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Data Analysis of the Energy Performance of Large Scale Solar Collectors for District Heating

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Abstract

District Heating systems are an interesting opportunity for the increase of renewable energy share in the heating and cooling sector. The possibility of a centralized heat production allows the integration of multiple sources, including RES such as biomass, heat pumps and solar energy. This paper provides an operation analysis of the energy performance of large scale solar collectors supplying heat to DH systems in Denmark. Thanks to the availability of hourly data it has been possible to track the evolution of the collectors' performance throughout the year, and compare it with the available radiation. The results show the good reliability of such systems, which are generally able to convert 40% to 60% of the available radiation, with annual production yields higher than 400 kWh/m^{2}y. The conversion efficiency shows some seasonal variations, being the winter months the less favorable, probably because of a lower direct radiation. The DH systems considered in the study show a similar performance but with some differences: other parameters such as slope, azimuth and operating temperatures could be the causes of these variations.

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Keywords: Solar Energy, District Heating, Renewables, Operation Analysis

1. Introduction

District Heating (DH) systems are an interesting solution for the increase of the share of Renewable Energy Sources (RES) in the heating and cooling sector, which is among the energy targets of the European Union [1,2]. DH systems can play a major role through sustainable and efficient thermal energy production, within the Smart Thermal Grids concept framework [3–5]. The centralized production of heat has multiple advantages, including a better generation management and integration of multiple sources, the possibility of Combined Heat and Power (CHP) generation and environmental benefits on pollutant emissions [5]. Moreover, DH systems can be used to increase the heat production from RES, including biomass, heat pumps and solar energy. A number of DH systems are using large scale solar collectors, often coupled with seasonal storage. Solar generation for DH systems is a mature technology in some countries, while it is gaining interest in other countries as an actual solution to lower the share of fossil fuels [6–8]. The average annual heat productivity from solar collectors is usually in the range 350 - 450 kWh/m^2 [9], depending

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however un multiple factors (available radiation, outdoor temperature, collectors features, operating temperatures, etc.).

There are usually some aspects to be considered for the development of solar systems coupled to DH networks, among which:

- supply and return temperatures of the DH network;
- daily and seasonal heat load profiles;
- interaction with existing generators;
- land availability and cost.

These aspects can be quite different from country to country and system to system, as they are related with a number of external factors. The first country where solar energy has been strongly used for DH supply is Denmark, thanks to some favorable factors and a strong political and cultural vision.

In this paper an operational analysis of large scale solar collectors is presented, with the aim of describing the actual performance of the systems that are currently in operation. The possibility of considering multiple sites and design conditions (e.g. type of collectors, makers, slope, etc.) allow for generalized results.

2. Methodology

2.1. Available Data

The data used for this analysis have been downloaded from Solvarme website [10], where a huge amount of hourly data are available for a number of solar DH networks. This website includes some of the Solar DH systems of Denmark. The analysis has been performed with R software [11].

Table 1 show the number of systems for which operation data are available over the years. The systems are not all the existing systems in Denmark, as many others are still not connected to this monitoring system. Moreover, some systems are in operation since before 2007, but there are no data available before 2007.

The number of monitored systems has considerably increased in last years, and so did the total collectors' surface. Considering all operating systems in Denmark, as of October 2016 the total installed surface has reached 1 million m^2 in 85 solar DH systems in the country [12]. And they are always getting larger: in Silkeborg (Central Denmark) the largest plant of the world has been built in the end of 2016:it has 156,000 m^2 of collectors' surface and a nominal peak power of 110 MW.

Table 1. Features of the systems per year

Year	DH Systems	Estimated Surface [m²]
2007	2	17,000
2008	3	22,000
2009	5	75,000
2010	10	115,000
2011	17	180,000
2012	25	256,000
2013	32	329,000
2014	40	469,000
2015	49	563,000
2016	56	723,000

The dataset, for which the narrowest available time step is one hour, contains: (1) Heat Generation, (2) Specific Heat Generation and (3) Available Radiation. The estimated total surface of Table 1 has been calculated using the ratio between heat and specific heat. As a result, this value is probably not precise, due to possible errors in the operation data.

