Yearly thermal performances of Danish solar heating plants

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Abstract

The number of Danish solar heating plants in district heating areas increased strongly from 16 plants in 2009 to 123 plants in 2019. Many of the plants were installed in district heating systems with natural gas boilers due to good economy. The thermal performance of most of the Danish solar heating plants have been measured for many years. The average yearly thermal performance for the solar heating plants for the period 2012-2023 is 459 kWh/m² solar collector and the yearly average utilization of the solar radiation for all the years is 40%.

Solar district heating plants are based on a simple, well proven and reliable technology. They supply heat with a relatively low cost of about 0.04 euro/kWh and the used solar collectors have a lifetime longer than 30 years. The solar heating plants provide about 2% of the total heat demand in Danish district heating areas.

In spite of the good experience from the plants, the Danish market for solar heating plants collapsed in 2020.

Solar heating plants are produced in Europe, the plants contribute to a global reduction of CO_2 emissions, even with a strong growth of installed systems. It is therefore hoped that the market for solar heating plants soon will be reestablished.

Keywords: Solar heating plants, measured thermal performances, district heating

1. Introduction

Solar heating plants in district heating areas consist of a high number of rows of serial connected solar collector panels. The rows are connected in parallel and the number of collector panels in each row can vary with up to 20 panels as shown in Figure 1.

Fig. 1: Solar district heating plant in Silkeborg (156,694 m²)

The technology for solar heating plants inclusive large solar collector panels was first developed in Sweden (Dalenbäck et al., 1981), and further developed and marketed in Denmark by Arcon Solvarme. The first Danish solar heating plant for district heating was installed in 1988 in Saltum (Jensen, 1990). The number of solar

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heating plants in Danish district heating areas increased strongly from 16 to 123 within 10 years, in the period 2009-2019. The collector area of the Danish solar heating plants in operation during the period from 2005 to 2023 is shown in figure 2.

There has been a strong growth of Danish solar heating plants until 2019. Many of the solar heating plants were installed by district heating companies using natural gas boilers, since solar collectors in such systems were economically favorable. The Danish market for solar heating plants collapsed in 2020.

Almost all the solar heating plants are based on flat plate solar collectors with one or two cover plates. During the period 2002-2012 Arcon Solvarme and the Technical University of Denmark had a close cooperation on development of the large solar collector panels marketed by Arcon Solvarme (Fan and Furbo, 2007; Fan et al, 2009; Bava and Furbo, 2019). The collector efficiency was strongly improved, and a cost reduction of the solar collectors was achieved at the same time during the period.

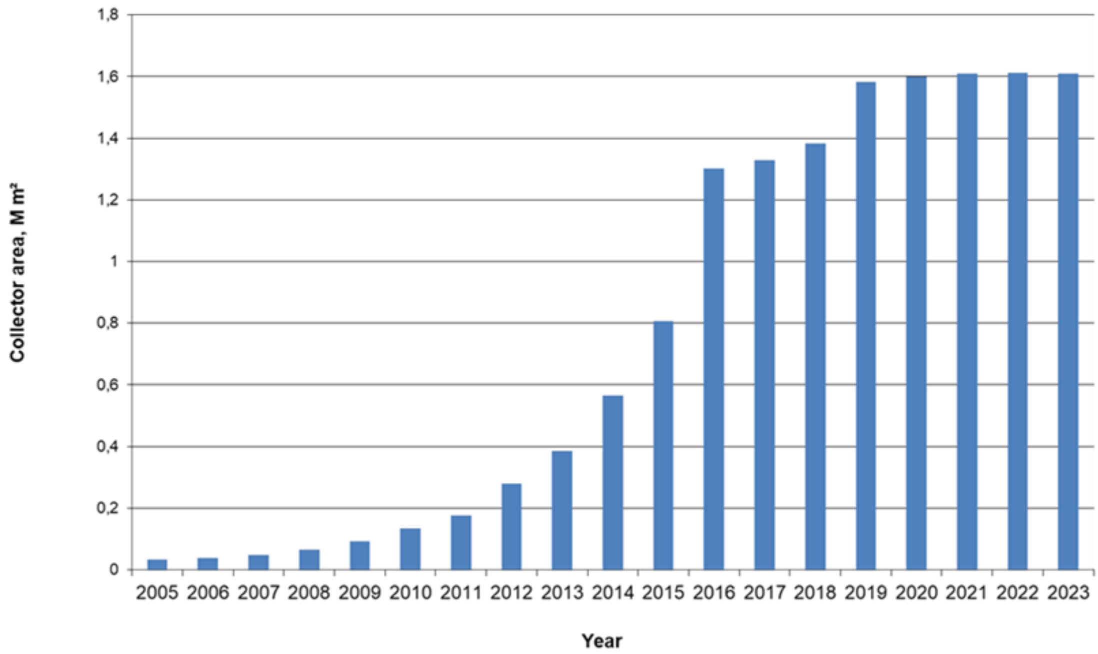

Fig. 2: Solar collector area of Danish solar heating plants during the period 2005-2023

