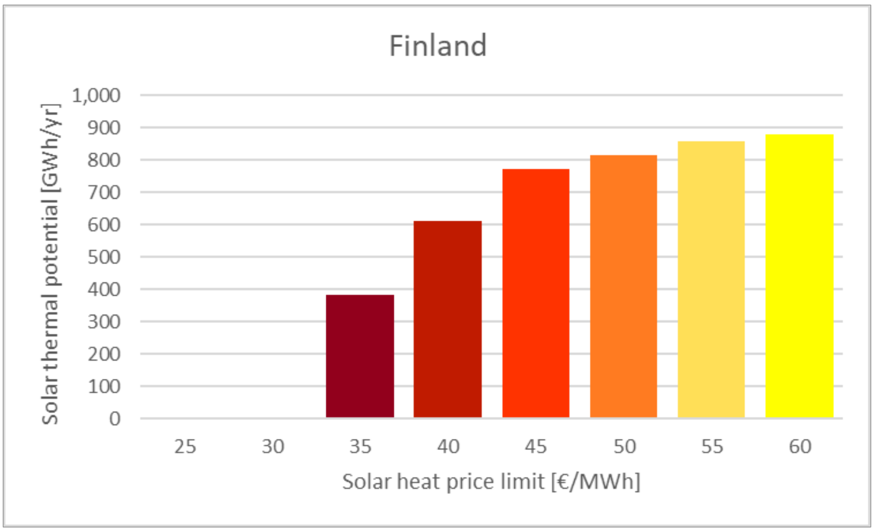

Bulgaria
Solar thermal potential [GWh/yr]
180
160
140
120
100
80
60
40
20
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

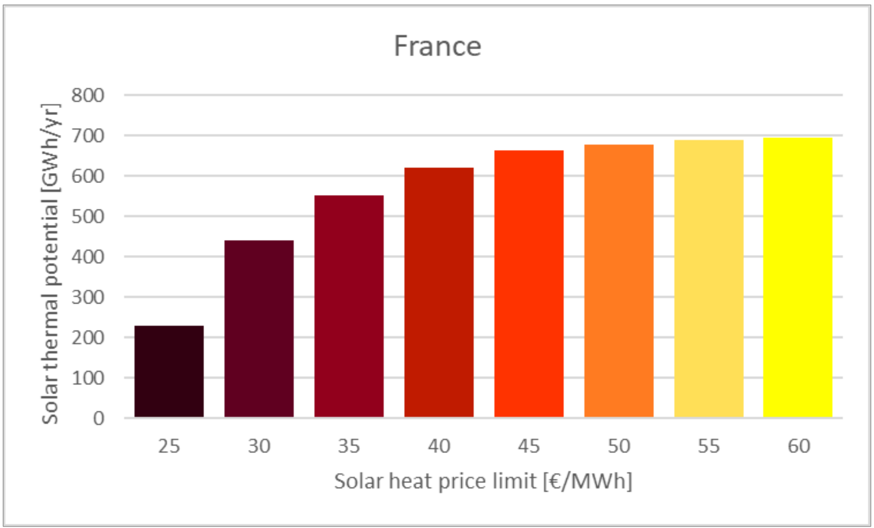

Croatia
Solar thermal potential [GWh/yr]
0
10
20
30
40
50
60
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

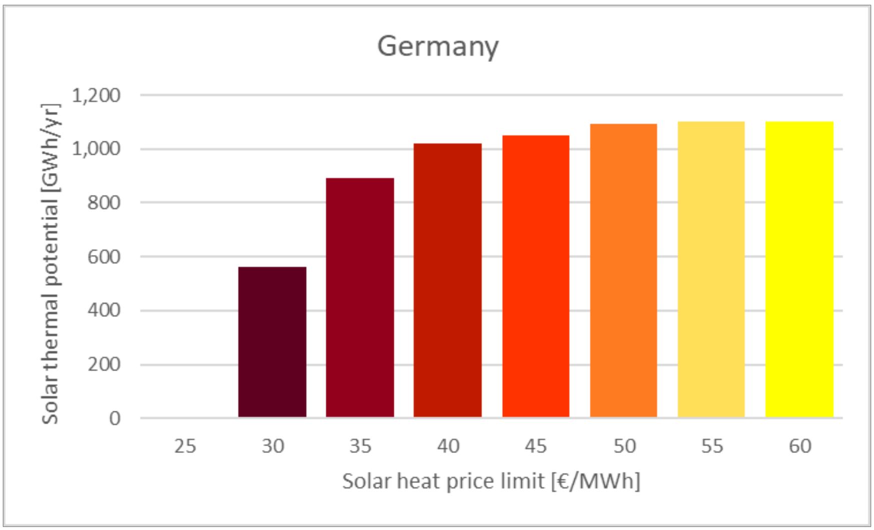

Czech Republic
Solar thermal potential [GWh/yr]
0
100
200
300
400
500
600
700
800
900
1,000
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

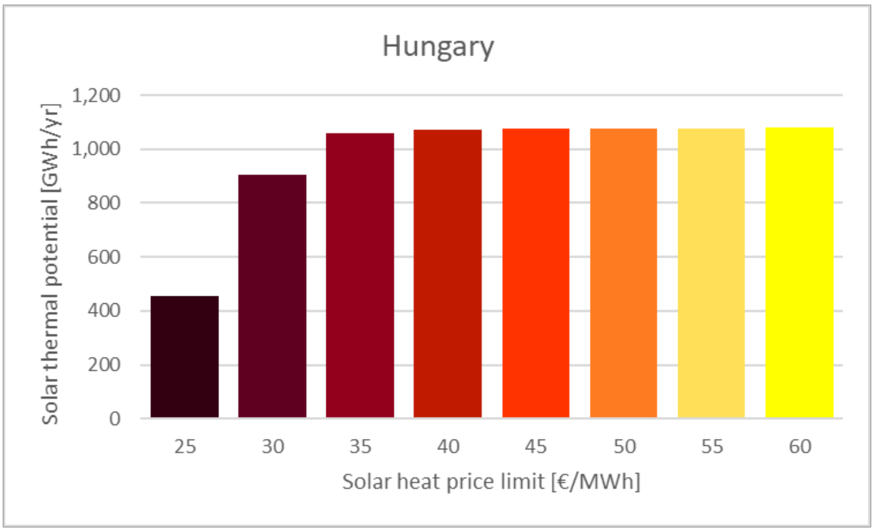

Denmark
Solar thermal potential [GWh/yr]
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

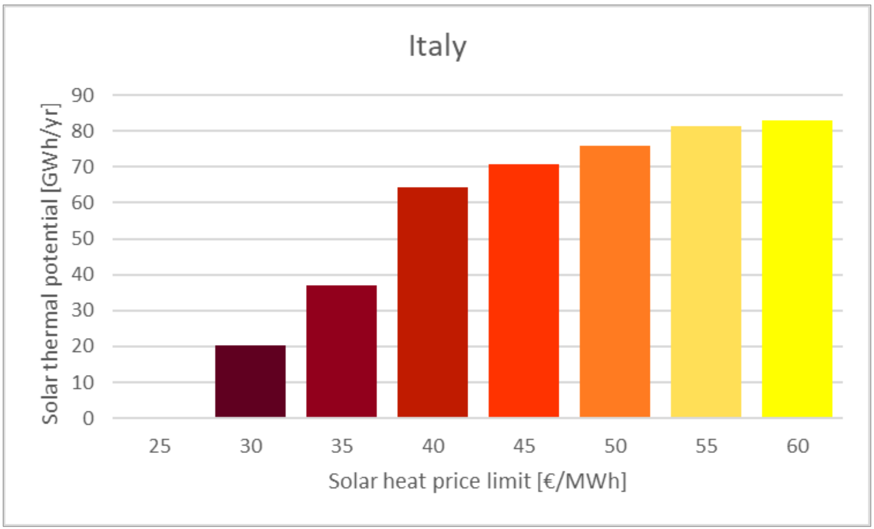

Estonia
Solar thermal potential [GWh/yr]
250
200
150
100
50
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