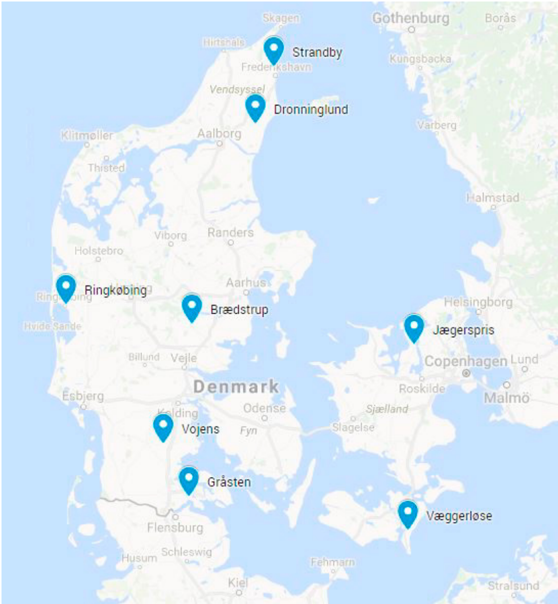

Fig. 1. Selected DH systems in Denmark (Map data: Google, GeoBasis-DE/BKG).

A data cleaning has been performed in order to remove a number of obvious errors that were included into the original dataset, such as: (1) outliers with non-physical meaning, (2) negative values, (3) ”fake” values resulting from constant heat generation also at night, (4) Specific Heat Generation higher than Available Radiation, (5) duplicates. During the cleaning process some records have been discarded, and the final dataset used for the analysis contains roughly half million records of actual heat generation (i.e. excluding night hours).

2.2. *Selected DH systems for a deeper analysis*

Although data were available for a number of systems in the country, this analysis has been limited to eight DH systems that have been chosen to be representative of the all systems. The systems chosen are represented in Figure 1 and their main features are in Table 2. The choice has been made by considering systems with different locations and some years of operation.

Table 2. Features of the DH systems considered in this study

Location	Collectors Surface (m^2)	Expected Solar Fraction	Angle of solar panels (*degrees*)
Brædstrup	18,612	20%	33
Dronninglund	37,573	50%	35
Gråsten	19,024	28%	38
Jægerspris	13,405	17%	40
Ringkøbing	30,000	14%	30
Strandby	8,019	18%	35
Væggerløse	12,094	19%	38
Vojens	70,000	50%	38

Moreover, the installed surface of some solar systems has been modified over the years. Figure 2 shows the surface of the collectors for each system over its years of operation.

