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Solar fractions of SHIP plants considering the availability of roof area based on OpenStreetMap data

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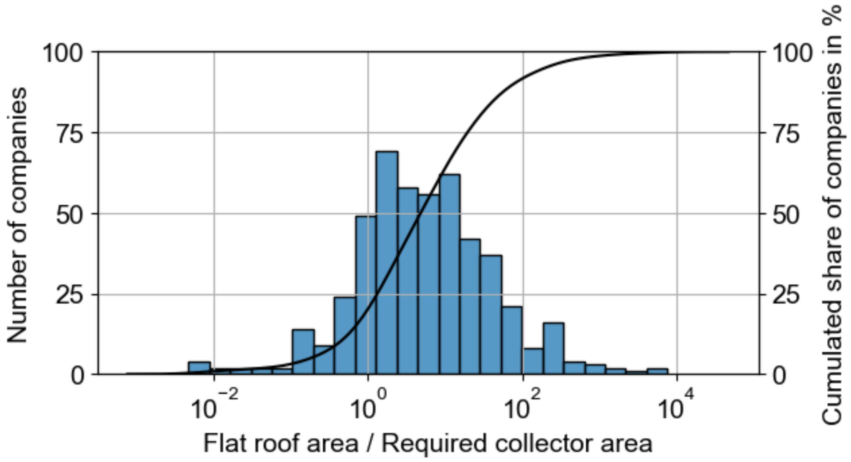
Abstract

Solar heat for industrial processes (SHIP) can be a key technology to decarbonize the industrial heat demand world-wide. Several national studies use either a bottom-up or a top-down-approach to assess the potential of solar process heat using estimated fixed solar fractions. Due to limited area available for the installation of solar collectors and the seasonality of the load profile, this solar fraction cannot be achieved in all cases. To address this limitation, another estimated factor is used in those studies. However, the impact of the lack of free area on solar fractions and overall solar potential has not been studied in detail so far. Therefore, a dataset with load profiles and roof areas from OpenStreetMap GIS data from 489 German companies from secondary and tertiary sector is set up in this study. Based on the standardized pre-design methodology of the VDI 3988 guideline, the evaluations show that one third of the regarded companies lack sufficient roof area whereas two third can provide their summer heat demand with solar collectors. Furthermore, the study shows that an ambient temperature dependent heat demand limits the solar potential in terms of solar fraction even more than the available roof area.



Keywords: Solar process heat; Roof area; OpenStreetMap; Pre-design

1. Introduction

The majority of energy in the EU consumed by industry is heat [1] . With respect to the targets regarding climate protection and reduction of CO_2-emissions, industrial process heat is to be provided with carbon free or at least low-carbon technologies. Compared to green electricity which can be produced off-site and transported via cables to the respective production sites, heat must be produced locally. Especially in some industries such as the chemical, basis metal, and not-metallic mineral products industry a significant share of the heat is needed at high temperatures with more

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than 400 °C and thus it cannot be provided by market-ready renewable technologies except direct electrical heater so far [2]. Nevertheless, a significant share of the heat demand for low temperature heat in other industries and the tertiary sector still results in a significant potential for heat pumps or solar collectors on national level as shown by several studies that analyse the potential of solar heat for process heat applications (Section 2.1). Typically, these case studies use a top-down approach analysing the overall industrial heat demand and temperature levels, thus calculating the theoretical potential with rough assumptions as no more information is available. In addition, some studies use a bottom-up approach that is based on a single-digit or low two-digit number of case studies. However, a bottom-up approach based on a broad database covering a high three digit-number of real companies is for the first time applied by this study. The solar potential is calculated based on both, the load profile of the company and the available roof area which are not available in other studies so far. This study addresses the potential of solar heating plants in industry and commerce on the pre-design level with respect to the load profile and the available roof area based on OpenStreetMap data. It is based on findings of previous research about the relevance of ambient dependent heat demand in industry [3,4] and on the VDI guideline 3988 “Solar Process Heat” which enhances the user to quickly calculate the collector area needed to cover the summer heat demand depending on region, temperature level and collector type [5,6].

2. Literature Review

Following the objective of this study to analyse the potential of solar process heat considering the load profile and the availability of roof area, national potential studies from literature are reviewed regarding these aspects. In addition, the literature review focusses on the lack of representative load profiles for industrial applications and how GIS data are used in solar research so far.

2.1 Potential studies for solar heating plants in industry

So far, two different approaches, either top-down or a bottom-up, are applied in studies to estimate the potential of the use of solar heat in industrial processes. The top-down approaches are based on statistical data on final energy demand for heat generation in industry, assumptions on efficiency and limitations of available area for solar collectors as well as an estimated solar fraction. In contrast, the bottom-up approaches analyse several companies in the respective countries in detail and assess the potential of solar collectors on a company-specific basis. These results are extrapolated to the entire industry in the country to evaluate the potential of solar collectors in industry.

2.1.1 Potential studies using a top-down approach

Van de Pol et al. [7] analyse the industrial heat demand in the Netherlands with a focus on hot water. They calculate the potential of solar heat with an estimated solar fraction of 30 % of the final energy demand for heating purposes. Limited roof areas are named as one major barrier without further quantification.

Müller et al. [8] assess the technical potential of solar heating plants in Austria. The authors differentiate between the potential for process heating and space heating. To estimate the short-term theoretical potential, the heat demand up to 100 °C is taken into account. The medium-term potential is calculated referring to the heat demand up to 250 °C. Based on that, the technical potential is calculated with the respective heat demand and the assumption that 60 % of the heat demand cannot be covered due to limitations on site (e.g., roof area) or a future increase of efficiency and a consequent decrease in heat demand. Using the remaining heat demand, a solar fraction of 40 % for process heating and 20 % for space heating is assumed to calculate the final technical potential. The authors do not differentiate between final energy demand for heating purposes and useful heat, but it can be assumed that the boiler efficiency is included in the lump-sum deduction of 60 %. To sum up, an overall solar fraction of the final energy demand for heating purposes of 16 % for process heating and of 8 % for space heating is determined for the defined temperature level.

Vannoni et al. [9] assess the potential in Greece, Wallonia, and some chosen processes in Germany. The study is focused on the industries chemicals, food and beverages, tobacco, paper, textiles, leather, and transport equipment. Hereby, they assume a solar fraction of 30 % of the final energy demand.

Lauterbach et al. [10] calculate the potential of solar process heat in Germany. Therefore, the heat demand in the suitable temperature level (below 300 °C) is determined. Based on this and following Müller et al. [8], Lauterbach et al. assume a reduction of the technical potential by 60 % due to efficiency measures and limited or statically unsuitable roof area. Finally, the technical potential is calculated by assuming a constant solar fraction of 30 % based on realized systems and previous studies. In contrast to Müller et al. [8], the authors do not differentiate between process and space heating. This results in an overall solar fraction of 18 % with respect to the suitable final energy demand of heat generation.

Within the APPSOL project, the company Aiguasol analyses the potential of solar collectors in the mining and non-mining industries in Chile [11]. Therefore, heat demand data are compared with region-specific irradiation data and a solar fraction of 30 % of the final energy demand is assumed.

For China, industry-wise solar fractions of the final energy demand are assumed to assess the technical potential of solar heating plants [12]. These solar fractions are in the range of 5 % to 10 %.

2.1.2 Potential studies using a bottom-up approach

To assess the potential of solar heating plants in industry for Spain and Portugal, Schweiger et al. [13] analyse more than 30 companies from eight industries in detail and extrapolate the results to the entire industry in both countries. In these case studies, a minimum solar fraction of 6 % and maximum solar fraction of 60 % with respect to the final energy demand is evaluated. The study yields that the available (roof) area is a limiting factor for the technical potential “in nearly all cases studied” [13]. The results of the case studies are extrapolated to the whole industries.

The potential study for Sweden [14] is based on the results of the methodology of Schweiger et al. for the Iberian Peninsula. They transfer the relation of the technical potential to the overall heat demand from Spain and Portugal to Sweden considering the lower irradiance and calculate thus a country-specific potential of solar heat in industry.