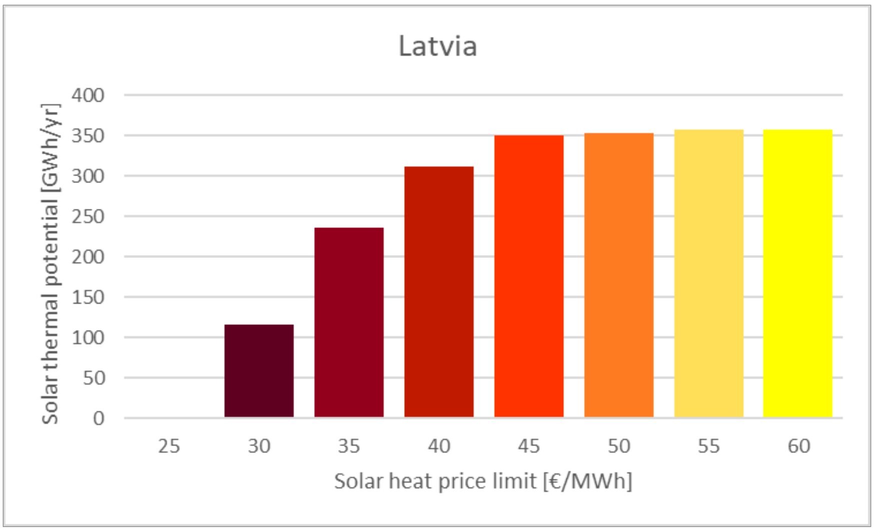

Finland
Solar thermal potential [GWh/yr]
1,000
900
800
700
600
500
400
300
200
100
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

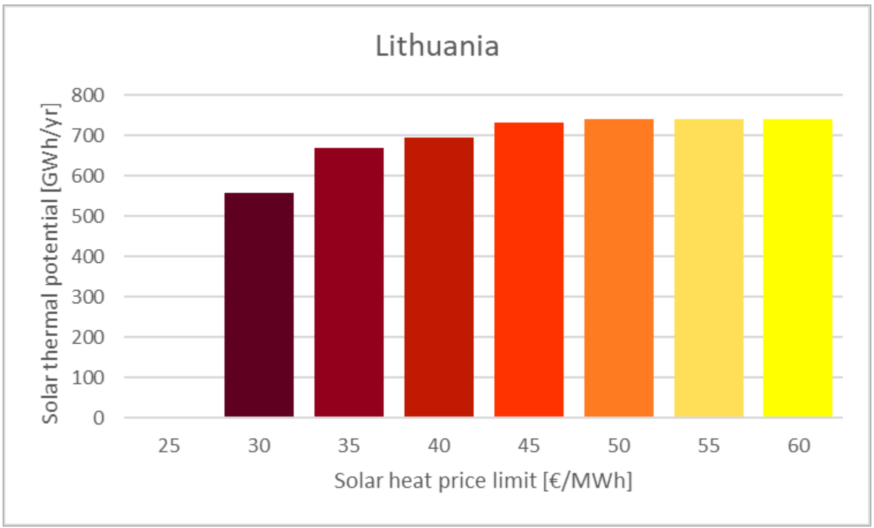

France
Solar thermal potential [GWh/yr]
800
700
600
500
400
300
200
100
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

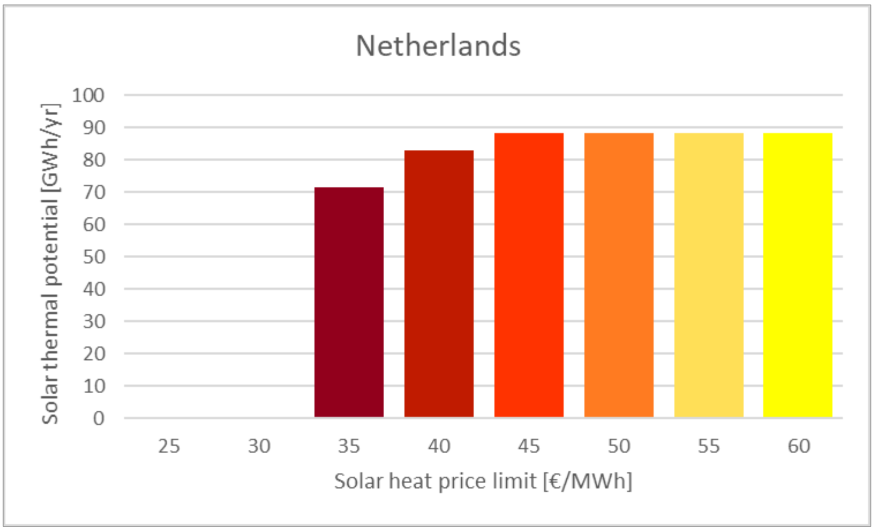

Germany
1,200
1,000
800
600
400
200
0
Solar thermal potential [GWh/yr]
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

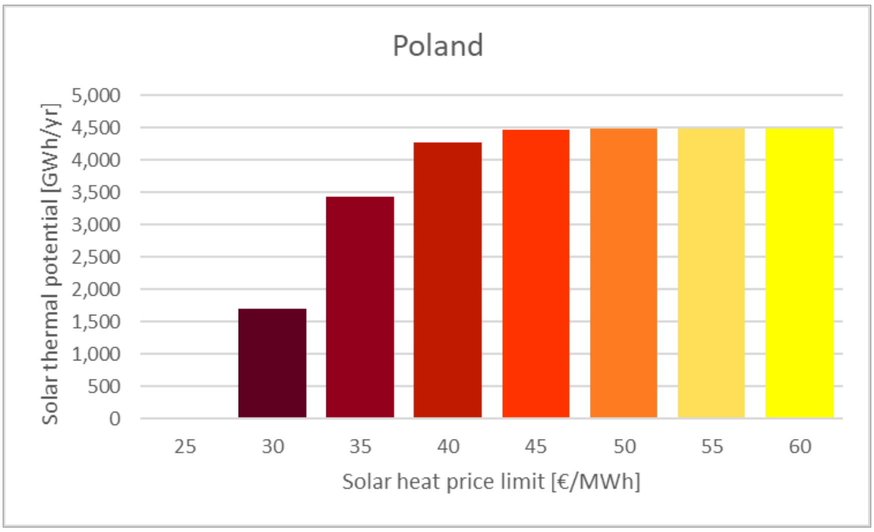

Hungary
1,200
1,000
800
600
400
200
0
Solar thermal potential [GWh/yr]
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

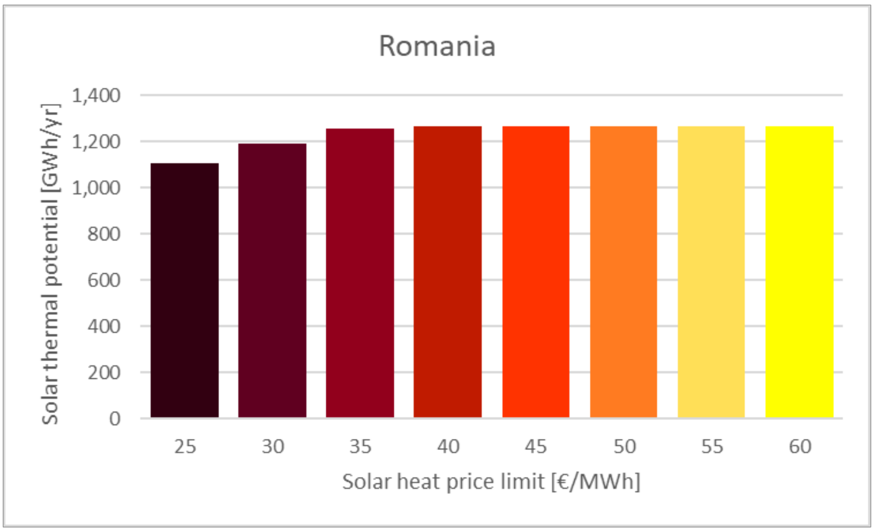

Italy
90
80
70
60
50
40
30
20
10
0
Solar thermal potential [GWh/yr]
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