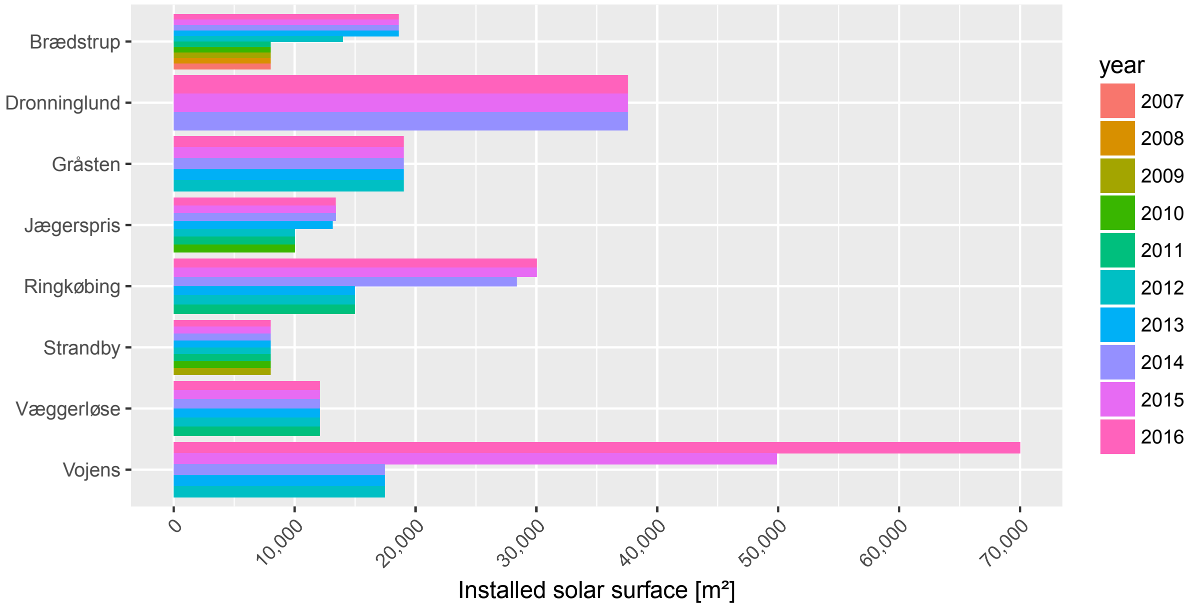

Fig. 2. Total installed collectors' surface (selected systems)

3. Results and Discussion

3.1. Selected DH systems

A first step in the analysis of the results is done by considering the selected systems, described in Figure 1 and Table 2.

Figure 3 compares their specific heat production over the years. The use of specific heat rather than heat allows comparing the performance of different DH systems. All the systems show annual specific productions between 400 and 500 kWh/m^2, with some differences from year to year. These variations are mostly related to weather conditions, but in some cases also the installation of new collectors can lead to a variation of the average efficiency. Moreover, the efficiency can have a decrease over the years due to fouling or glass transparency deterioration, but this effect is not noticeable on such a short range of time. In some cases the first year of operation show a low level of energy production, due to the fact that the operation of the system has started during the year and not at the beginning.

The specific energy production can be compared with the measured available radiation, in order to calculate the efficiency of the system in converting the available solar energy. The measured radiation is measured at the same slope of the solar collectors, and therefore the ratio between heat production and available radiation represents the conversion efficiency. Figure 4 shows the correlation between available radiation and specific heat production, by considering each hour of operation. The correlation appears quite linear, with some point scattering that is related to a number of different parameters (e.g. operation temperatures, outdoor temperature, ratio between direct and diffuse radiation, etc.). The scattering appears higher in the bottom left of the chart, due to the fact that in this region the weight of system inertia is more important. The hours with less radiation are usually the ones where system is heating up in the morning or cooling down in the evening, and therefore the variability is higher and the relation poorer.

A monthly summary of the conversion efficiency is reported in Figure 5. The average monthly efficiency in summer months is always in the range 40% - 50%, with some variations mainly related to weather conditions. There seems to be no relevant difference between DH systems, and even between different years. The efficiency drops significantly in autumn and winter months, probably for the combined effect of lower outdoor temperatures and higher share of diffuse radiation w.r.t. direct radiation. Due to the Danish weather conditions, which have usually foggy winters, the use of solar energy needs to exploit as much as possible the summer months. For that reason usually large seasonal storage systems are installed to use during the year the excess heat produced during summer.