2.1.3 Summary potential studies

To sum up, the presented potential studies use comparable methods to calculate the potential of solar collectors. All studies have in common that they work with roughly estimated values which are assumed to be representative for the entire industry (e.g., solar fraction of 30 % of the final energy demand in top-down approaches) or with detailed calculations for a few companies which cannot be regarded as representative for the entire industry as the number of companies is quite low (bottom-up). All top-down approaches are based on data about the final energy consumption. A boiler efficiency is not considered to calculate the heat demand but partially a lump sum discount is used to derive the technical from the theoretical potential which could implicitly contain losses of heat supply infrastructure. With respect to the final energy demand for heating purposes, the range of the solar fraction is between 8 % [8] and 60 % [13] for the different countries. In addition, several studies highlight the limitations of available roof area without further quantification of this limitation.

Tab. 1: Summary of the national potential studies for solar process heat

Country	Approach	Analysed demand	Efficiency factor reducing heat demand	Estimated solar fraction	Roof area mentioned as limiting factor	Ref.
Netherlands	top-down	Final energy demand for hot water generation		30 %	x	[7]
Austria	top-down	Final energy demand for heating purposes with suitable temperature range	60 %	30 % / 20 %	x	[8]
Greece, Wallonia, Germany	top-down	Final energy demand of chosen processes	-	30 %		[9]
Germany	top-down	Final energy demand for heating purposes with suitable temperature range	60 %	30 %	x	[10]
Chile	top-down	Final energy demand for heating purposes in mining industry	-	30 %		[11]
China	top-down	Final energy demand for heating purposes in selected industries	-	5-10 %		[12]
Spain and Portugal	bottom-up	Final energy demand for heating purposes in case studies and selected industries	-	6-63 %	x	[13]
Sweden	bottom-up	Final energy demand for heating purposes in case studies and selected industries	-	-	x	[14]

2.2 Load profiles

In contrast to residential applications, representative heat load profiles from industry and commerce have not been in the focus of research so far. Hellwig [15] presents a method to develop aggregated load profiles for commercial applications, however with no reference to industrial heat loads. He describes the daily natural gas consumption for (space) heating purposes as a normalized function of the daily mean ambient temperature. In the national potential studies using a top-down approach, realistic load profiles are not part of the analysis. The authors estimate the load profiles to be constant throughout the year. This enables higher solar fractions compared to load profiles with significant differences between summer and winter loads. The study from Schweiger et al. [13] describes the results from several case studies, so the load profiles are estimated to be considered which might explain the big differences in the potential solar fractions. Recently, the authors of this study presented a methodology for representative load profiles for industries from the secondary and tertiary sector which is summarized in section 3.1.

2.3 Estimation of roof area based on GIS-data

It is beneficial to install solar collectors on the roof of the respective building which should be supplied with solar energy. However, as described in section 2.1, the availability of suitable roof area is named as a limiting factor in several case and potential studies without a sound quantification of the limitation. Nonetheless, a certain reduction factor is used to calculate the potential of solar heating plants based on the final energy consumption in the respective countries that are analysed. In contrast to studies on the solar heating sector, several studies addressing photovoltaic applications analyse the availability of roof area. Mellius et al. [16] summarizes different possibilities to assess roof area and distinguish between three types of methods. Constant value methods evaluate the roof area based on projections from typical rooftop configurations and rough estimations of the proportion of the roof parameters such as slope, orientation, and type of roof [16,17]. These methods allow a quick and simple estimation. Manual selection methods are based on a manual evaluation of roofs based on satellite data or other aerial photographs [18–20]. These analyses allow - if data are available - a very detailed calculation of the roof area but can be very time-consuming. Finally, GIS-based methods allow the analysis of a big datasets in acceptable time and have become quite popular in research in recent times [21]. A lot of studies are based on the work with GIS software such as ArcGIS [22], SRI's ArcMap [23], ArcVIew [17], and QGIS [24]. Typically, the use of this software enables precise analyses, but the data must be purchased for this purpose. The software tools partially even offer 3D information about the building stock that are derived from LIDAR data (Light Detecting and Ranging). Therefore, only a certain area is detected and divided into a grid as used by [19]. The shapes of several thousands of houses can be measured and the roof slope can be estimated with an accuracy of 0 ° to 5 °. As this methodology offers a very good quality, it has been used to create several solar cadastres in Germany [25–27], primarily addressing the PV sector, with the aim to evaluate the solar potential based on roof area but not related to heat load profiles.

GIS-data are recently used primarily to analyse the potential of roof-mounted photovoltaic (PV) systems. Ali et. al. analysed the potential of roof-mounted PV on the Maldives based on Google Earth pro Data [18]. Therefore, a polygon is drawn on the outline of the roof to estimate the footprint area of a building assuming every roof to be flat. The authors estimate this to be a conservative estimation as sloped roofs are slightly bigger than flat roofs. Without any further explanation, a usability factor between 30 % and 50 % is assumed to estimate the respective PV potential. As no real electric load profiles are available, solar fractions cannot be indicated. A comparable approach has been chosen by Charabi et al. [19] who estimated the potential of PV in Oman and based their calculation also in data from Google Earth. To estimate a realistic use of the available area, they considered a distance of 1.2 m between the collector rows and the edge of the roof and other limitations such as a certain distance to avoid significant shading, resulting in a 54 % fraction that is available. Consumption data are not available and could not be considered. Alhamwi et al. [28] assessed the potential of decentralized renewable energy generation in Oldenburg, Germany. Based on footprint areas of building, which were calculated from OSM data, a potential of roof-mounted PV is calculated and compared to the electricity consumptions estimated from a standard load profile. If only satellite data are available, deep learning algorithms are used to identify roof areas by Huang and Mendis [20] at the example for Wuhan. But also in this case, the slope and shape of roof area are not available, so the roof was estimated to be flat to estimate to respective available area.

2.4 Summary of literature review

The presented literature review shows that the availability of roof area is mentioned in several studies as a potential limit for solar solutions. Nonetheless, none of the studies quantifies the limitations based on a relevant number of case studies. Vice versa, available studies considering the roof area based in GIS or satellite data only refer to the roof area without taking into account the load profiles.

So far, the authors are not aware about available studies on the solar potential based on a roof area analysis based on GIS data. Furthermore, there are no studies available, that analyse the technical potential of solar heating plants or PV plants based on real load profiles in conjunction with the available roof area. Typically, load profile data (heat and electricity) are not available for a large number of consumers. This is especially true for industrial applications. If the energy consumption is taken into account in the studies about the availability of roof area, only standard load profiles or other generic load profiles are used to calculate solar fractions.

3. Methodology

First, the underlying database and the pre-work regarding the seasonality of the load profiles with the respective cluster assignment is described which play a significant role for this study. Second, the conversion from gas consumption the heat demand is defined and the pre-design methodology of the VDI 3988 guideline is summarized. Finally, it is outlined how addresses of the companies are used to estimate available roof area from the companies using the OSM database.

3.1 Pre-work and description of the database

In a previous study, the authors of this paper analysed a non-representative but large database with 797 natural gas load profiles [3] which is the basis for this study. The methodology for pre-processing, filtering, and clustering is the described in detail in the author’s previous study and therefore only briefly summarized in the following. The database of originally 797 annual heat load profiles with an hourly resolution is reduced by dropping incomplete load profiles or load profiles with strong anomalies due to special events, e.g., long maintenance shutdowns. In addition, companies using a combined heat and power plant (CHP) are excluded as their gas consumption profiles do not represent the actual heat demand. Finally, 489 companies are remaining in the pre-processed database.