2. Thermal performances of solar heating plants

The thermal performances of many Danish solar heating plants are available on the homepage (https://solvarmedata.dk/), (Furbo et al., 2018). Most of the plants are based on flat plate collectors from Arcon Solvarme, Sunmark or Arcon-Sunmark. In 2015, the two main producers of large flat plate collectors, Arcon Solvarme and Sunmark merged to form Arcon-Sunmark.

For the period 2012-2023 yearly thermal performances have been determined for 78 solar heating plants. The thermal performances are measured with energy meters on the water side of the heat exchangers in the solar collector loops. In this way the accuracies of the measurements are estimated to be about ±2%, and not influenced by the propylene glycol/water mixtures used as solar collector fluids. Further, the solar radiation on the solar collectors is measured with pyranometers. Often inexpensive pyranometers are used resulting in relatively high inaccuracies, about ±10%.

The collector areas of the investigated solar heating plants varied between 2970 m² and 156694 m². The tilts of the solar collectors varied between 30° and 45°, and the solar heating plants were installed between 1996 and 2021. Wang et al. (2012) suggested to divide Denmark in six different solar radiation regions as shown in figure 3. Table 1 shows the number of solar heating plants investigated in each solar radiation region.

Measured yearly thermal performances for the solar heating plants for the period 2012-2023 appear from table 2. The thermal performances are shown as kWh per m² aperture solar collector area. The number of plants, the variations of thermal performances and the average yearly performance of the plants are shown for each year.