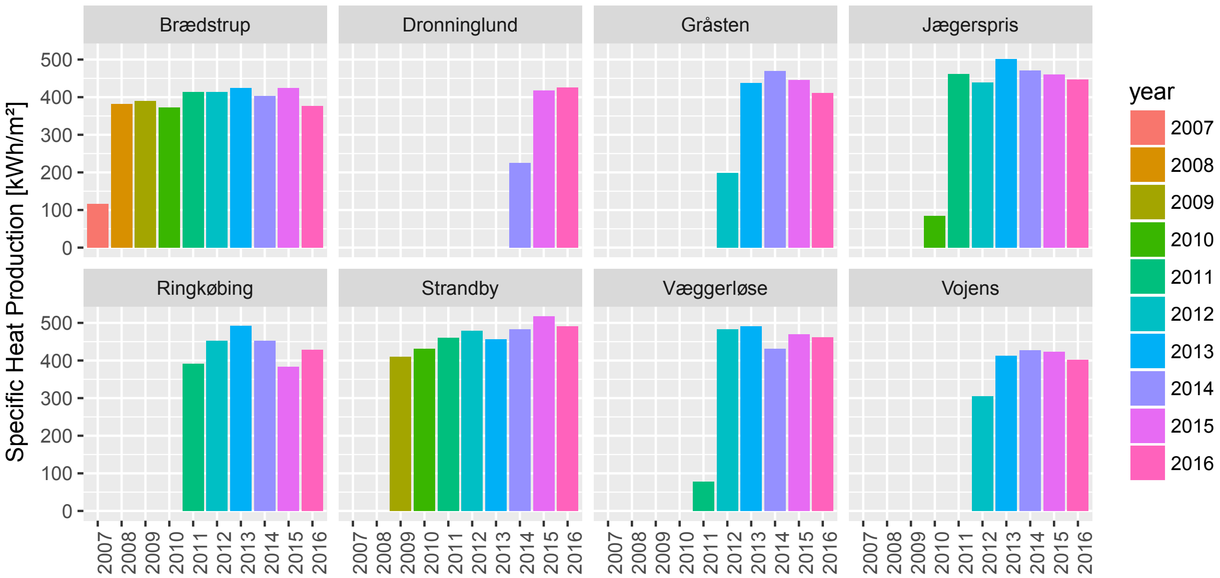

Fig. 3. Specific production (selected systems)

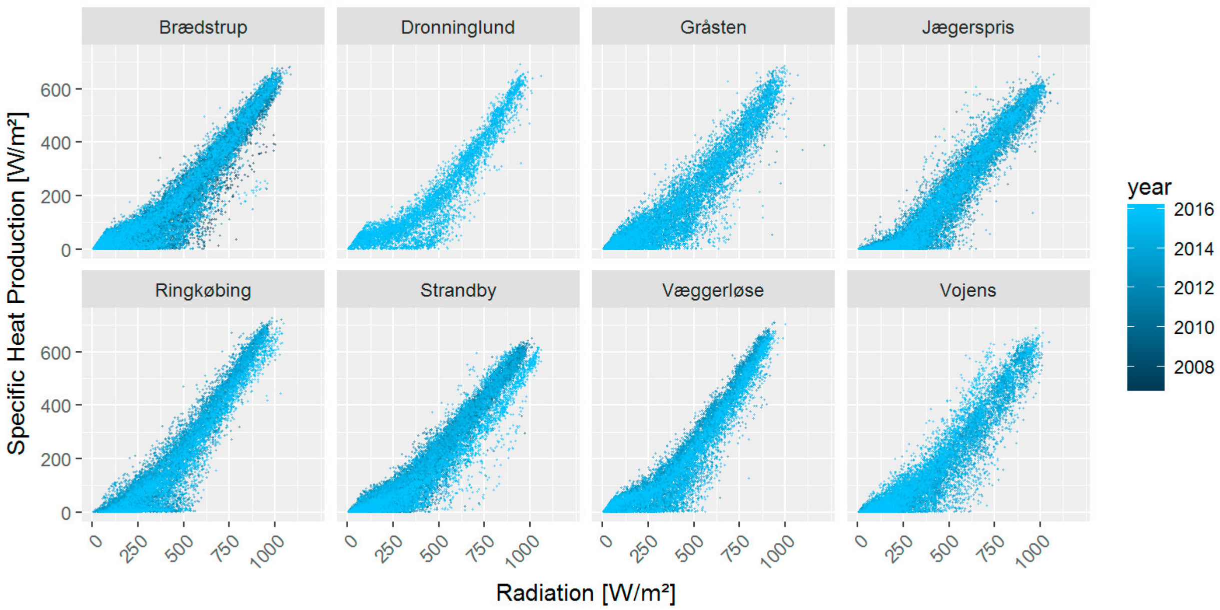

Fig. 4. Relation between specific production and available radiation (hourly values, selected systems)

3.2. *All DH systems*

The extension of the analysis on all systems allows to generalize the trends expressed above. The DH systems can be compared by means of monthly specific heat production (see Figure 6) or monthly average efficiency (see Figure 7). Both figures show a larger scattering than in the previous section, due to the comparison of a number of different systems with various features and climate conditions. Some outliers can be caused by the startup of the DH system during a particular month, or for some failures in available radiation measurements.