In line with Pag et al. [29], the study yields that space heating also accounts for a significant share of the total heat demand in industry. Fig. 1 shows characteristic functions for the heat demand for four different clusters separately for weekdays (Fig. 1 (a)) and five different clusters for holidays (Fig. 1 (b)). The daily heat demand is calculated based on the daily mean ambient temperature and normalized to the heat demand at a day with 8 °C mean temperature according to Hellwig [15]. The clusters can be distinguished based on their different dependence on the ambient temperature and thus their fluctuations over the course of the year. As shown in Fig. 1 (a), cluster 0 represents a company with nearly constant heat demand throughout the year which is typical for processes with no reference to ambient air such as hot water heating, cooking or high temperature processes. In contrast, cluster 3 represents companies with a low heat demand at high ambient temperatures (summer) but facing high heat loads during winter. In consequence, the heat demand in industry cannot be assumed to be constant over the year for every company. The more the heat load profile depends on the ambient temperature, the lower is the heat demand in summer in relation to the heat demand in winter. Consequently, this has an impact on the solar fraction, which can be achieved at affordable costs.

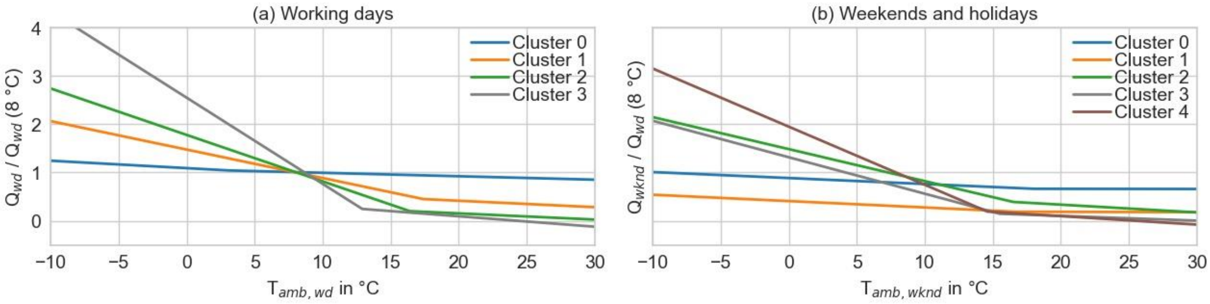

Fig. 1: Linear cluster regression functions for working days (a) and weekends and holidays (b). $Q/Q_{wd}(8°C)$ is the daily heat demand normalized to the mean heat demand on working days with a mean ambient temperature of 8 °C [3].

Depending on the industry, companies operate with specific processes in their production. These processes mainly determine the course of the heat load profile over the year. There is no specific information available about the companies analysed in this study, their processes, or their heat supply infrastructure. Based on the head load profile, each company is assigned to a cluster representing the ambient temperature dependency of the head load according to Jesper et al. [3]. In addition, each company was assigned to an industry from the secondary or tertiary sector according to the NACE classification [30] based on manual research. Industries which are represented by less than ten companies were grouped by “Others”. As Fig. 2 shows, each identified heat demand clusters can be found in nearly each industry. Nonetheless, in some industries ambient temperature dependent clusters dominate versus constant load profiles and vice versa. To give an example, the food industry is dominated by companies from cluster 0, i.e., companies with constant heat load profiles throughout the year. This can be explained by typical processes within the food industry, such as cooking, pasteurizing and water heating [3]. Their heat demand is dominated by heating fluids or air streams without any interaction to the ambient air. In contrast, all industries with a high share of assembly work (e.g., manufacture of motor vehicles, manufacture of machinery, machinery of electrical equipment, and manufacture of computer products) show a relevant share of ambient temperature dependency in the heat demand. This can be deduced to ventilation systems and space heating which are needed to comply with the working conditions. Next to the heat load profiles, only the addresses of the companies are available.

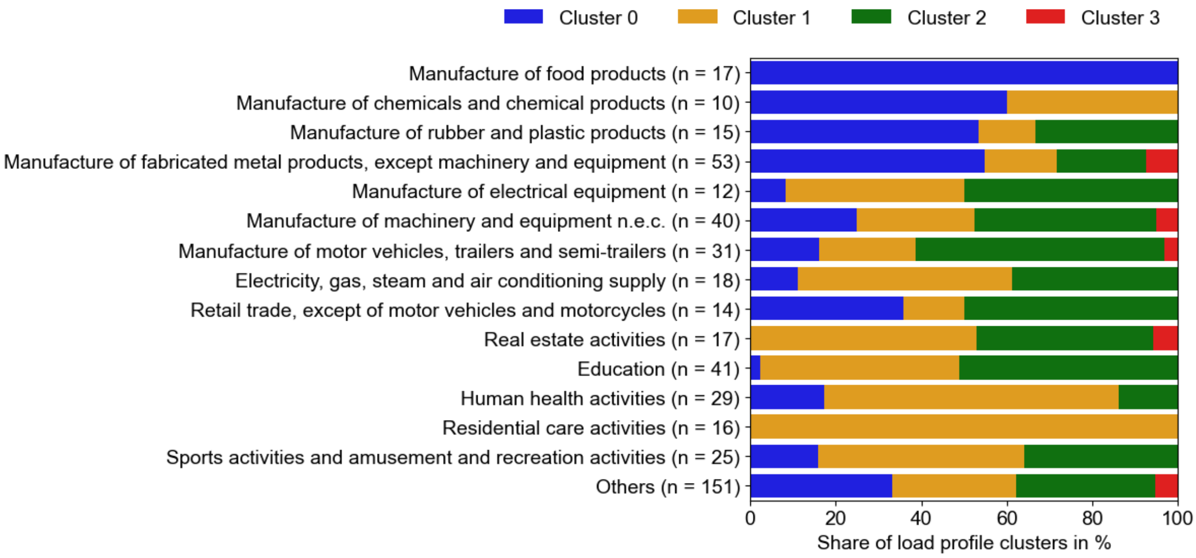

Fig. 2 Distribution of working day clusters in secondary and tertiary sector [3], industries which are represented by less than ten companies were grouped by “Others”

Finally, the authors want to highlight, that the respective database of industrial gas consumption profiles cannot be regarded as representative by itself as the companies were not specifically selected but only provided by the gas network providers. Nonetheless, this database outnumbers the number of companies which are analysed in the bottom-up potential studies in the past (see 2.1.2) by far and it represents a large spectrum of industries and applications. Information about the companies is confidential and cannot be provided in this paper as agreed with the utilities that provided the data.

3.2 Boiler efficiency

The load profiles used in this paper represent the hourly natural gas consumption of the respective company. In this study, it is assumed that the entire amount of natural gas is used to provide heat. This assumption is evaluated in the author's previous study. They find that other heat generators and gas uses are still rare and consequently the resulting error is small [3]. While the authors developed normalized load profiles over the year in the earlier study, the focus of the present study is on the absolute heat demand. An annual boiler efficiency of 75 % according to [31] is applied to calculate the heat demand from the natural gas consumption. Only little information on annual boiler efficiencies in industry is available [32,33], but an annual efficiency of the boiler of 75 % seems to be realistic from the authors' experience.

3.3 Design methodology and calculation of the solar yield

The solar heating plant is designed according to VDI 3988 guideline [5]. Herby, the solar collector field is dimensioned to fully cover the mean daily heat demand with solar heat on a sunny summer day. This system design aims to avoid solar excess heat and to reach favourable economic operation. The median of the daily heat demand is evaluated on weekdays for the period between July 1st and August 31st and used as the summer-day mean daily heat demand for the VDI evaluations. The VDI 3988 guideline contains design values for the collector field in m^2/kWh_{gr} as a function of the mean collector temperature for two regions (Northern/Central and Southern Europe) and different collector types. The mean collector temperature is calculated by eq. 1 taking into account the process temperatures as well as a temperature difference for each of the heat exchangers (n) between the solar heating plant and the heat sink. As it is typical for most installed solar heating plants, two heat exchangers are assumed, one separating collector and storage charging loop and one separating storage discharging loop and heat sink.

$$T_{mean,col} = \frac{T_{process,flow} + T_{process,return}}{2} + n \cdot 5K \qquad \text{eq. 1}$$

The solar yield is calculated in several steps. Firstly, the collector yield with an independent heat sink (collector annual output) is calculated according to [34] and as used in Solar Keymark certificates assuming an ideal inclination and orientation. So, all heat that is generated by the solar collector is used and any kind of losses are not considered. Consequently, this is a very positive estimation of the solar yield. Secondly, a correction factor is used to consider heat losses, storages losses in dependence of the mean collector temperature and the type of load profile (five-day vs. seven-day week). Finally, correction factors for orientation and inclination are used. Due to these factors, the calculated solar yield is reduced, and the solar collector area increases to still completely cover the heat demand on a sunny summer day. For this work, an orientation with an azimuth angle of 0 °and tilt angle of 35 ° is chosen as no information about roof style, orientation, or slope is available as discussed in 0. This orientation and inclination shows best results [5] and is typical for Northern and Central Europe.

eq. 1 needs the process flow and return temperature to calculate the mean collector temperature. A process temperature of 80 °C and a return temperature of 60 °C is defined for the reference case as this is a typical mean temperature level in industry [10,35,36]. Taking the temperature level into account, a vacuum tube collector is chosen for the system pre-design in this study. Central Europe is selected as the location.