Tab. 1: Locations of 78 investigated solar heating plants

Region	1	2	3	4	5	6	Total
Number of plants	13	19	19	20	7	0	78

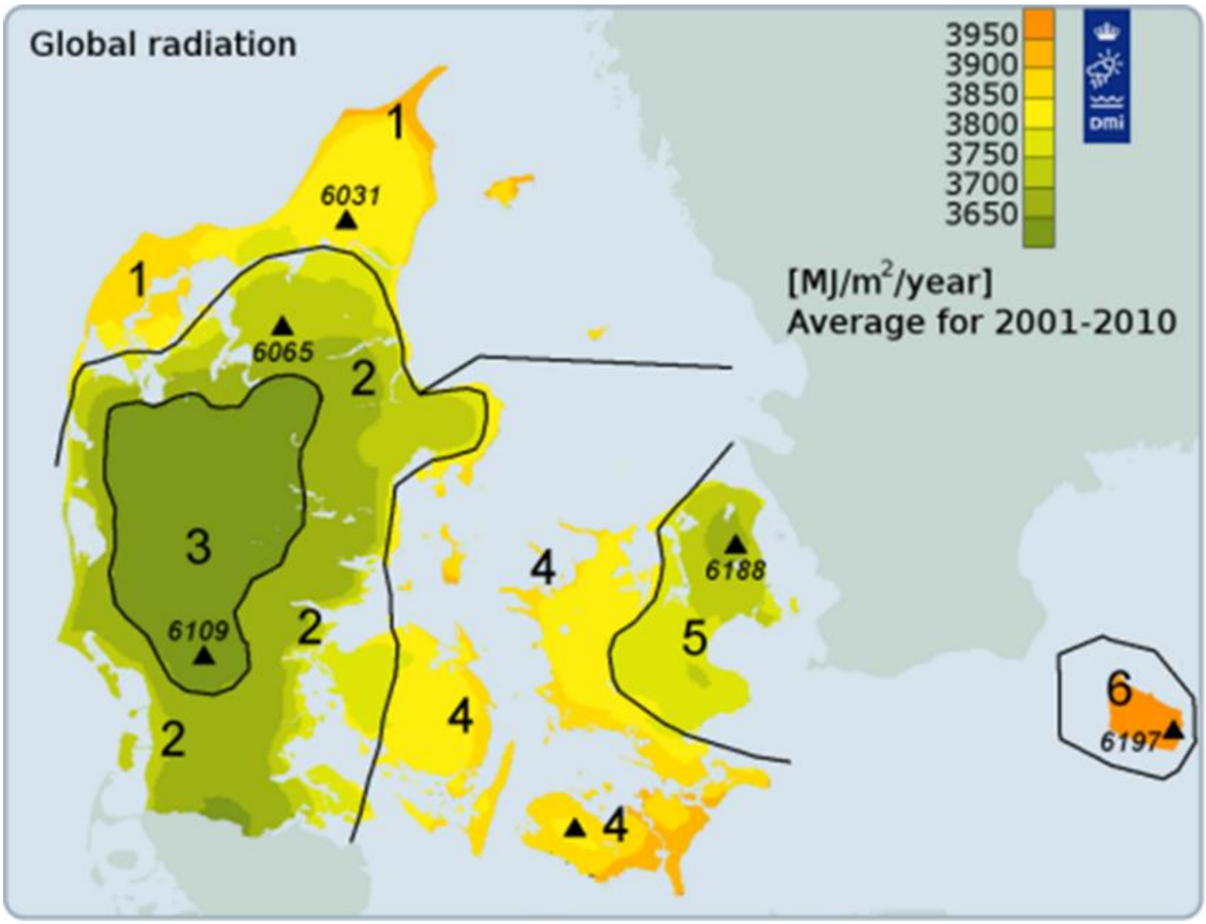

Fig. 3: Six Danish solar radiation regions

Tab. 2: Measured yearly thermal performances of Danish solar heating plants

Year	Number of solar heating plants	Yearly thermal performance, kWh/m²	Average yearly thermal performance, kWh/m²
2012	16	313 – 484	411
2013	21	389 – 493	450
2014	31	390 – 577	463
2015	36	322 – 518	439
2016	41	324 – 538	433
2017	54	318 – 495	407
2018	52	349 – 602	494
2019	55	378 – 616	454
2020	56	355 – 638	504
2021	33	332 – 585	445
2022	42	343 – 635	512
2023	42	359 – 617	490

Table 3 shows the yearly measured total solar radiation on the solar collectors and the utilization of the solar radiation for the investigated solar heating plants. The utilization is the ratio between the thermal performance and the total solar radiation on the collectors. The number of plants, the variations of the solar radiation and utilizations and the average yearly solar radiation and utilization of the plants are shown for each year.

Tab. 3: Measured solar radiation and utilization for Danish solar heating plants

Year	Number of solar heating plants	Yearly solar radiation, kWh/m²	Average yearly solar radiation, kWh/m²	Yearly utilization of solar radiation, %	Average yearly utilization of solar radiation, %
2012	16	942 – 1274	1102	28 – 45	37
2013	21	1039 – 1363	1135	31 – 46	40
2014	31	991 – 1474	1114	30 – 51	42
2015	36	876 – 1325	1101	31 – 47	40
2016	41	975 – 1444	1153	30 – 49	38
2017	54	848 – 1491	1133	26 – 48	36
2018	52	942 – 1479	1246	27 – 49	40
2019	55	913 – 1435	1179	29 – 58	39
2020	56	948 – 1625	1241	30 – 50	41
2021	33	891 – 1190	1095	30 – 55	41
2022	42	843 – 1300	1125	32 – 58	45
2023	42	866 – 1294	1154	30 – 52	42

Figure 4 shows yearly thermal performance as a function of the yearly solar radiation on the collectors for all investigated solar heating plants for all years. Each point corresponds to one year for one plant and the location of the plant is indicated as a specific solar radiation region.