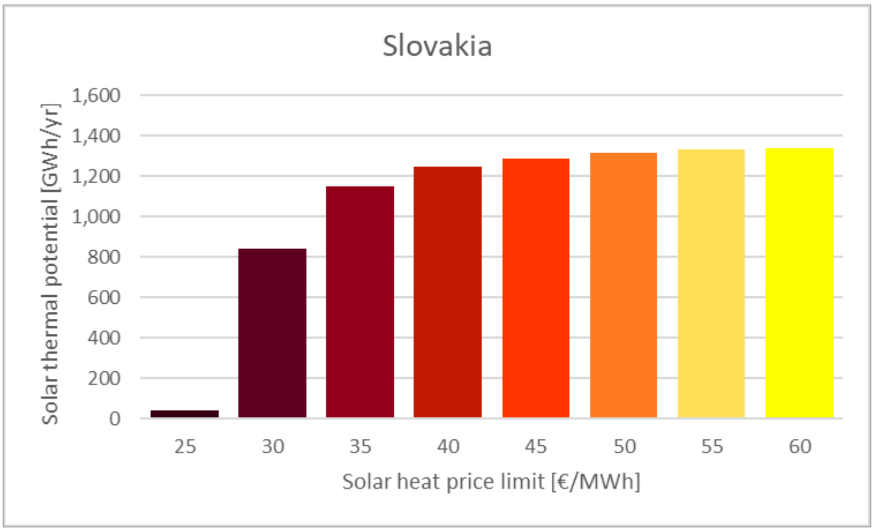

Latvia
Solar thermal potential [GWh/yr]
0
50
100
150
200
250
300
350
400
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

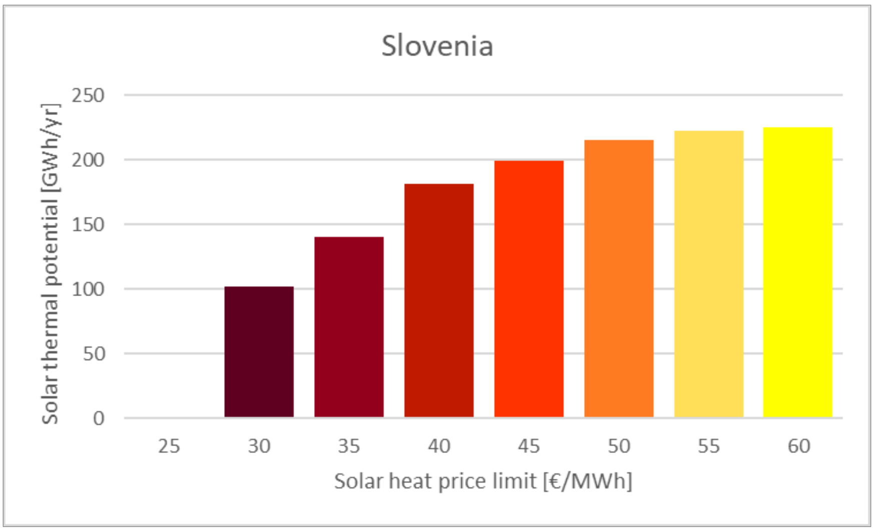

Lithuania
Solar thermal potential [GWh/yr]
0
100
200
300
400
500
600
700
800
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

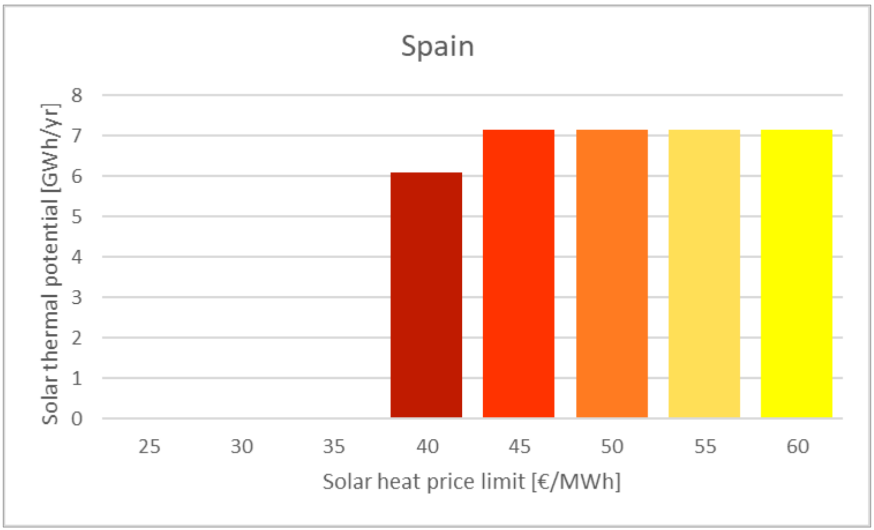

Netherlands
Solar thermal potential [GWh/yr]
0
10
20
30
40
50
60
70
80
90
100
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

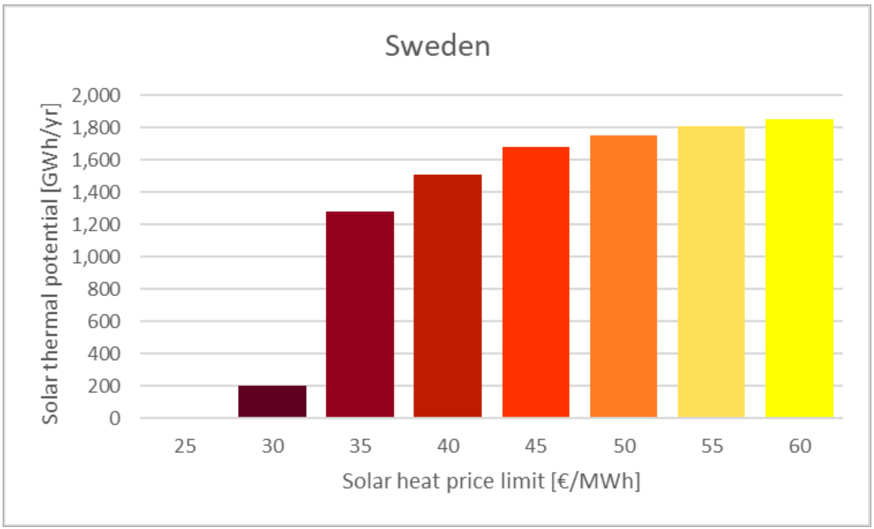

Poland
Solar thermal potential [GWh/yr]
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

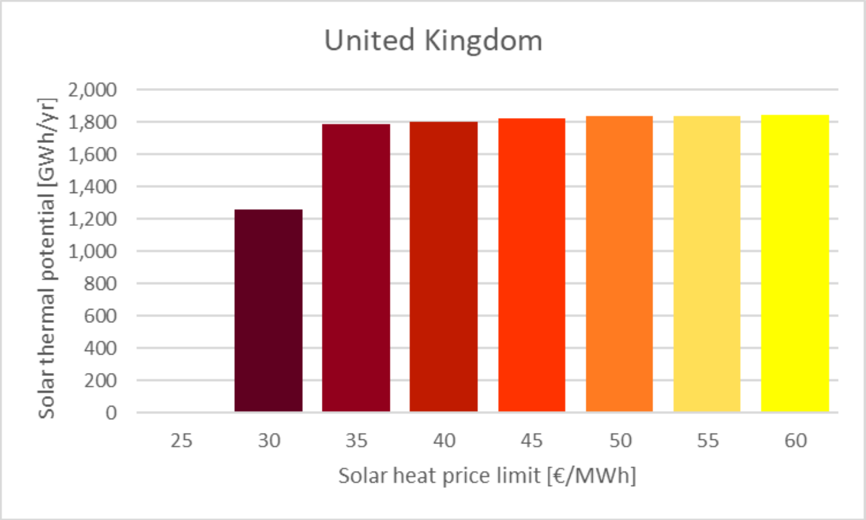

Romania
Solar thermal potential [GWh/yr]
1,400
1,200
1,000
800
600
400
200
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

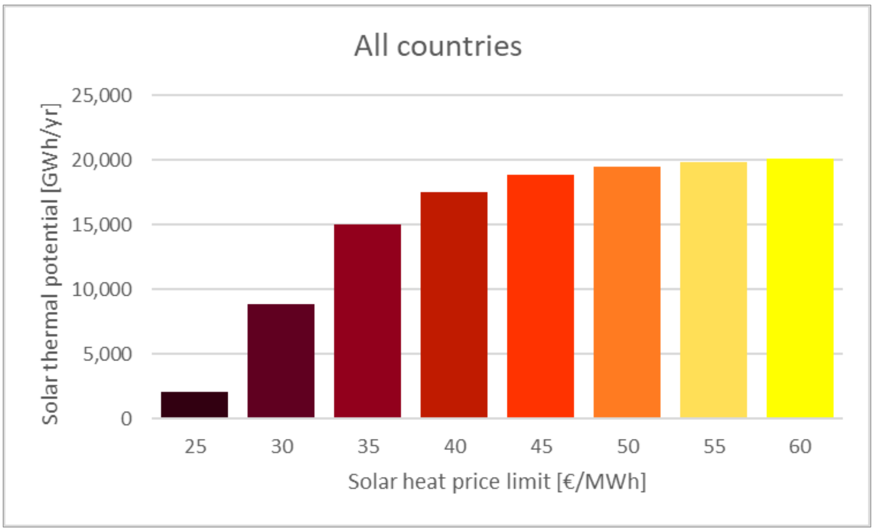

Slovakia
Solar thermal potential [GWh/yr]
1,600
1,400
1,200
1,000
800
600
400
200
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]