In the following, the collector area, which is calculated according to the VDI 3988 methodology, is defined as “required collector area”. The solar fraction is calculated as the relation between the solar yield and the useful heat demand of the respective company according to [37]. In case the required collector area is higher than the available roof area, the possible solar yield is decreased linearly with the available roof area. In consequence, the specific solar yield is constant independent of an over- or under sizing of the solar heating plant. In many cases, solar heating plants are installed as a preheating plant. Hereby, the specific solar yield increases if the solar collector area is undersized to meet the heat demand. Assuming the specific solar yield to be constant is corresponding to a set temperature control as it is common in large solar heating plants [38]. Nonetheless, the authors underline, that this is a conservative assumption for the solar heating plant and its solar yield. Consequently, the solar fraction could be higher in the case of an optimized system control.

3.4 Calculation of roof areas based on OpenStreetMap

To approximately estimate roof areas, freely available data of the OpenStreetMap (OSM) project [39] are used. OSM is a crowdsourced spatial database, nowadays widely used in different educational, research, governmental and industrial applications [21]. In comparison with other sources, OSM provides good quality of data which is also due to regular updates of the large OSM community [21,40]. In OSM, various physical entities such as buildings, roads, or even trees are represented by their 2D geometries (e.g., polygons, line strings, points) in a geographic coordinate system. The basic data structure of OSM consists of nodes, ways, and relations. A node is defined by its coordinates. A way is a connection of several nodes and can define a non-closed object, e.g. a street, or a closed object, e.g. the footprint of a building [40]. Furthermore, every node or feature can be tagged to attach attributes which describe the respective item. The number of tags is unlimited and there is no fixed list of tags, but anyone can create new tags as needed. A tag consists, comparable to a dictionary, of a pair: a key and a value. The key is used to describe a property name whereas the value describes the key-specified feature. For this work, the keys “building” and “landuse” are relevant and used as explained below. A building can also be tagged with more information on the roof characteristics. For example, the roof shape can be characterized by the most typical shapes such as “gabled”, “flat”, etc. In addition, information about “orientation”, “height”, “inclination of the sides”, and the “material” of the roof can be specified. Since only the minority of buildings has more detailed roof information, it not used in the presented study.

The following steps are carried out to identify the roof areas based on the addresses of the companies:

- Geocoding of the addresses with Nominatim package from the GeoPy library to their respective coordinates
- Verification, if the coordinates are located within a building polygon
- Selection of the polygon nodes
- Calculation of the ground area of the polygon
- Verification, if the building polygon is located within a larger surrounding polygon – a land area with the property “landuse” being either “industrial” or “commercial” as the land use property describes the primary use of a property and thus it can be identified if the building is part of a coherent industrial complex
- Selection of the polygon nodes
- Selection of all building polygons with the land area and calculation of the respective area

- Verification, if all polygons within the same land area can be assigned to the single company by a detailed manual evaluation based on OSM data, googlemaps and web pages of the companies
- Assignment of the respective area to the company

Since the OSM does not provide reliable information about the form, slope, or orientation of the roof, all the roofs are assumed to be flat. The area of the roofs is supposed to be equal to the ground area of the building. It cannot be estimated if the roof area is over- or underestimated under this assumption. If the roof has a slope, the area is increased compared to the projected area and in addition, no distances between the collectors must be taken into account to avoid shading. On the other hand, if the roof has a slope and is oriented accordingly towards the south, half of the area cannot be used as it is oriented to the north. Finally, it is assumed, that all roofs are statically suited to be used with solar collectors which is expected to be a very optimistic assumption.

In the further work, the roof area is compared to the required collector area of the solar heating plant which is evaluated with the area availability factor according to eq. 2. It describes if the flat roof area is a restriction to the design of the collector area.

$$f_{roof/col} = \frac{A_{roof}}{A_{col,req.}} \qquad \text{eq. 2}$$

Furthermore, an exploitation factor is introduced which evaluates the exploitation of the roof area with solar collectors by geometric limitations to estimate a realistic use of the roof by solar collectors.

$$f_{exploitation} = \frac{A_{col}}{A_{roof}} \qquad \text{eq. 3}$$

An exploitation factor of 1, represents an optimistic and not realistic case, as it means that the roof area equals the collector area without considering distances between the collector rows to avoid shading, distances to the roof edges, and other limitations such as light bands, ventilation systems, or also PV modules. As stationary solar collectors are typically installed with a certain slope, an exploitation factor of around one third is more realistic. For example, to avoid shading with an inclination angle above 15 ° with a typical collector length of 2.2 m (compare e.g. [41,42]) in Central European regions, a distance between the collector rows of 4.7 m is needed, resulting in an exploitation factor of 0.33 [5]. However, that also means that the entire roof area can be utilized without restricting light bands and ventilation systems. Consequently, the exploitation factors could be even lower as additional limitations such as statics of the roof cannot be considered in this study.

The collector area which can be installed by available roof area and load profile can be determined by eq. 4. Hereby, the roof availability factor is defined to less than or equal to one.

$$A_{col} = A_{col,req.} \cdot f_{roof/col} \cdot f_{exploitation} \qquad \text{eq. 4}$$

4. Results

This section summarizes the results of the study and the limitations by roof area and load profile for solar process heat plants. Firstly, the annual absolute and specific heat demand in the different industries and cluster is shown. Second, the estimated available roof area and the calculated required collector are compared. In the next step, the results of a sensitivity analysis regarding the temperature level of the process are illustrated. Finally, the results are merged in the assessment of the limitation in the potential solar fractions considering the available roof area and the characteristics of the load profile differentiated by the industries and clusters.

4.1 Absolute and specific heat demand in industries and clusters

The annual heat demand of the companies in the database is calculated with the annual boiler efficiency. Fig. 3 shows the heat demand for each industry of the NACE classification. It is quite diverse among and within the industries. Only few companies show an annual heat demand below 1 GWh/a. This can be traced back to the dataset as utility providers usually measure the hourly gas consumption if the annual gas consumption is higher than 1.5 GWh/a. Most of the companies consume gas in the range between 1 and 10 GWh/a but also some outliers show higher gas consumption up to more than 200 GWh/a. Taking the roof analysis into account and calculating the specific heat demand related to the projected roof area for each company, the relation between the industries does not change significantly. There is not even a significant difference in the specific heat demand between the secondary sector on the one hand (seven industries at the top) and the remaining tertiary sector related to commercial applications on the other hand. Most of the companies show a specific heat demand of more than 100 kWh/m²a which is comparable to the unrenovated or partly renovated buildings in the residential sector. Nonetheless, some companies show a very high specific heat demand with more than 1000 kWh/m²a. This can have several reasons.

1. These companies have a very high heat demand (natural gas consumption) considering their roof area, possibly due to energy intensive high temperature processes, e.g., using ovens.
2. For the calculation of the specific heat demand, only the projected roof area is used. Some buildings might have several floors and the heated area is much larger than the projected roof area.
3. Not all roof areas could be identified with the algorithm that are related to the roof area, so the roof area is underestimated and consequently the specific heat demand is overestimated.