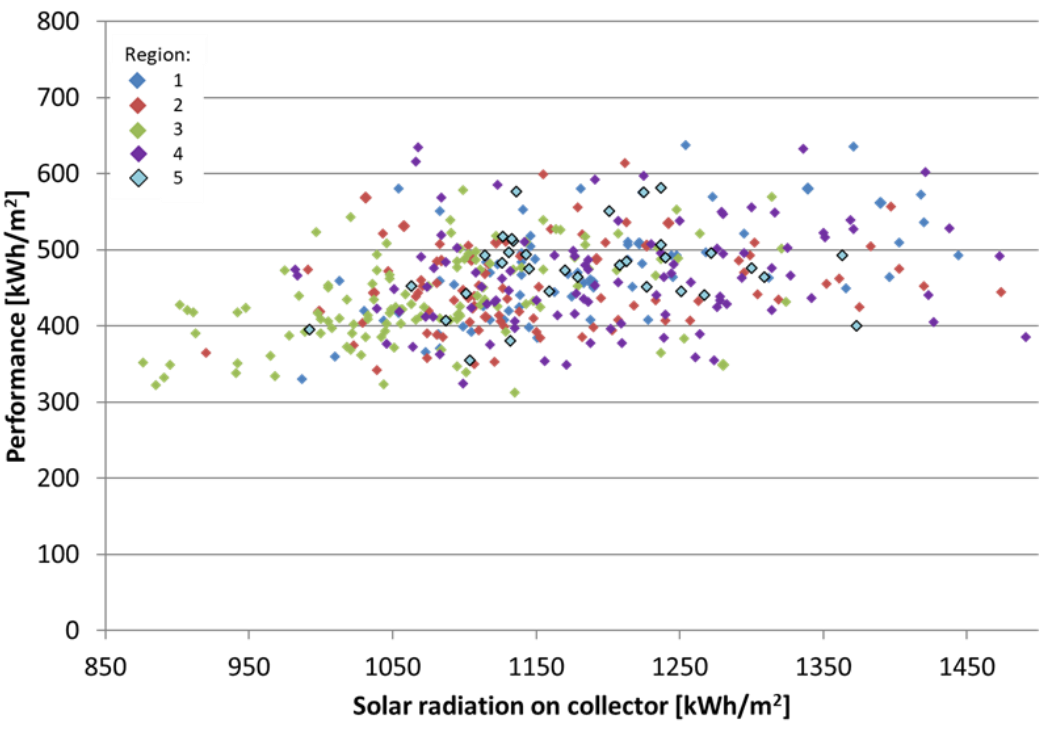

Fig. 4: Yearly thermal performance as function of solar radiation on solar collectors for Danish solar heating plants

There are large variations of the thermal performances and solar radiation from plant to plant and from year to year. There are many reasons for the variations of the thermal performances. Among other things, the following reasons can be mentioned:

- Different temperature levels of the solar collector fluid in the solar collectors. The thermal performance will be high if the temperature level is low
- Different weather conditions. The thermal performance will be high if the solar radiation and ambient air temperature are high
- Different solar collectors and different designs of solar collector fields
- Different operation strategies inclusive different flow rates
- Different heat losses from pipes in solar collector loops
- Different tilts, shadow conditions, moisture conditions, snow conditions and dirt conditions on the glass covers for the collectors
- Some plants have long-term heat storages charged to high temperatures during summer. Consequently, the high temperature levels of the solar collector fluid in these plants will result in relatively low thermal performances per m² solar collector

Figures 5 and 6 show yearly average thermal performances and yearly average utilizations of solar radiation for the investigated solar heating plants year by year. The yearly average thermal performances variates between 407 kWh/m² and 512 kWh/m² and the yearly average utilizations vary between 36% and 45%. The average thermal performance for all years is 459 kWh/m² solar collector and the average utilization for all years is 40%.