Slovenia
Solar thermal potential [GWh/yr]
0
50
100
150
200
250
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

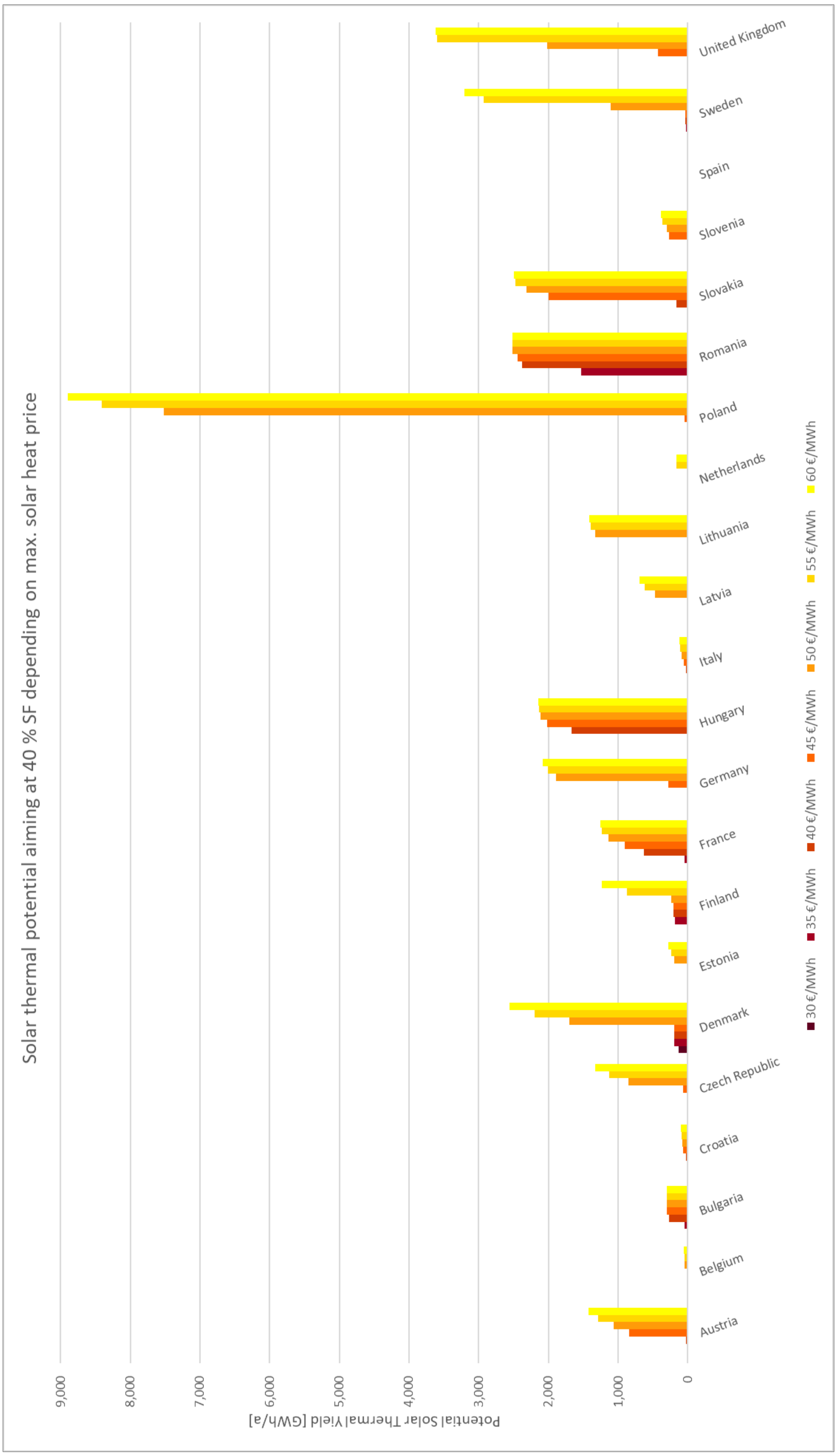

Spain
Solar thermal potential [GWh/yr]
0
1
2
3
4
5
6
7
8
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

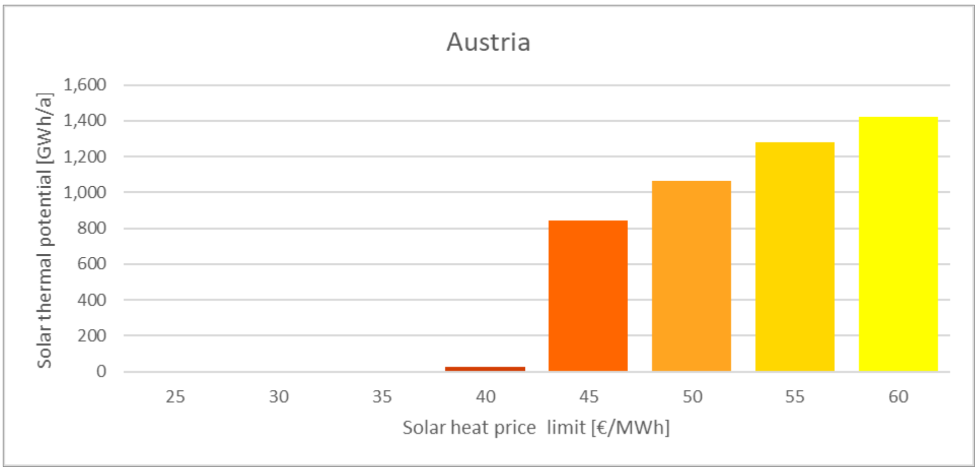

Sweden
Solar thermal potential [GWh/yr]
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
2,000
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

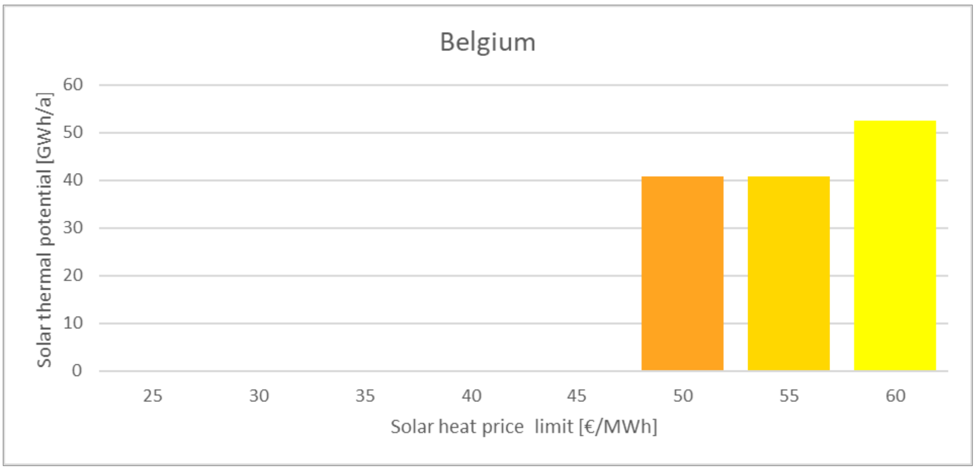

United Kingdom
Solar thermal potential [GWh/yr]
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