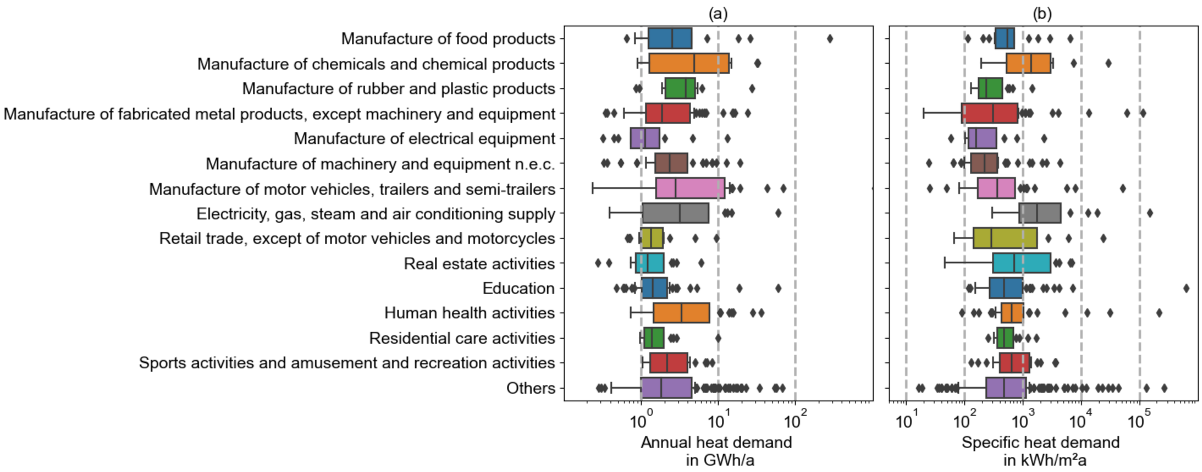

Fig. 3: (a) Absolute heat demand in GWh/a and specific (b) heat demand in kWh/m²a by industry (m² footprint area of the buildings)

The authors cannot estimate the probability of the options but with respect to this study, only the latter possible reason affects the results as it influences the suitable and useful roof area and thus also the relation between required collector area and roof area. However, the OSM data could also represent roofed open areas which are not heated which would increase the calculated roof area and decrease the specific heat demand.

The spectrum of the absolute and specific heat demand is underlined by Tab. 2. The 0.25 quantile is given by the origin of the database as gas providers usually measure the hourly gas consumption if the annual gas consumption exceeds 1.5 GWh. The 0.75 quantile of the annual head demand is more than twice of the median which can be explained by the large number of outliers of companies with a high head demand. The quantiles of the specific heat demand show the same relations with a factor around two between median and 0.25 quantile and a factor of more than two between 0.75 quantile and median.

Tab. 2: Quantiles and median of the absolute and specific heat demand of the analysed companies

489 companies	0.25 quantile	median	0.75 quantile
Absolute head demand in GWh/a	1.1	1.9	4.5
Specific heat demand in kWh/m²a	207.9	457.2	1,056.9

In contrast to the industries, there is a significant difference between the different clusters, which represent the seasonality of the heat load profile as discussed in 2.2, in terms of absolute (a) and specific (b) heat demand as shown in Fig. 4. The lower the dependence on ambient temperature and the more constant the heat load profile is over the year (top), the higher the absolute as well as the specific heat demand. Cluster 3 with a very high ambient temperature dependence shows the lowest absolute and specific heat demand. Nonetheless, as expected, there is no clear distinction but a smooth transition between the different clusters. Especially for a higher demand, there are a lot of outliers in each cluster.

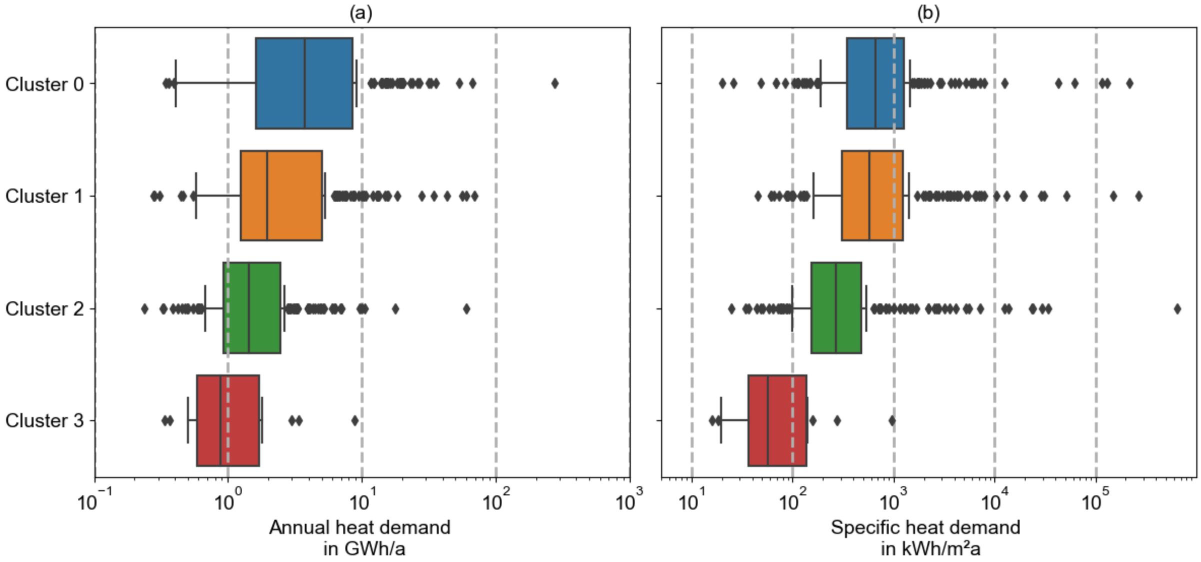

Fig. 4: (a) Absolute heat demand in GWh/a and (b) specific heat demand in kWh/m²a grouped by clusters

4.2 Comparison between available roof area and required collector area

For each company, the required collector area is calculated according to VDI 3988. In addition, the roof area is estimated based on OSM data. The relation of these values gives an insight if the roof area is sufficient to cover the summer heat demand by only using the companies' roofs. Fig. 5 shows this comparison company-wise, one dot representing one company. Three lines for different exploitation factors (see chapter 3.3) are highlighted to enhance the understanding. As outlined in section 3.4, an exploitation factor of 0.33 appears to be realistic if shading of the collector rows is minimized. For the dots above one of the three lines, this means that the available roof area is not sufficient for the pre-designed collector area. Vice versa, each point below the dashed lines represents a company with sufficient roof area with respect to the required collector area of the pre-design. As shown in Fig. 5, many companies do not have enough space available on their roofs. The lower the exploitation factor is, the more companies have not sufficient area available. In consequence, these companies need more ground area nearby for solar collectors or other technologies to meet the summer heat demand with renewables.

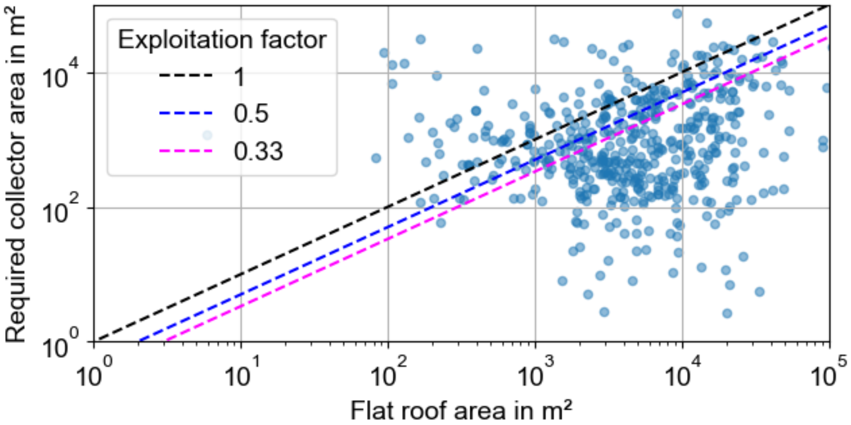

Fig. 5: Company-wise comparison of the available roof area (x-axis) and the required collector area based on the mean summer heat demand and the pre design according to VDI 3988 (y-axis)

Fig. 6 shows the number of companies over the area availability factor $f_{roof/col}$. It allows to quantify the number of companies that do not have enough roof area depending on the exploitation factor. Assuming an ideal utilization of the roof ($f_{roof/col} = 1$), less than 25 % of the companies do not have sufficient space available. Due to the reasons outlined above, a lower exploitation factor is realistic. Assuming an exploitation factor of 0.33, still more than 50 % of the companies have a sufficient roof area available.

