Thermal performance of concentrating tracking solar collectors

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Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

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Report

Department of Civil Engineering
2013

DTU Civil Engineering Report R-292 (UK)
August 2013

DTU Civil Engineering
Department of Civil Engineering

List of contents.

Nomenclature

Pyrheliometer = Instrument to measure direct normal irradiation from the sun (DNI).

Pyranometer = Solar instrument for measurement of total (or diffuse) radiation onto a certain plane.

Gdni = Direct normal irradiation (DNI) from the sun disk (no diffuse radiation included) [W/m^2]

Gbeam = Beam radiation = Direct radiation. Beam is used to avoid the abbreviation D that can be mixed with Diffuse radiation [W/m^2]

Gd = Diffuse radiation = Solar radiation originating from the sky outside the sun disk area, plus reflected scattered radiation from the ground and surroundings. [W/m^2]

Gt = Total radiation = Direct + Diffuse radiation onto a specific plane. [W/m^2]

Global radiation = Total radiation onto a <u>horizontal</u> surface. [W/m^2]

CSP= Concentrating Solar Power. Normally Electric Power generation with a high temperature Collector, Steam generator, Steam turbine and Electric generator. The thermal solar collector technology can also be used for various purposes like: Hot water for District heating, Process heat, Powering of heating pumps, Powering of cooling pumps, Powering of desalinations plants. The normal use is for Steam generation. *In this report we only evaluate the CSP collector array thermal performance and preliminary economy.*

Aperture area= Optically active area of a collector where the solar radiation comes into the collector. [m^2]

Gross area= Outer "Mounting" area of a collector. Total outer Length * Width in the aperture plane. [m^2]

Ground area= Horizontal area needed for the collector field. (Usually 2-3 times the collector area.) [m^2]

Tm= Mean operating temperature of the collector Tm = (Tin+Tout)/2 [°C]

Thermal power= Fluid Density * Fluid specific heat * Flow rate * (Tout-Tin) [W]

Efficiency = Useful Thermal Power Output from collector/ Solar radiation input onto the collector. [-]

Tracking= Rotation after the solar position in the sky, to minimize the incidence angle for beam radiation onto the collector aperture area, all the time.

Trough = Long mirror with a "half cylindrical" parabolic shape. It is made of smaller mirror sections to allow replacement and take up thermal expansion and wind deformations locally, without breaking the glass mirrors.

Absorber= Black surface that converts solar radiation into heat with high efficiency often >95%.

Selective surface= A surface with wavelength dependent optical properties to enhance useful energy output. Often applied on absorbers and very important for a CSP operating at high temperatures.

Vacuum tube = Glass tube surrounding the absorber. This dramatically reduces the heat losses by removing the air between the glass and the absorber. Only radiation losses will remain then.

η_0 = Zero loss efficiency. The maximum efficiency of a collector when operating at ambient temperature for the heat transfer fluid inside the collector. [-]

$K_{beam}(\theta)$= Incidence angle modifier for beam radiation onto collector. $K_{beam}(\theta)=\eta_0(\theta)/\eta(0)$ [-]

K_{diff} = Diffuse Incidence angle modifier. Kdiff = $K_{beam}(60°)$ in this report [-]

p = Incidence angle coefficient in the equation $K_{diff} = 1 - \tan(\theta/2)^p$ [-]

a_1 = Heat loss coefficient. Heat loss per m^2 aperture area per K over-temperature of the fluid above ambient. [$W/m^2/K$]

a_2 = Temperature dependence in heat loss coefficient. [$W/m^2/K^2$]

θ = Incidence angle. Angle between the normal to the collector aperture area and the rays coming from the sun. [°]

Azimuth = Angular deviation along the horizon from south. South =0° , East = -90° , West = 90°.

Zenith angle = Angle between the zenith direction and beam rays from the sun disk. (= 90° - Solar Altitude).

1. Introduction

This report describes the work carried out at Department of Civil Engineering, Technical University of Denmark in cooperation with Aalborg CSP A/S in the EUDP Project: Verifikation af ydelse for CSP-solvarmeanlæg (forfase). *It should be remembered that this is a prestudy (forfase) and more elaborate results can be derived in later steps.*

A prototype CSP plant in Thisted built by Aalborg CSP has been monitored and evaluated during the spring and summer 2013, by DTU Byg in close cooperation with Aalborg CSP. The aim is to see how well a concentrating collector of the Aalborg CSP design perform in the Danish climate, as well as making comparison with flat pate solar collectors.

The design is called parabolic trough. Figure 1 shows an overview picture of the Aalborg CSP Collector array.

Figure 1. Overview picture of the Aalborg CSP plant in Thisted.

The solar rays are focused by the mirrors onto a long absorber tube sorrounded by a vacuum glass tube. Gaps in the mirror are necessary for ground supports and thermal expanion elements. Note also the leight weight support structure for the mirrors. This is very important for optimization of cost and performance. There are just 2 tracking units in the whole array located in the middle of each trough, see figure 2.