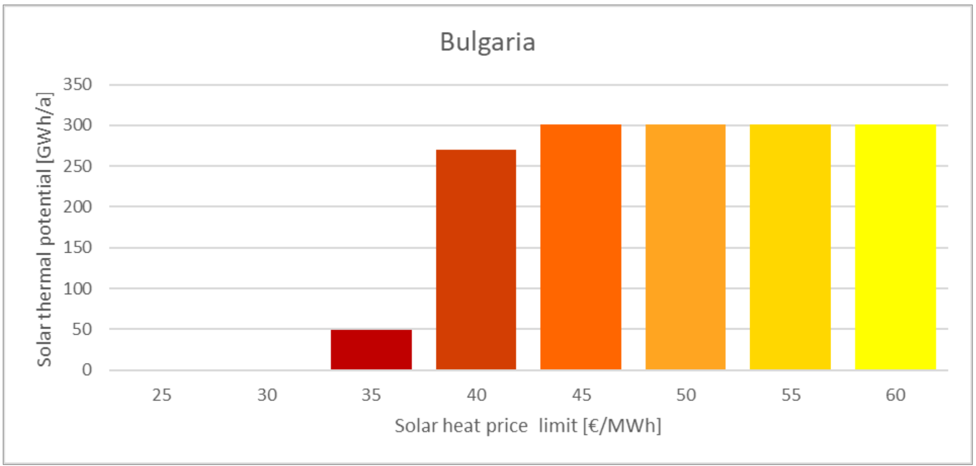

All countries
Solar thermal potential [GWh/yr]
25,000
20,000
15,000
10,000
5,000
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

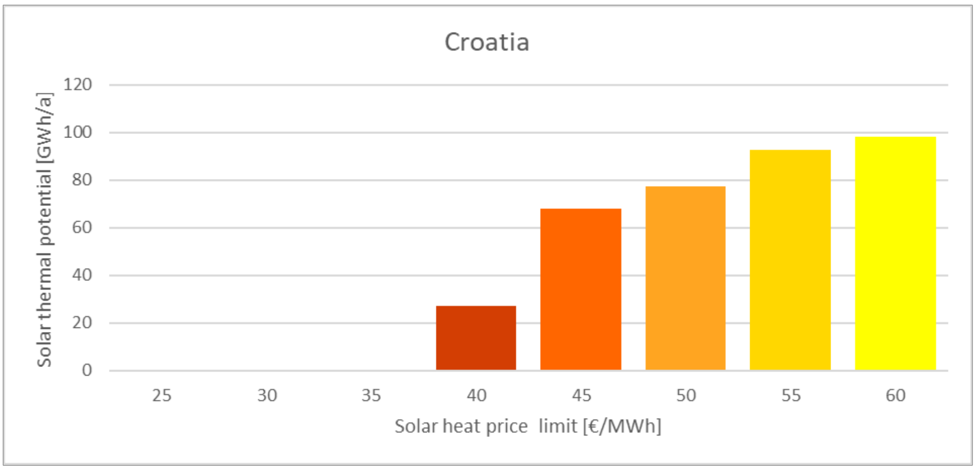
## Part B: Solar Fraction Target of 40 %

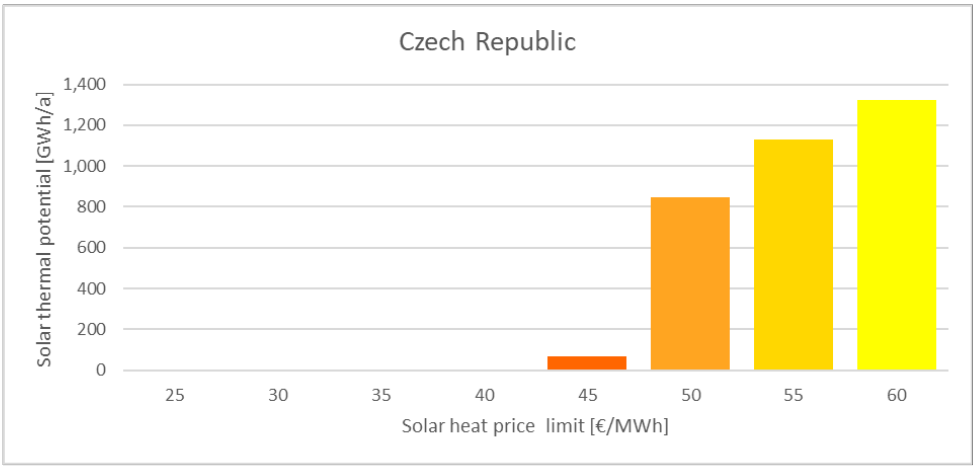


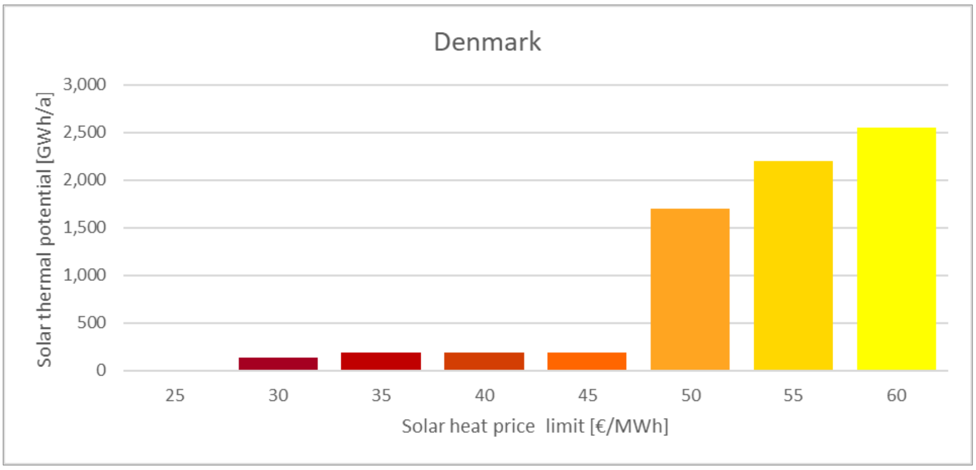

Austria
Solar thermal potential [GWh/a]
1,600
1,400
1,200
1,000
800
600
400
200
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

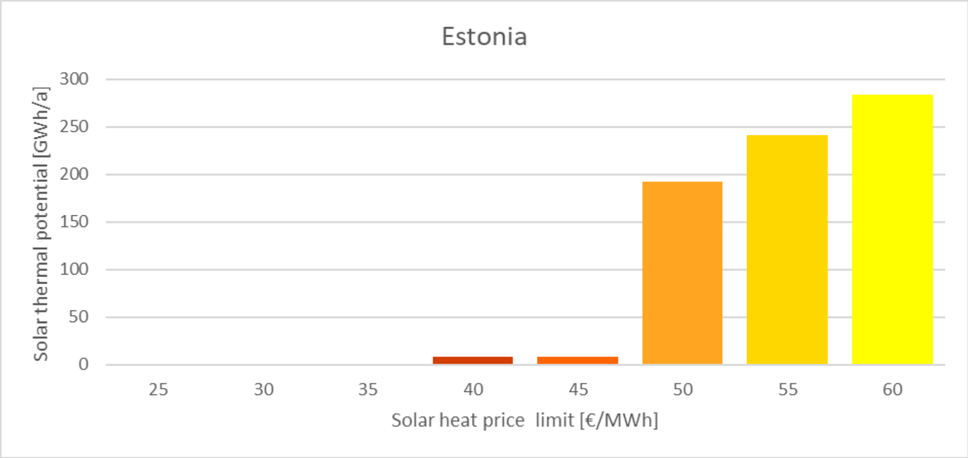

Belgium
Solar thermal potential [GWh/a]
60
50
40
30
20
10
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

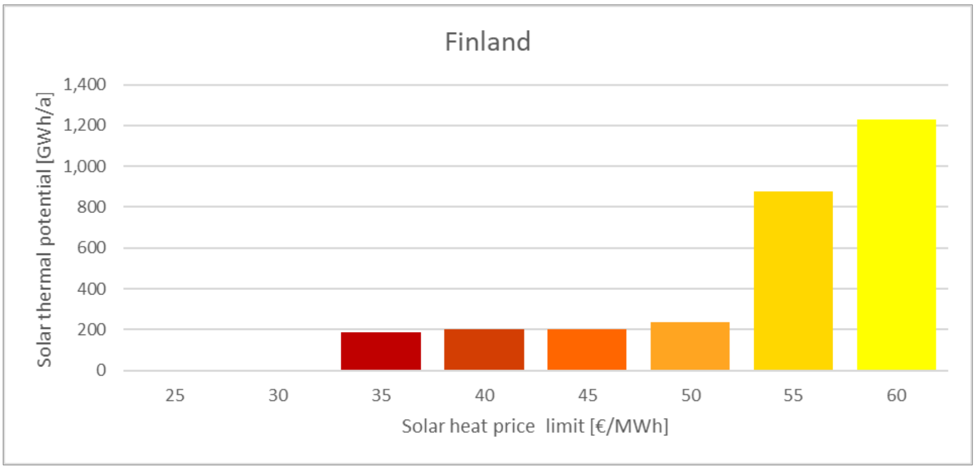

Bulgaria
Solar thermal potential [GWh/a]
350
300
250
200
150
100
50
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