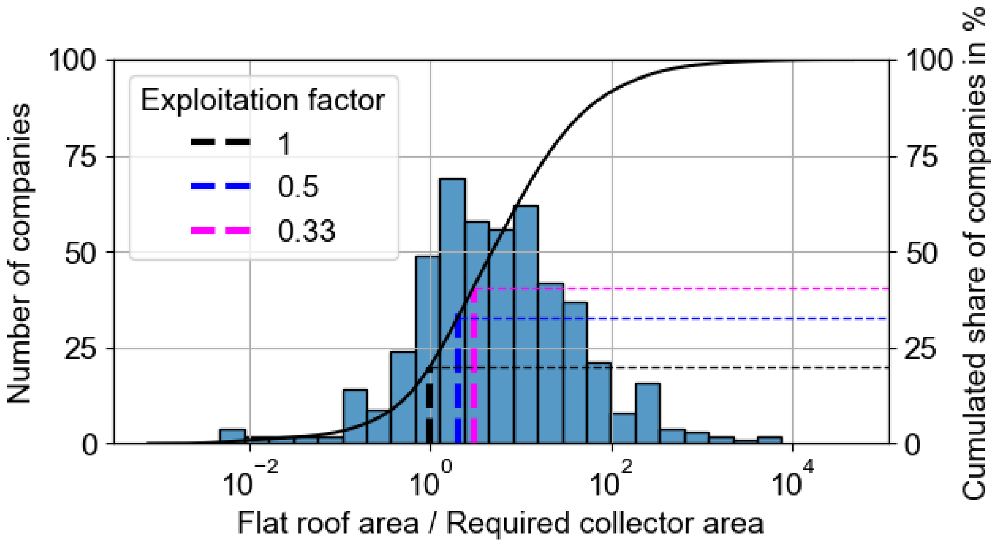

Fig. 6: Absolute number of companies and cumulated share of companies as a function of the relation of the flat roof area and the required collector area (area availability factor) in logarithmic scale.

4.3 Sensitivity analysis: temperature level and its influence on sufficiently available roof area

As discussed in 0, a mean collector temperature of 80 °C was assumed to pre-design the collector field, e.g., for a process with 80 °C supply and 60 °C return temperature and two heat exchangers between solar heating plant and heat sink. To estimate the influence of the mean collector temperature on the results of this study, a sensitivity analysis is conducted. The mean collector temperature is varied in the range of 40 to 100 °C and a pre-design is adapted to the different temperature levels. Based on Fig. 6, the intersection between the dashed lines representing the exploitation factors and the cumulated share of the companies (black line) is determined.

The three lines in Fig. 7 show the share of companies with sufficient roof area for a solar heating plant evaluated according to the VDI 3988. The lines are based on three different exploitation factors. As expected, the share of companies with sufficiently available roof area is decreasing with increasing collector temperatures as the collector field must be designed larger to still meet the summer heat demand. With an exploitation factor of 0.33 the share of companies is increased from around 60 % with a mean collector temperature of 80 °C to 64 % with 40 °C. Thus, there is a certain influence of the collector temperature, but the increase of 4 %-points is relatively small considering the significantly different temperature levels. Thus, it can be concluded, that the temperature level does not influence the ratio of required collector area and the available roof area substantially. However, other parameters important for the economic efficiency of solar thermal systems, such as the specific solar yield or the solar fraction, are much more sensitive to higher temperatures, which can be clearly seen in the diagrams for collector field dimensioning in the guideline VDI 4646 [5].

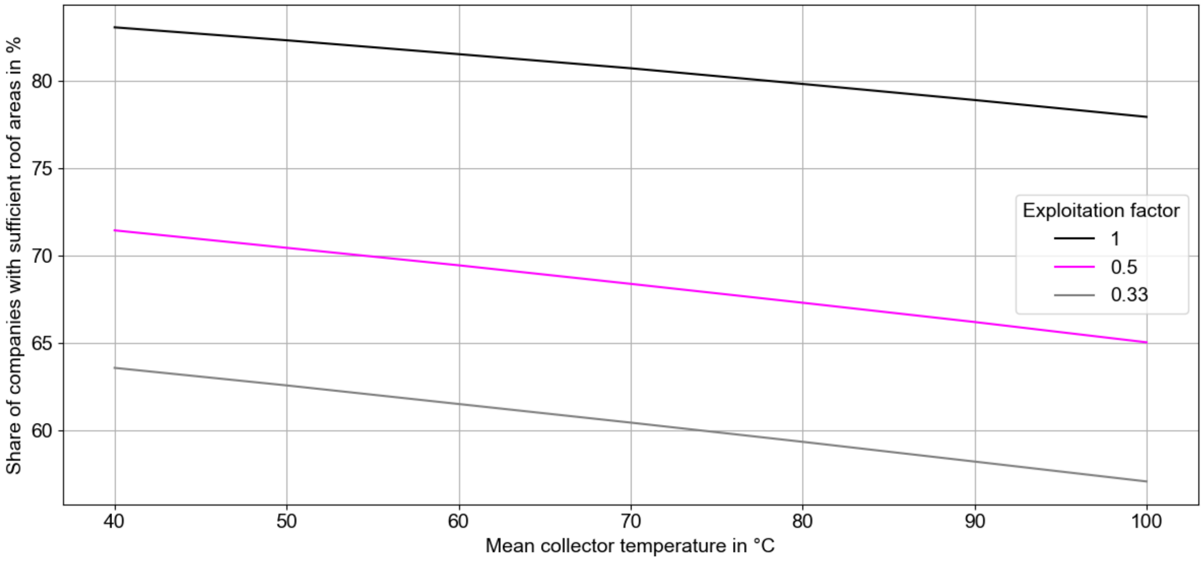

Fig. 7: Influence of the mean collector temperature on the share of companies with sufficiently available roof area

4.4 Realistic solar fractions under consideration of the roof area

The comparison of the available roof area with the required collector area reveals that a lack of roof area will practically hinder a relevant share of companies to reach the intended solar fraction determined by the established design guideline VDI 3988. This reduces the overall potential of solar collectors in the secondary and tertiary sectors.

Next to the absolute potential, it is important to know about the solar potential in relation to the heat demand and which solar fractions can be achieved. Fig. 8 shows the Kernel density estimation distribution of the solar fractions that can be reached considering unlimited roof area (green) and the total available (grey) as well as reduced roof area with different exploitation factors (blue and pink). The greater the distance between the collector rows, i.e., the lower the exploitation factor, the lower the potential solar fractions are. For lower exploitation factors, the density of companies with higher solar fractions in the range of 30 to 50 % is decreased, whereas the density in the range below 10 % is increased. A solar fraction of 30 % is assumed in several potential studies to be a realistic approach for space heating and process heating applications in secondary and tertiary sectors (see section 2.1). Even if the roof area is not limited, a solar fraction of at least 30 % is only reached by 14 % of the companies in this study according to the pre-design methodology of the VDI 3988 guideline. These relatively low solar fractions compared to literature are mainly due to the consideration of realistic load profiles. Previous studies like Lauterbach et al. [10] only considered load profiles with a constant heat demand on all working days over the whole year. As the previous studies by the authors revealed, such constant load profiles are not the regular case for most of the almost 500 investigated companies. Most of these companies show a significantly higher heat demand on winter days than on summer days what results in low solar fractions if solar surpluses are to be avoided as far as possible. If a realistic exploitation factor of the roof of 0.33 is considered, the share of companies with a solar fraction above 30 % is decreased to only 3 %, respectively and around 60 % of the companies can only realize low solar fractions below 10 %.