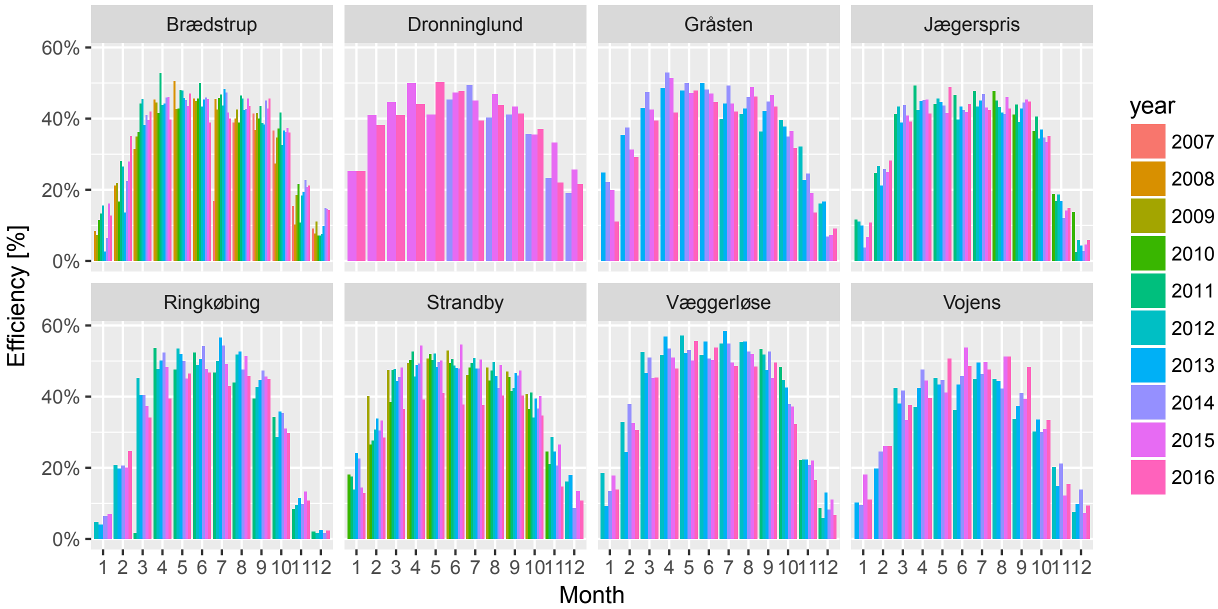

Fig. 5. Monthly conversion efficiency (selected systems)

Due to the high number of systems and the low availability of information related to system layouts, a detailed analysis of the outliers has not yet been performed, but can be the object of a future work.