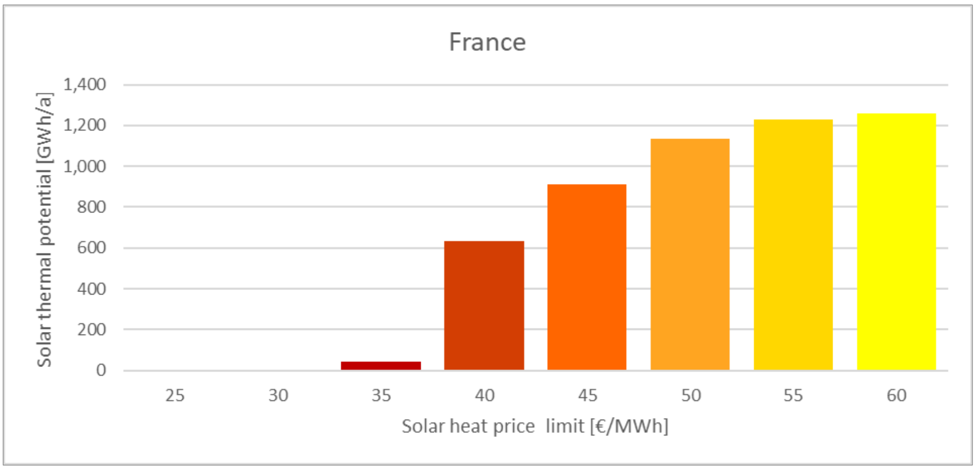

Croatia
Solar thermal potential [GWh/a]
0
20
40
60
80
100
120
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

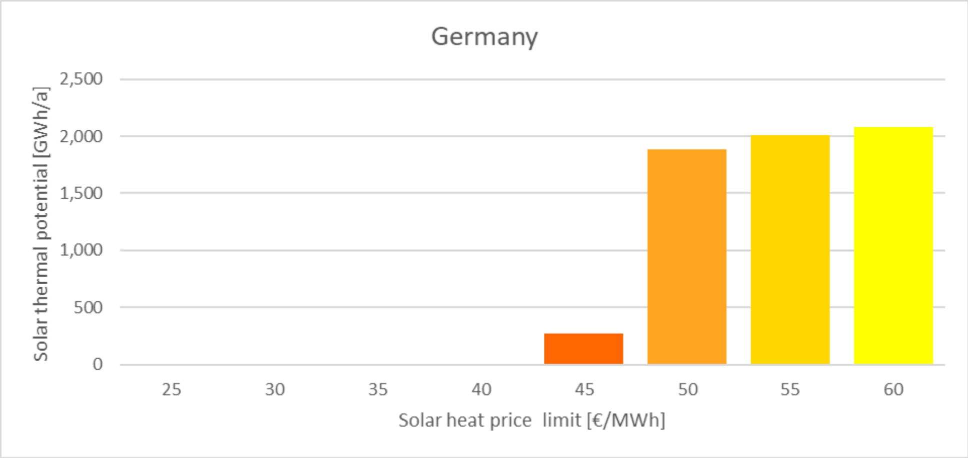

Czech Republic
Solar thermal potential [GWh/a]
0
200
400
600
800
1,000
1,200
1,400
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

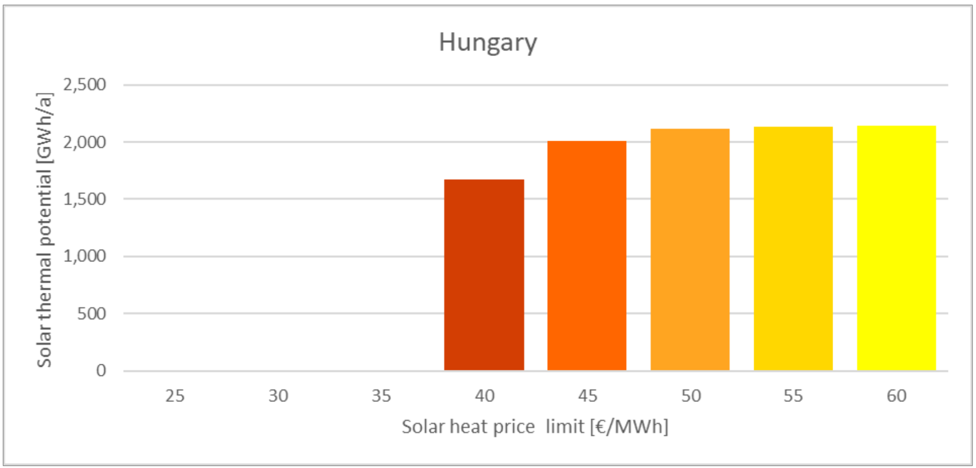

Denmark
Solar thermal potential [GWh/a]
0
500
1,000
1,500
2,000
2,500
3,000
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

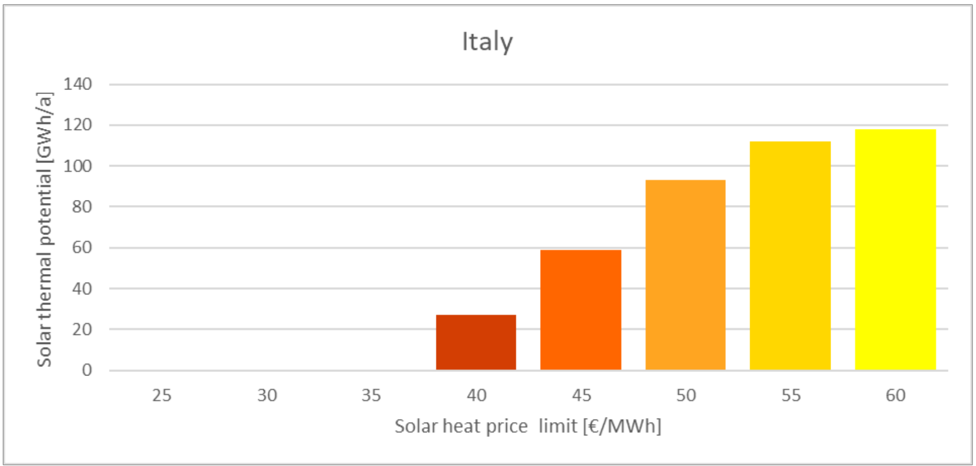

Estonia
Solar thermal potential [GWh/a]
300
250
200
150
100
50
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

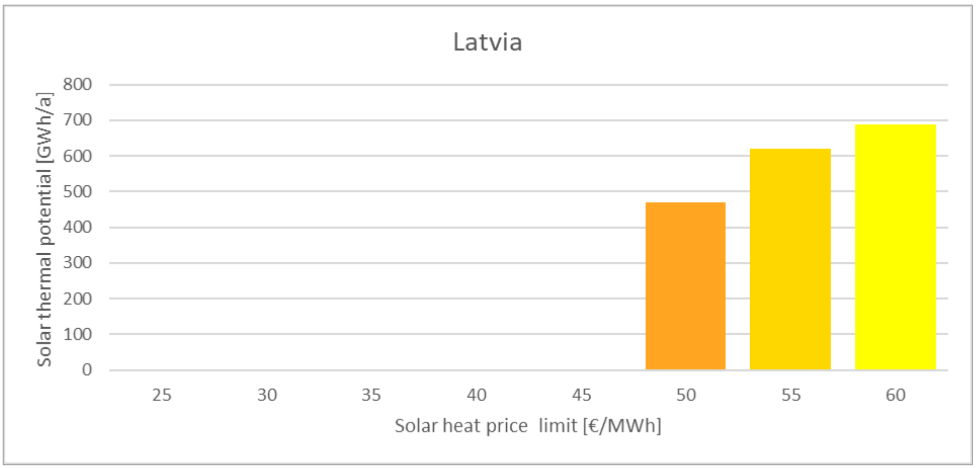

Finland
Solar thermal potential [GWh/a]
1,400
1,200
1,000
800
600
400
200
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