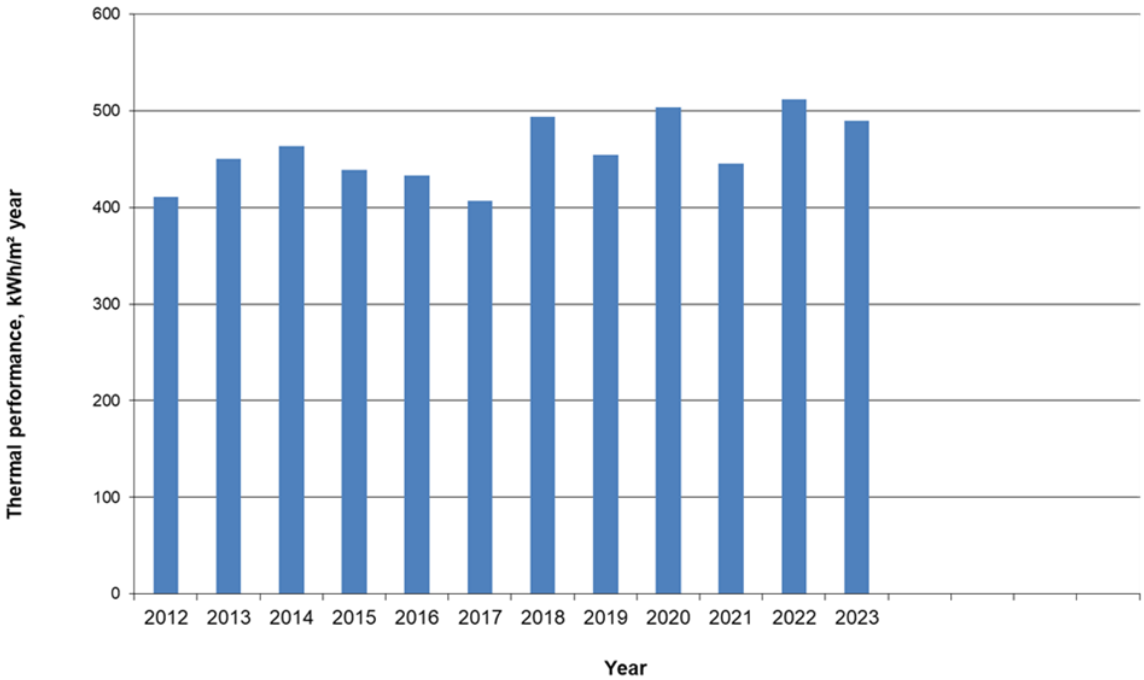

Fig. 5: Average yearly thermal performances of Danish solar heating plants

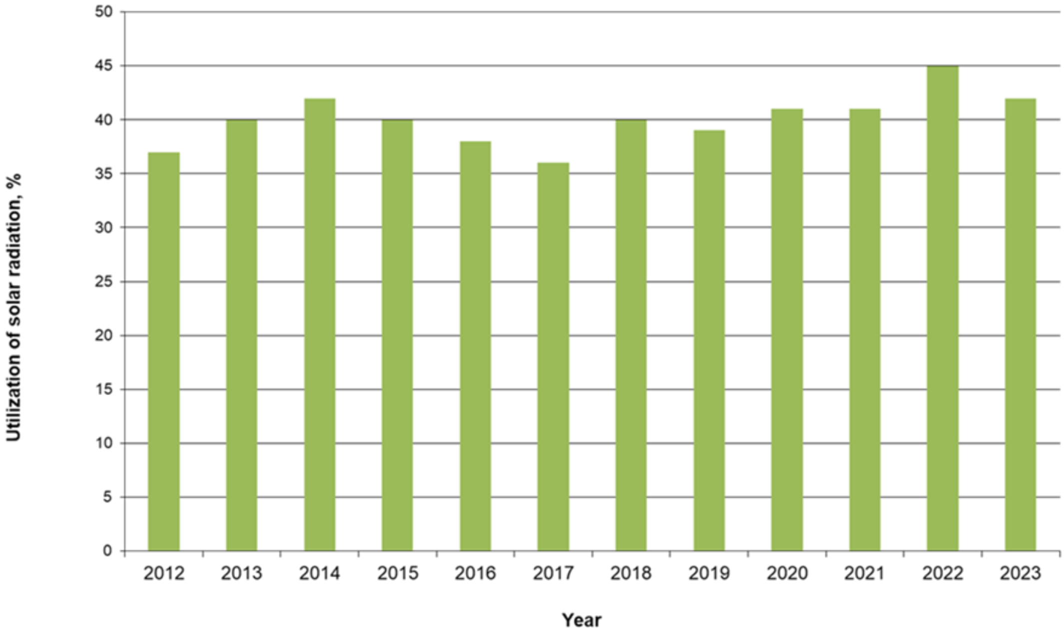

Fig. 6: Average yearly utilization of solar radiation of Danish solar heating plants

Figure 7 shows average yearly thermal performances of all Danish solar heating plants as well as yearly thermal performances of solar heating plants in solar radiation regions 1, 2, 3, 4 and 5. For most years the solar heating plants located in regions 1 or 5 perform best while the solar heating plants located in the "dark" region 3 perform worst. The average yearly thermal performance for all years for all solar heating plants is 459 kWh/m², and the average yearly thermal performances for the solar heating plants in regions 1, 2, 3, 4 and 5 are 477 kWh/m², 453 kWh/m², 435 kWh/m², 466 kWh/m² and 483 kWh/m² respectively. That is, the plants in sunny region 5 performs in average 11% better than the plants in region 3.