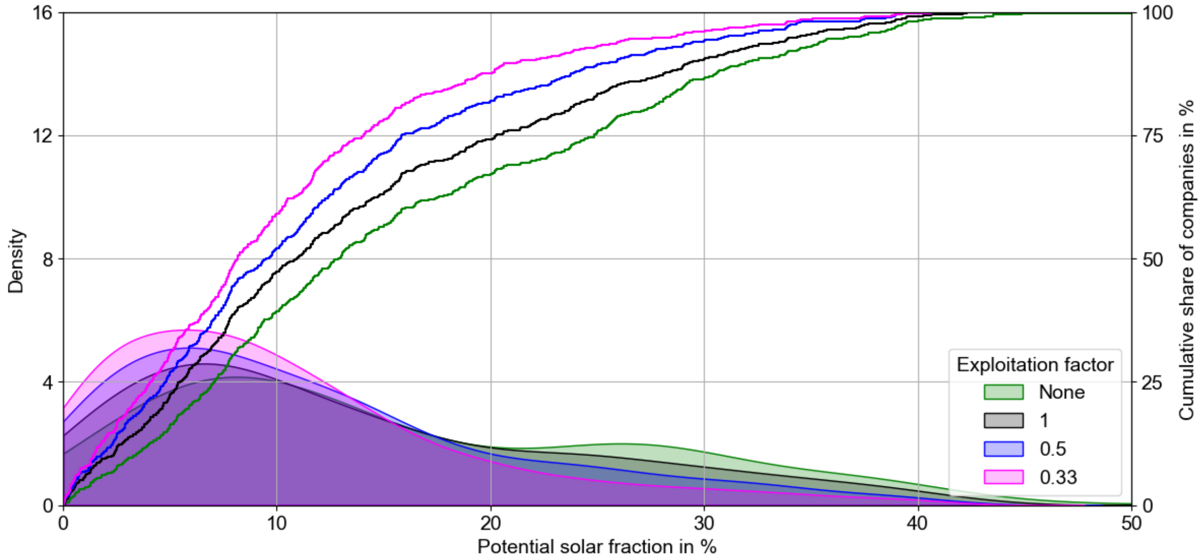

Fig. 8: Distribution of the potential solar fractions of the annual heat demand (left y-axis) and the cumulative share of companies with a certain solar fraction for different exploitation factors (right y-axis)

Although the roof area limits the solar potential in 30 % to 50 % of the companies, the seasonality of the heat load profiles limits the solar potential even more. Fig. 9 shows the potential solar fractions that can be reached by each company for the four clusters representing the seasonality of the heat load. Fig. 9 (a) neglects the potential limitation of the collector area by the size of the roof. It shows the potential solar fraction that can be achieved by a solar heating plant pre-design based on the summer heat demand according to the VDI 3988. Fig. 9 (b) shows the solar fractions considering an exploitation factor of 0.33. It can be concluded that the seasonality of the load profile is a relevant limiting factor for the potential fraction of solar heat in the secondary and tertiary sector. The clusters can be clearly differentiated with respect to the potential solar fractions. The companies in cluster 3 with a high seasonality of the load profile rarely achieve solar fractions above 10 %, already without taking into account the available roof area. Due to the low summer heat load, the pre-designed collector area is rather small, and the absolute solar yield is low in relation to the annual heat demand. Companies from cluster 2 predominantly reach solar fractions in the range of 5 to 15 %. Considering the exploitation factor, flat roof area is smaller than the required collector area for some of them (below the dashed line) and thus the solar fraction is reduced significantly. Within cluster 1, solar fractions between 10 and 25 % can be realized if the roof area is unlimited. However, the share of companies with limited roof area and consequently limited potential solar fractions is increasing. Companies from cluster 0 are significantly limited using solar heating plants due to their available roof area. With unlimited roof area, they achieve solar fractions in the range of 20 to 45 %. Considering the available roof area and assuming an exploitation factor of 0.33, the solar fractions are significantly reduced, partly from more than 40 % to below 5 %. As stated above the solar fractions are calculated with respect to the annual heat demand. If the solar fractions are calculated with respect to the final energy demand, the solar fractions will be even lower.

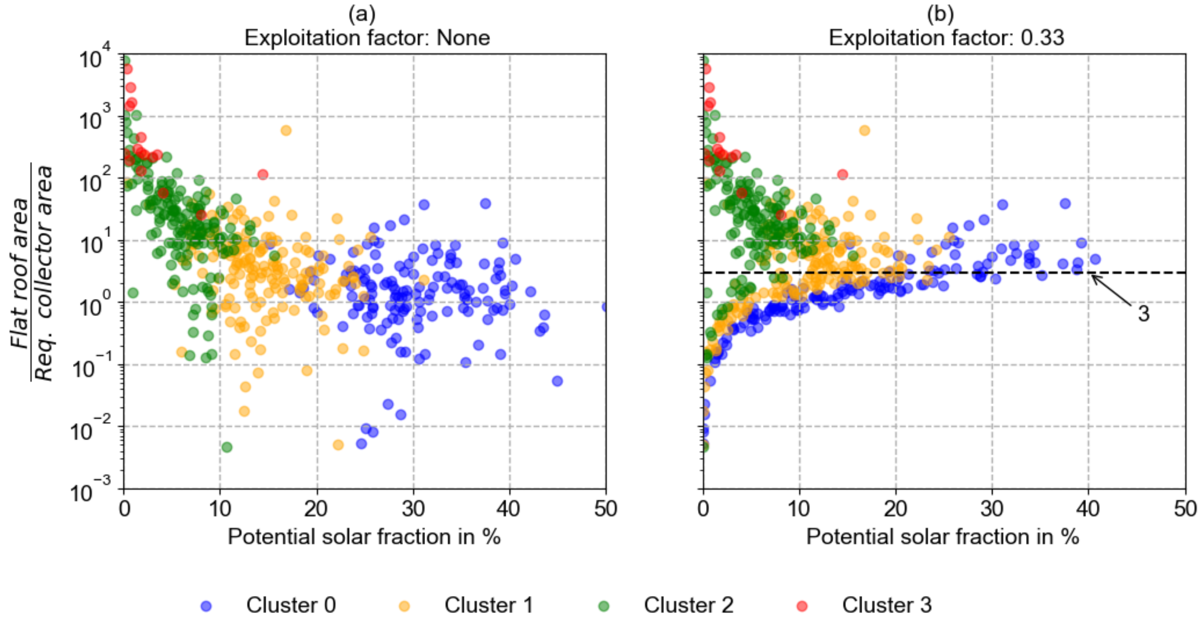

Fig. 9: Ratio of flat roof area and required collector area as a function of the potential solar fraction, (a): The collector area is as large as needed according to the VDI 3988 and is not limited to the roof area; (b): Only one third of the total roof area is utilized as collector area at a maximum representing an exploitation factor of 0.33, which is a realistic estimation, assuming a tilted collector field and the collector spacing needed to avoid significant shading as well as taking into account distances to the edge of the roof, the dashed line shows the threshold, below which the roof area is non sufficient

The comparison of the potential solar fractions in the different industries reveals significant differences as shown in Fig. 10. The industries listed at the top show higher solar fractions on average. The food industry shows the highest consistency within an industry. This is because almost all companies can be assigned to cluster 0 in the database (ref. Fig. 2), which allows for a higher solar fraction due to constant load profiles throughout the year. In addition, these companies show a comparably low specific heat demand (ref. Fig. 3) and seem only be rarely affected by limited roof area. In contrast, the chemical industry shows higher specific heat demands and lower potential solar fractions , even though these companies also have no (cluster 0) or low seasonal load profiles (cluster 1). Consequently, roof area proves to be a limiting factor for these companies. In the industries in which a relevant share of space heating can be assumed (cluster 2 or 3, e.g., manufacture of motor vehicles or education), comparably small solar fractions in the range of 10 % or below can be reached which can mainly be deduced to the course of the load profile over the year.