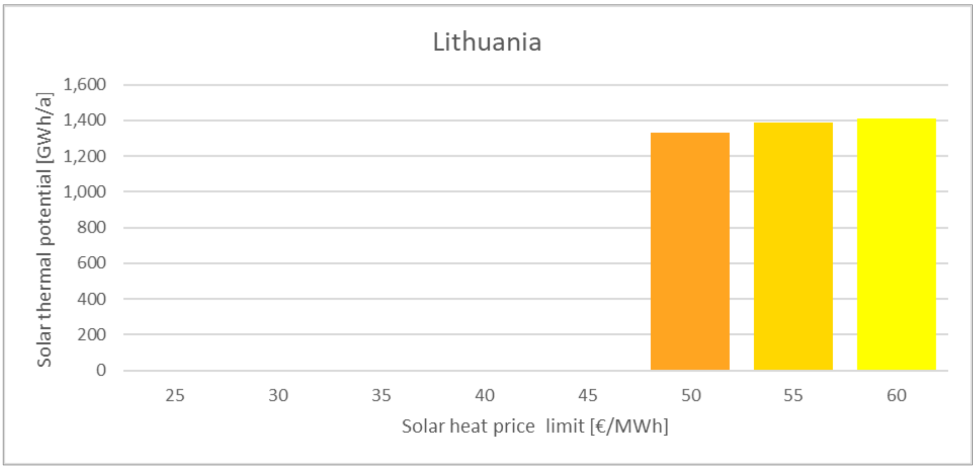

France
Solar thermal potential [GWh/a]
1,400
1,200
1,000
800
600
400
200
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

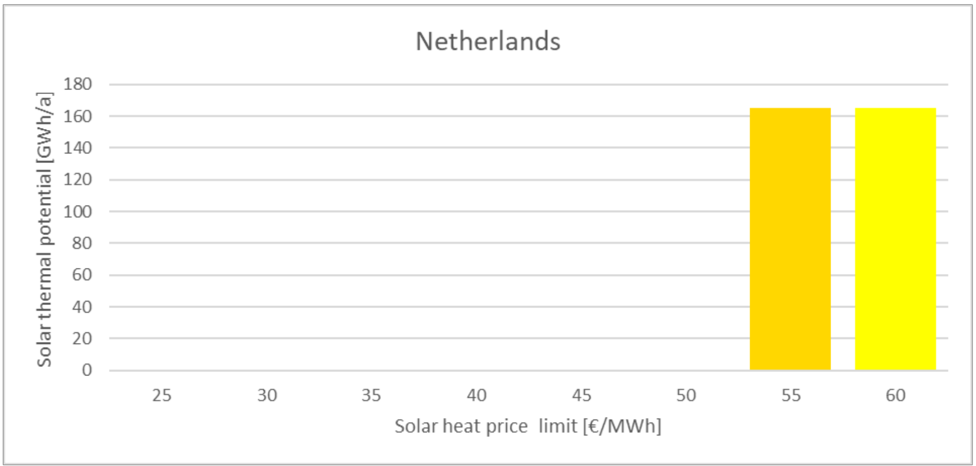

Germany
Solar thermal potential [GWh/a]
2,500
2,000
1,500
1,000
500
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

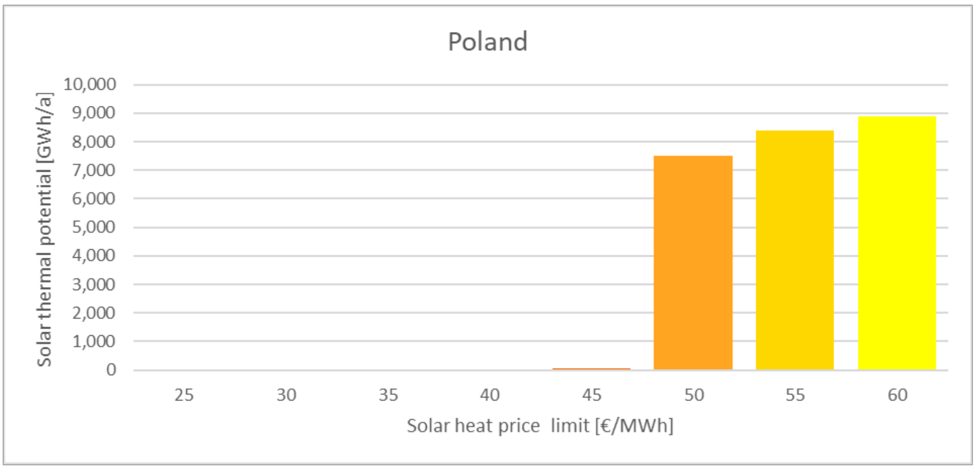

Hungary
Solar thermal potential [GWh/a]
2,500
2,000
1,500
1,000
500
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

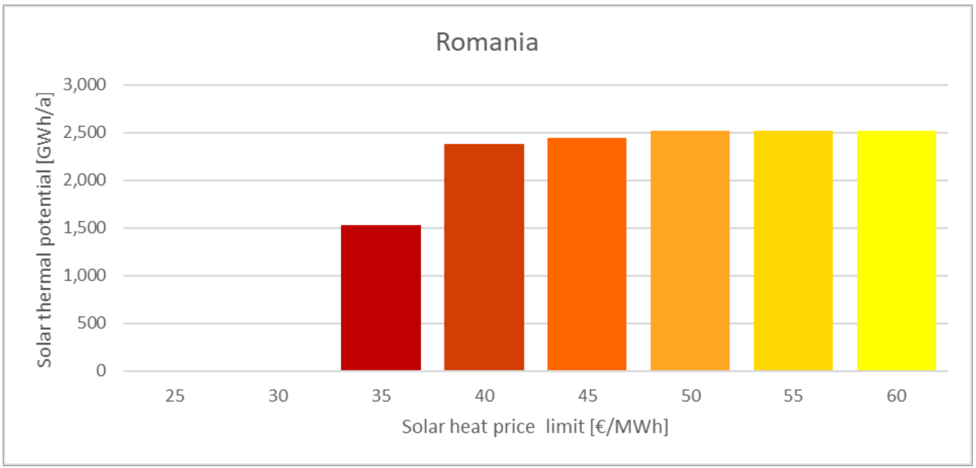

Italy
Solar thermal potential [GWh/a]
140
120
100
80
60
40
20
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

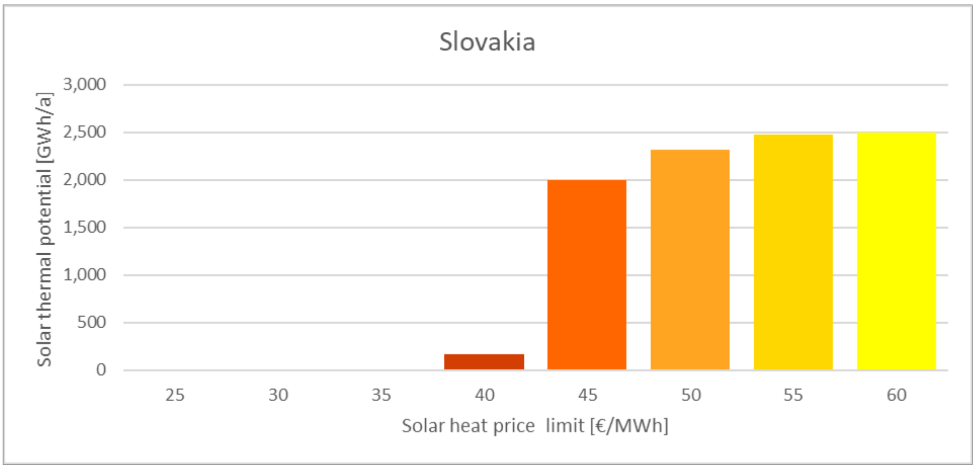

Latvia
Solar thermal potential [GWh/a]
0
100
200
300
400
500
600
700
800
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