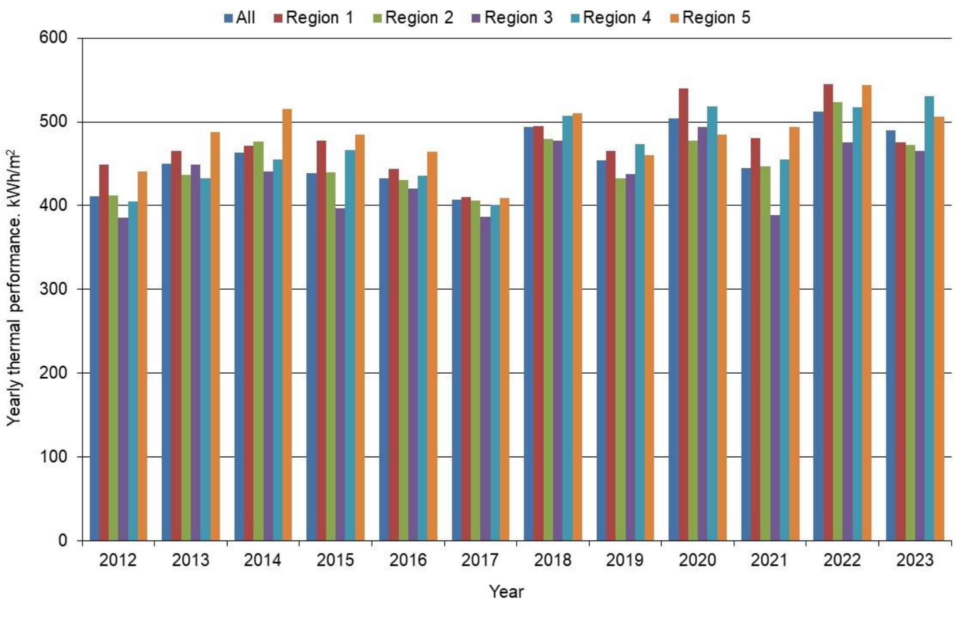

Fig. 7: Average yearly thermal performances of Danish solar heating plants in different solar radiation regions

Four of the solar heating plants in the investigations are equipped with large seasonal water pit storages: The solar heating plants in Marstal located in region 4, Dronninglund located in region 1 as well as Gram and Vojens, both located in region 2. These heat storages are charged to high temperatures of about 90°C during summer. This results in high temperature levels in the solar collector loops and relatively low collector efficiencies during summer. Measurements show that the average yearly thermal performance of these plants for all years is about 10% lower than the average yearly thermal performance of all the plants.

3. Potential of solar heating plants

Table 4 shows approximate quantities of solar heating contribution from all Danish solar heating plants to the total Danish district heating consumption for the period 2011-2023. During the last 6 years solar heating plants have covered about 2% of the total heating demand in Danish district heating networks. Together with individual solar heating systems solar heating covers about 1% of the total energy consumption in Denmark.

Tab. 4: Solar heating contribution to Danish district heating consumption

Year	Total district heating, PJ/year	Solar district heating, PJ/year	Solar district heating, %
2011	132	0.33	0.3
2012	136	0.55	0.4
2013	135	0.68	0.5
2014	122	0.98	0.8
2015	130	1.26	1.0
2016	135	2.03	1.5
2017	136	1.93	1.4
2018	132	2.47	1.9
2019	131	2.59	2.0
2020	127	2.87	2.3
2021	142	2.58	1.8
2022	130	2.97	2.3
2023	135	2.84	2.1

There are 445 district heating systems in Denmark supplying heat to about 66% of all Danish buildings. 123 of the systems have solar heating plants. The energy mix covering the heat demand of the Danish district heating systems appear from figure 8 for the period 1990-2022. The share of fossil fuels has been strongly reduced during the last decades and replaced by renewables. Today 76% of the energy supply to district heating is considered to be renewable. Most of the renewable energy is, however, biomass, and most of the biomass is imported from abroad. Consequently, the district heating systems are emitting CO_2 and are not operated in a sustainable way. There is a need to transform district heating systems into truly sustainable systems. In this connection district heating companies have in the last five years installed large electrically driven heat pumps in high numbers because electricity costs for district heating companies are expected to be low in the future. Further, the installation of such heat pumps is supported economically by the government.

Our electricity demand is expected to increase strongly in the future. There are many reasons for this increase:

- The number of electric cars will increase strongly
- New Power-to-X systems for production of sustainable fuels, chemicals and materials based on green hydrogen will be installed
- New data centers with high electricity consumption will be installed
- Many buildings outside district heating areas will in the future be heated by electrically driven heat pumps

The strong growth of electricity consumption requires high investments and CO_2 emissions, both due to installation of new wind farms and new PV solar fields and due to the needed reinforcement of the electricity grid. Therefore, electricity savings should be a high priority in future energy plans. The use of solar heating systems is an efficient way to reduce electricity consumption in the future.