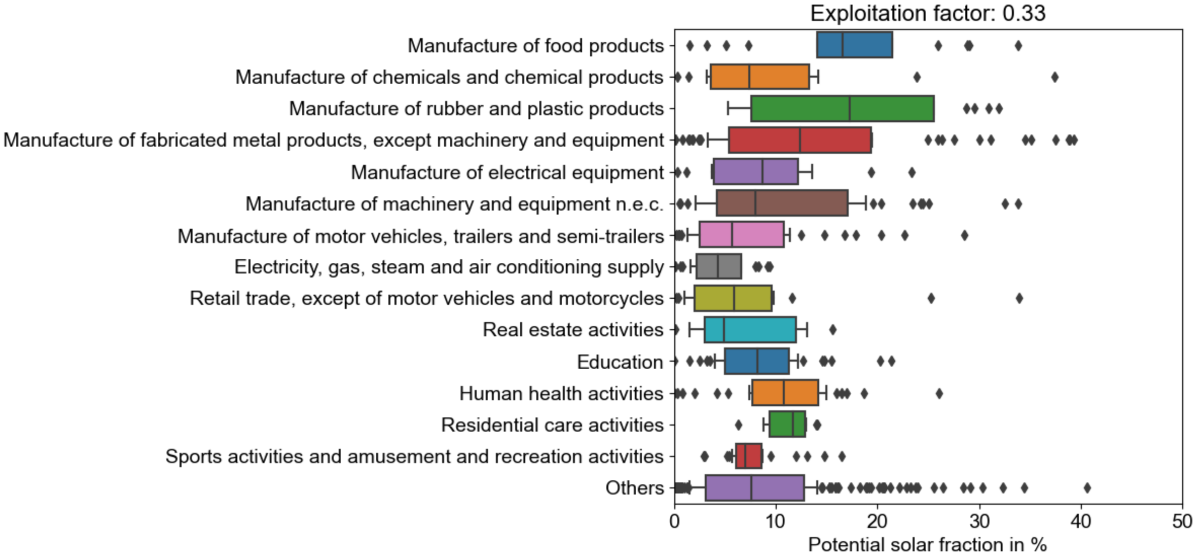

Fig. 10: Potential solar fractions for the different industries under consideration of the flat roof area and a realistic roof utilization

5. Discussion

The comparison of this study's results with previous potential studies for solar process heat mentioned above highlights that reaching a solar fraction of 30 %, which is assumed by most previous studies to be realistic, is quite optimistic for Northern and Central Europe locations. This is mainly due to two reasons:

1. In these regions, space heating or other ambient temperature dependent heat demand play a significant role not only in residential buildings but also in many industries of secondary and tertiary sectors. As in these cases the summer heat load is relatively low compared to the winter heat load, the pre-design according to the VDI 3988 guideline results in a smaller collector area since solar heat surpluses are avoided as far as possible. In consequence, the potential solar fractions are decreasing.
2. For consumers with an almost constant heat demand on working days over a year, solar fractions in the range of 20 % to 45 % are possible. However, the resulting pre-designed collector area partly exceeds the available roof area, and the potential solar fractions decrease if no other ground area nearby is available for the installation of solar collectors.

- The presented top-down approaches from literature partly use a lump-sum deduction of the suitable heat demand. To consider limited area for collector installation or other barriers, 60 % of the heat demand in the suitable temperature level on national level is excluded from the calculation. In consequence, a solar fraction of 8 to 16 % regarding final energy demand for heating purposes in the suitable temperature level on national level is determined. In this study, the solar potential is calculated considering the entire heat demand of real companies without estimating energy efficiency measures. As a result, 50 % of the companies reach a solar fraction of maximum 8 % if a realistic area exploitation factor of 0.33 is considered and 13 % if unlimited area would be available. In contrast to previous studies from the literature, in this study the solar fraction is calculated in relation to the usable heat consumption. If the solar fraction were related to the final energy consumption, as it is done in the previous studies from the literature, the solar fractions would be even lower. In contrast, future efficiency measures could reduce the heat demand. As a result, more companies will have sufficient roof area and higher solar fractions could be reached.

Due to a lack of detailed information on the heating systems and buildings of the investigated consumers, assumptions had to be made. The resulting uncertainties, outlined in the following, possibly effect the results of this study:

- The entire roof area is estimated to be statically suitable and other limitations such as PV installations or ventilation systems onto the roof are not considered. This will probably lead to an overestimation of the available roof area and would limit the solar potential even more.
- The complete natural gas consumption of the consumers is assumed to be used for heat generation in a standard natural gas boiler with an efficiency of 75 %. Heat generators with a different efficiency or other natural gas uses are potential source of error but assumed to be minor.
- The complete heat demand is assumed to be at a temperature of 80 °C flow and 60 °C return temperature. As shown in a sensitivity analysis, the temperature does not significantly influence the required collector area but the solar fraction. Especially in industries such as chemical products or basic metals, the largest part of the heat demand is at a temperature level that cannot be provided by non-concentrating solar thermal systems in Central or Northern Europe. The companies' heat demand at suitable temperatures will be lower than this study's estimation. If only the heat demand at suitable temperatures is considered, the solar fractions would be increased. For other industries such as food, which's heat demand is mostly in a suitable temperature range [10], the results of this study will be more precise.

6. **Conclusion**

This study is based on a non-representative but large database of industrial and commercial heat load profiles with an hourly resolution and the assignment of the profiles to four clusters describing the ambient temperature dependency. The database was supplemented with GIS-data from OpenStreetMap enabling the evaluation of the availability of roof area und a pre-design of a solar heating plant according to the VDI 3988. Two main findings can be derived from this analysis. First, the availability of sufficient roof area is a limiting factor for 30 to 50 % of the companies especially in companies with a constant heat load profile over the year. If a realistic distance between the collector rows is taking into account, approximately one third of the companies is limited in its solar potential by the availability of roof area. The more the heat demand is dependent on the ambient temperature, the less the available roof area limits the potential of solar collectors. Second, to reach a high solar fraction in the range of 30 % or above is only possible if the heat demand is constant throughout the year under the premise that the solar heating plant is designed to meet summer heat demand without solar excess heat. As several industries also show a (high) seasonality of the heat demand, lower solar fractions in the range of 5 to 20 % are common in industry and commerce.

Regarding the application of solar heating plants in industry and commerce, the results of this study have a relevant influence on the design of future sustainable heating systems in industry and commerce. Solar heating plants can play a relevant role, but only as a supplement to heat generation systems that combine multiple renewable heat technologies. As the energy density in industry is high and the seasonality of the heat load profile cannot be neglected, PV-heat pump systems face the same challenge and cannot be a stand-alone solution for an entire decarbonisation. In consequence, there needs to be a greater focus on hybrid systems combining several technologies such as solar collectors, heat pumps, district heating systems, or even low carbon combined heat and power plants.

CRediT authorship contribution statement

Felix Pag: Conceptualization, Methodology, Funding acquisition, Project administration, Writing - original draft, Visualization, Software. **Mateo Jesper:** Methodology, Writing - review & editing, Data Pre-processing, Software. **Oleg Kusyy:** Data Pre-processing, Software. **Klaus Vajen:** Funding acquisition, Supervision. **Ulrike Jordan:** Supervision, Writing - review & editing.

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The Map data is copyrighted by OpenStreetMap contributors and available from https://www.openstreetmap.org

Data Availability

The original load profile database examined in this study cannot be published for data protection reasons. Roof areas are extracted from the OpenStreetMap database [39] with the given methodology in Section 2.3.

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