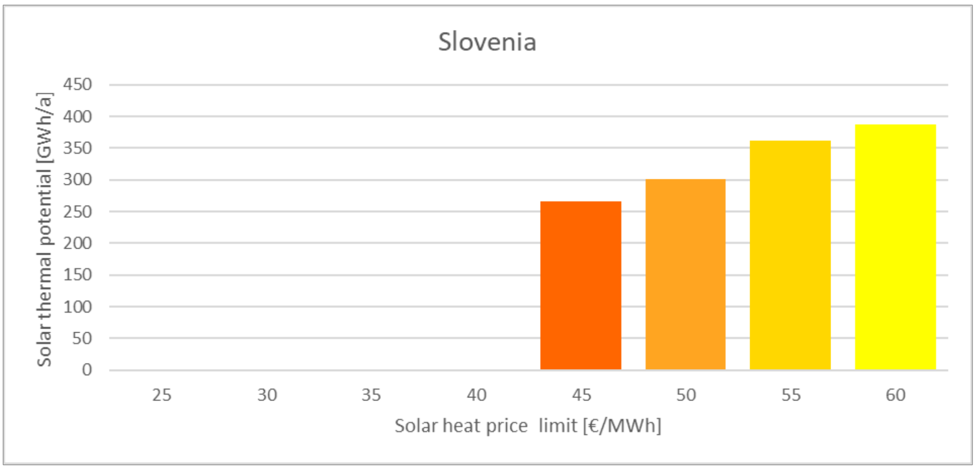

Lithuania
Solar thermal potential [GWh/a]
0
200
400
600
800
1,000
1,200
1,400
1,600
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

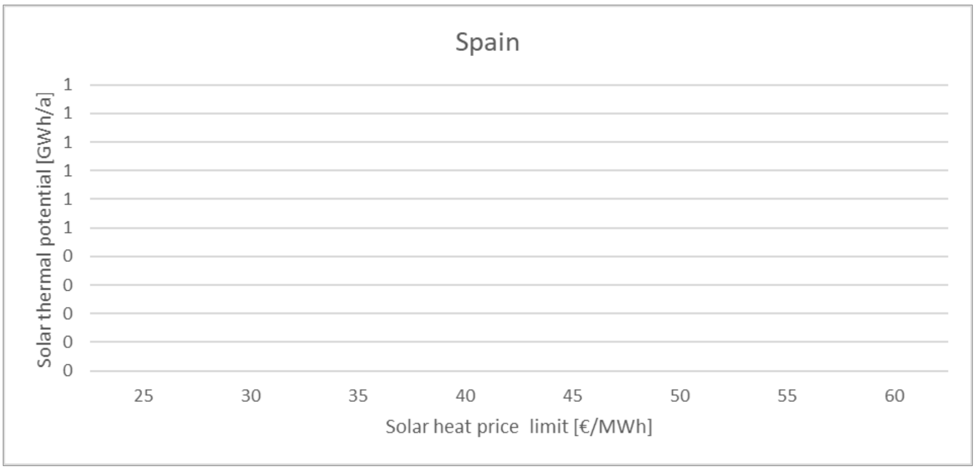

Netherlands
Solar thermal potential [GWh/a]
0
20
40
60
80
100
120
140
160
180
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

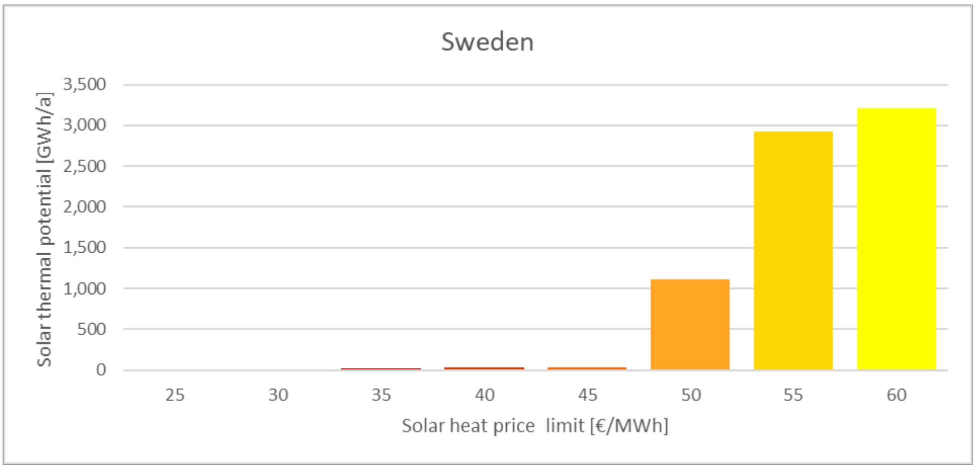

Poland
Solar thermal potential [GWh/a]
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

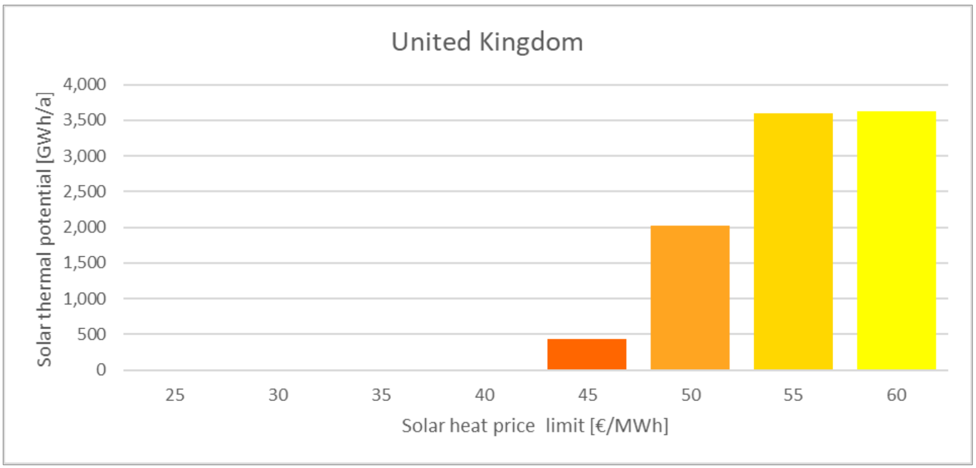

Romania
Solar thermal potential [GWh/a]
3,000
2,500
2,000
1,500
1,000
500
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]

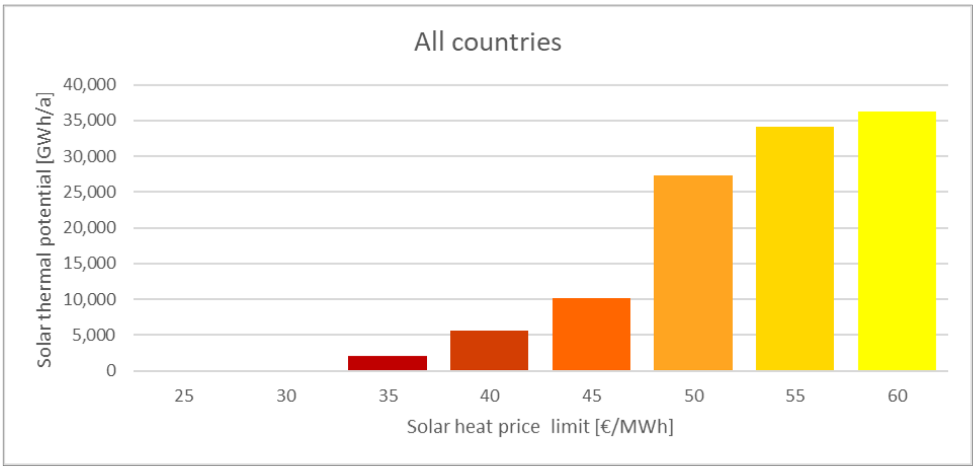

Slovakia
Solar thermal potential [GWh/a]
3,000
2,500
2,000
1,500
1,000
500
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]


Slovenia
Solar thermal potential [GWh/a]
450
400
350
300
250
200
150
100
50
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]


Spain
Solar thermal potential [GWh/a]
1
1
1
1
1
1
0
0
0
0
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]


Sweden
Solar thermal potential [GWh/a]
3,500
3,000
2,500
2,000
1,500
1,000
500
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]


United Kingdom
Solar thermal potential [GWh/a]
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]


All countries
Solar thermal potential [GWh/a]
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
25
30
35
40
45
50
55
60
Solar heat price limit [€/MWh]