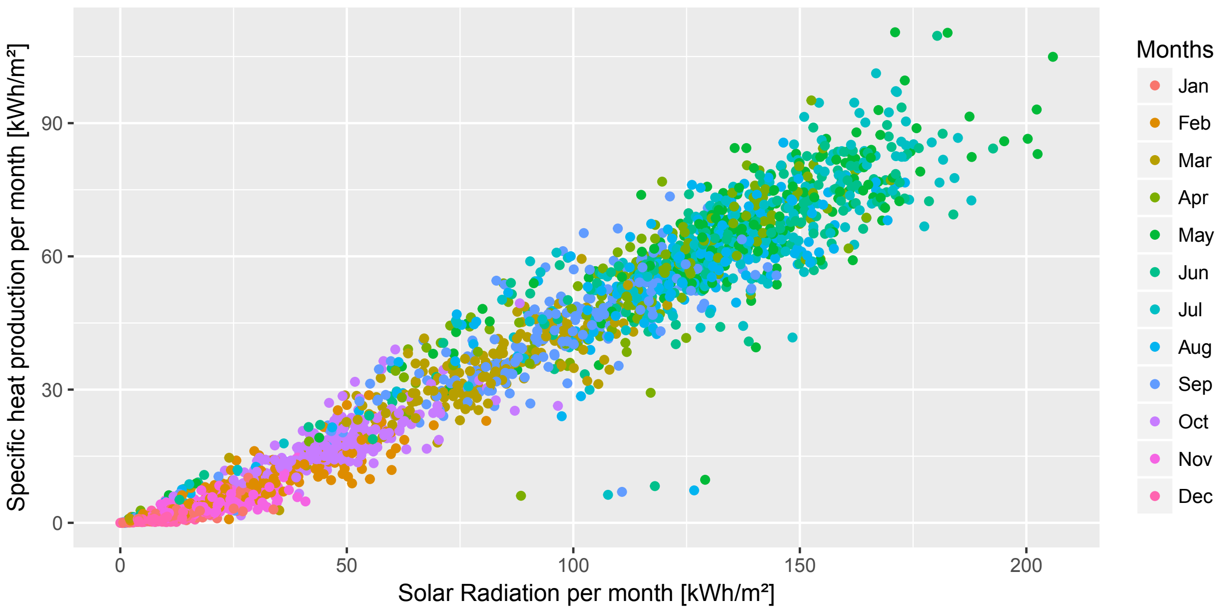

Fig. 6. Relation between Monthly specific production and Available radiation (all DH systems)

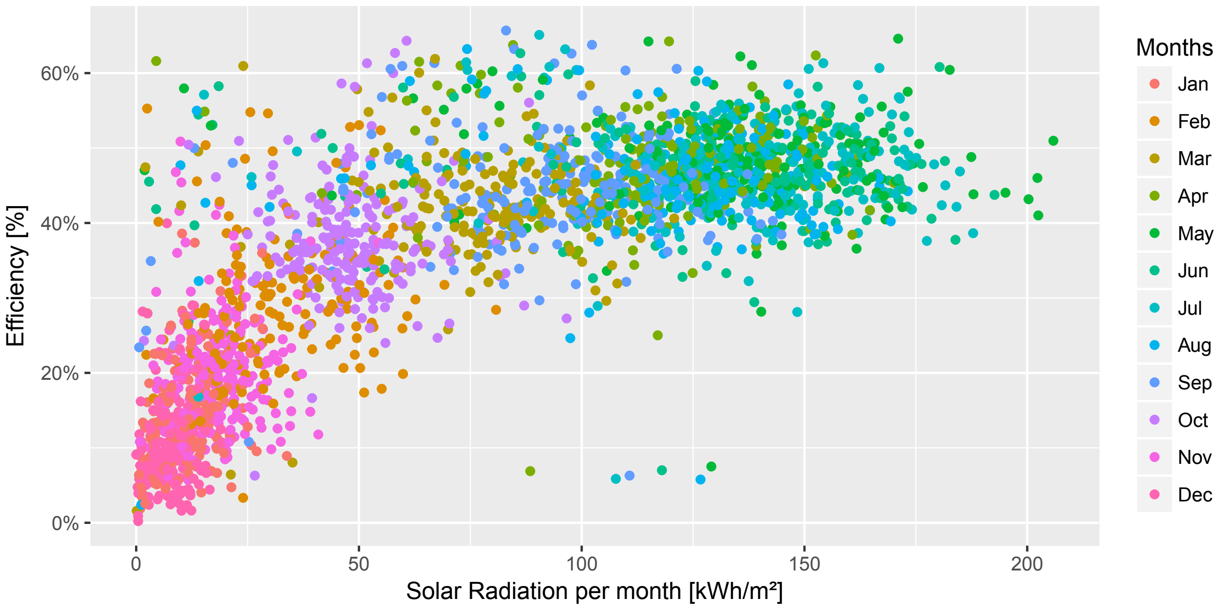

Fig. 7. Relation between monthly efficiency and Available radiation (all DH systems)

4. Conclusions

This paper presents the results of a data analysis on the actual performance of several large scale solar systems connected to district heating networks. The operation data are available for different years in different DH networks in Denmark.

The results of the analysis show that the systems have a comparable performance, and no significant differences have been found with respect to location, collectors angle or age of the system. However, some monthly and annual variations are related to the weather conditions. The relation between available radiation and specific heat production is rather linear, with average monthly conversion efficiency in the range of 40% to 50% during the summer. Winter months show a significant decrease of production, due to the low available radiation in the country and the lower outdoor temperatures than in summer.

Future works could study with more detail the weight of different parameters in the conversion efficiency of the solar collectors. However, there is a need of more operational and design data such as operating temperatures, system layouts, availability and features of heat storage systems and others heat generators.

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