The following advantages of solar heating plants for district heating should be considered:

- The plants are based on a simple, well proven, and reliable technology
- High thermal performance of existing solar heating plants: About 460 kWh/m² year
- Long lifetime of marketed solar collectors, > 30 years
- Low heat price for solar heat, about 0.04 euro/kWh
- Low maintenance costs, 0.00027 euro/kWh (Bava et al, 2025)
- No unexpected solar heat costs
- Good interplay with the energy system, since the heat storages of the plants can be used by different energy systems
- Produced in Europe
- Limited heat loss from solar collectors to ambient air resulting in low contribution to increase of ambient temperature

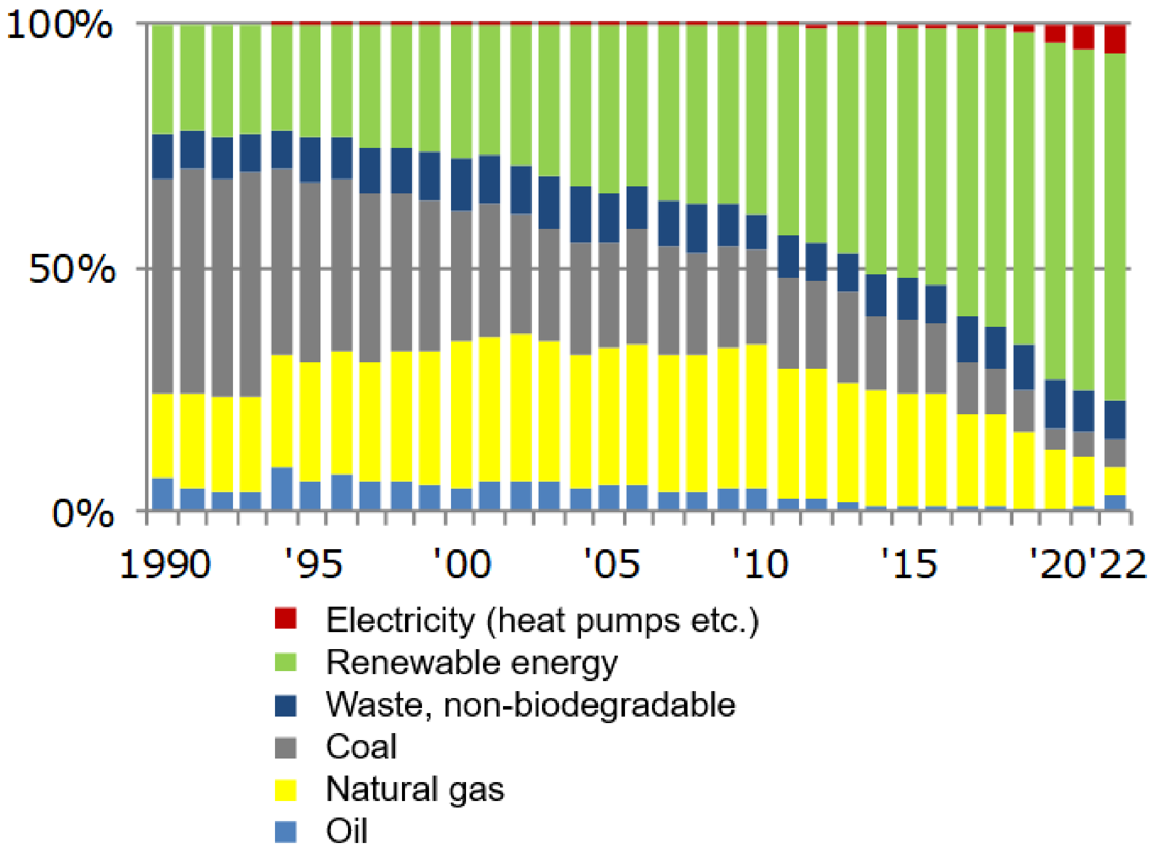

Fig. 8: Energy mix for Danish district heating systems

The strong growth of use of large electrically driven heat pumps in district heating systems is economically favorable. But, is it a sustainable solution for society?

To answer this question, a comparison on CO_2 emissions between a solar heating plant and a heat pump solution combined with a PV field is given in the following.

CO_2 emissions related to production of large solar collectors in Europe and PV panels with complete glass back sheets produced in Chine appear from table 5.

Tab. 5: CO_2 emissions from production of solar collectors in Europe and PV panels produced in China (Carlsson et al, 2014; Reichel et al, 2022)

Panel	Solar collector	PV panel
CO_2 emission	89 kg/m² panel	810 kg/kWp, corresponding to 178 kg/m² panel

CO_2 emissions from heat production from Danish district heating systems and from Danish electricity production are decreasing year by year. The CO_2 emissions for heat production in district heating systems was in 2022 in average 17 kg/GJ, corresponding to 61 g/kWh (https://ens.dk/service/statistik-data-noegletal-og-kort/noegletal-og-internationale-indberetninger) and for electricity production the CO_2 emissions was in 2023 81 g CO_2/kWh (https://energinet.dk/media/drikubl5/milj%C3%B8redeg%C3%B8relse-2023.pdf).

Based on the above mentioned CO_2 emissions and a yearly thermal performance of solar collectors of 459 kWh/m² in agreement with the average performance of the investigated solar heating plants and a yearly electricity production of PV panels of 200 kWh/m², the yearly CO_2 emission reduction is 28 kg CO_2/m² collector for solar collectors and the yearly CO_2 emission reduction is 16.2 kg/m² PV panel. That is: The number of panel operation years needed until the CO_2 emitted by the panel productions is saved is 3.2 year for solar collectors and 11 years for PV panels.

If the CO_2 emissions connected to transportation of the panels and the CO_2 emissions related to heat pump production were considered, the difference between the CO_2 emission pay back time for the two solutions will be even larger than mentioned above, even if a high SPF for the heat pump is assumed.

Further, it should be mentioned that a strong growth of yearly installed systems with a high CO_2 pay back time result in strongly increased global CO_2 emissions for society, until the growth is deceased.

It is concluded that from a CO_2 emission point of view solar heating plants produced in Europe is a much better solution for district heating systems than PV panels produced in China combined with heat pumps.

Consequently, it is hoped that the Danish market for solar heating plants soon will be reestablished.

4. Ups and downs for the market of solar heating plants

The strong growth of Danish solar heating plants until 2019 has many reasons. Besides the advantages mentioned in the previous section the following should be mentioned:

- Denmark has an ambitious energy plan. By 2050 the country must be independent of fossil fuels
- Denmark has a lot of district heating. Today 66% of all Danish buildings are heated by district heating
- Danish district heating systems operate with low temperature levels. A typical forward temperatureto towns is about 80°C and a typical return temperature from towns is about 40°C
- Danish district heating companies are often nonprofit cooperatives
- There are high taxes for fossil fuels in Denmark. Typical tax is about 0.035 euro/kWh produced heat
- The Danish energy system is decentralized
- There is a high share of wind energy for electricity production. In 2023, 54% of the Danish electricity consumption was produced by wind turbines
- The costs for marketed solar collector fields installed on the ground are relatively low, about 150 euro/m²
- In many cases relative low ground costs are available
- There is a good cooperation between solar heating plant owners. Among other things, regular meetings with experience exchange are arranged

In 2020 the Danish market for solar heating plants collapsed. There are several reasons for the collapse:

- There is no taxation on biomass fuels. Consequently, biomass fuels are used in large amounts by district heating companies.
- The taxation of electricity for district heating companies was reduced from the start of 2021 from 0.028 €/kWh to 0.0005 €/kWh.
- The Danish Energy Agency supports district heating companies on installation of large heat pumps in district heating systems economically and inexpensive electricity is foreseen in the future. Consequently, heat pumps are installed in high numbers by district heating companies due to good economy.
- In 2020 Arcon-Sumark was sold to GreenOneTec. Therefore, the most important actor in the field is no longer a Danish company.

5. Conclusions

The number of Danish solar heating plants in district heating areas increased strongly from 16 plants in 2009 to 123 plants in 2019. Many of the plants were installed in district heating systems with natural gas boilers due to good economy.

The average yearly thermal performance for the solar heating plants for the period 2012-2023 is 459 kWh/m² solar collector and the yearly average utilization of the solar radiation for all the years is 40%.

Solar district heating plants are based on a simple, well-proven, and reliable technology. They supply heat with a relatively low cost of about 0.04 euro/kWh, and the used solar collectors have a lifetime longer than 30 years. The solar heating plants provide about 2% of the total heat demand in Danish district heating areas.

Despite the good experience from the plants, the Danish market for solar heating plants collapsed in 2020, mainly because district heating systems are installing large electrically driven heat pumps.

Solar heating plants are produced in Europe and the plants contribute to a global reduction of CO_2 emissions, even with a strong growth of installed systems. It is therefore hoped that the market for solar heating plants will soon be re-established.

6. Acknowledgements

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