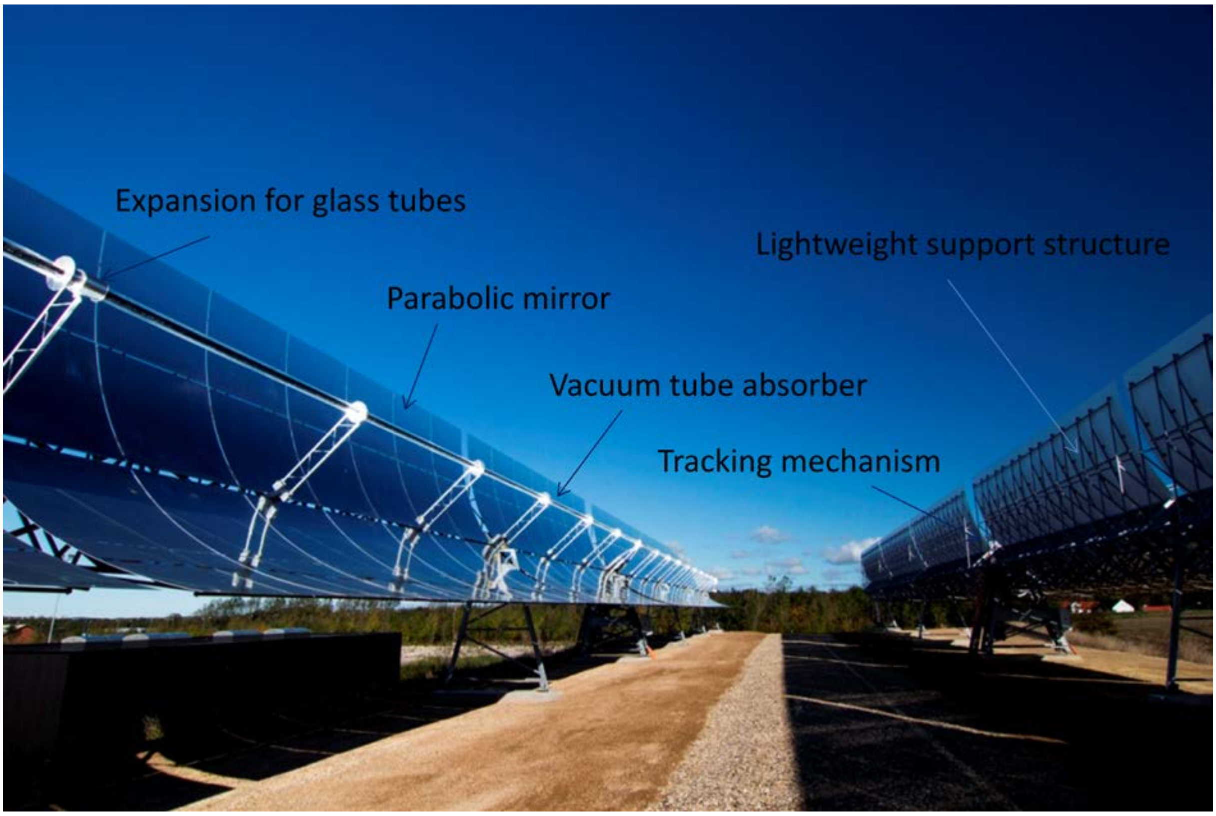

Figure 2. Closeup of the Aalborg CSP concentrating collector array at Thisted. Note also the leight weight support structure for the mirrors.

The aperture area is 808 m^2 defined as the optically active area of the collector = Length * width of the mirrors, minus mounting and thermal expansion gaps, between mirror elements, see separate calculation in appendix A.

The nominal thermal power given by Aalborg CSP is 500 kW for Thisted. This corresponds to 620 W/m^2. This is a little less than the traditional 700 W/m^2 used for nominal power from solar thermal collectors in official statistics. The power value does not affect the results in the report, so it is given here for general information corresponding to how traditional boiler plants are designed and sold. (Photovoltaic Systems for electricity generation are also sold in nominal electrical Wp=peak watts.)

The wording CSP normally refer to solar applications for Concentrating Solar Power, using a high temperature collector, steam generator, steam turbine and electric generator. The Electric power step is not tested here. Just the thermal power output characteristics, for the application in district heating.

The Thisted plant has been carefully instrumented with high class, calibrated sensors and monitored with a high time resolution. Solar radiation was measured with a pyrheliometer, see figure 3.

Figure 3. Pyrheliometer for measurement of direct radiation. A problem with soiling of the sensor was identified and regular cleaning was applied to have accurate longterm data. Construction work nearby the plant probably enhanced this problem significantly. On other pyrheliometer instruments the rain shelter is not there, leading to self cleaning in the Nordic climate conditions.

The output power of the collector array was measured with a Kamstup Multical 801 energy meter using PT500 resistance sensors for the temperature difference measurement.

One problem for the evaluation was the used variable ”event driven” sampling interval individual for each channel. Raw data first had to be condensed to hourly mean values, before the evaluation procedure and then normal methods could be applied for performance model validation. The event driven sampling method is good to reduce the amount of data, for processes with large dynamics in the behaviour. Another problem was the 15° offset from north south direction of the rotation axis, in the plant, see figure 4. This lead to an interesting and useful model expansion, that may be used to even out the seasonal performance.

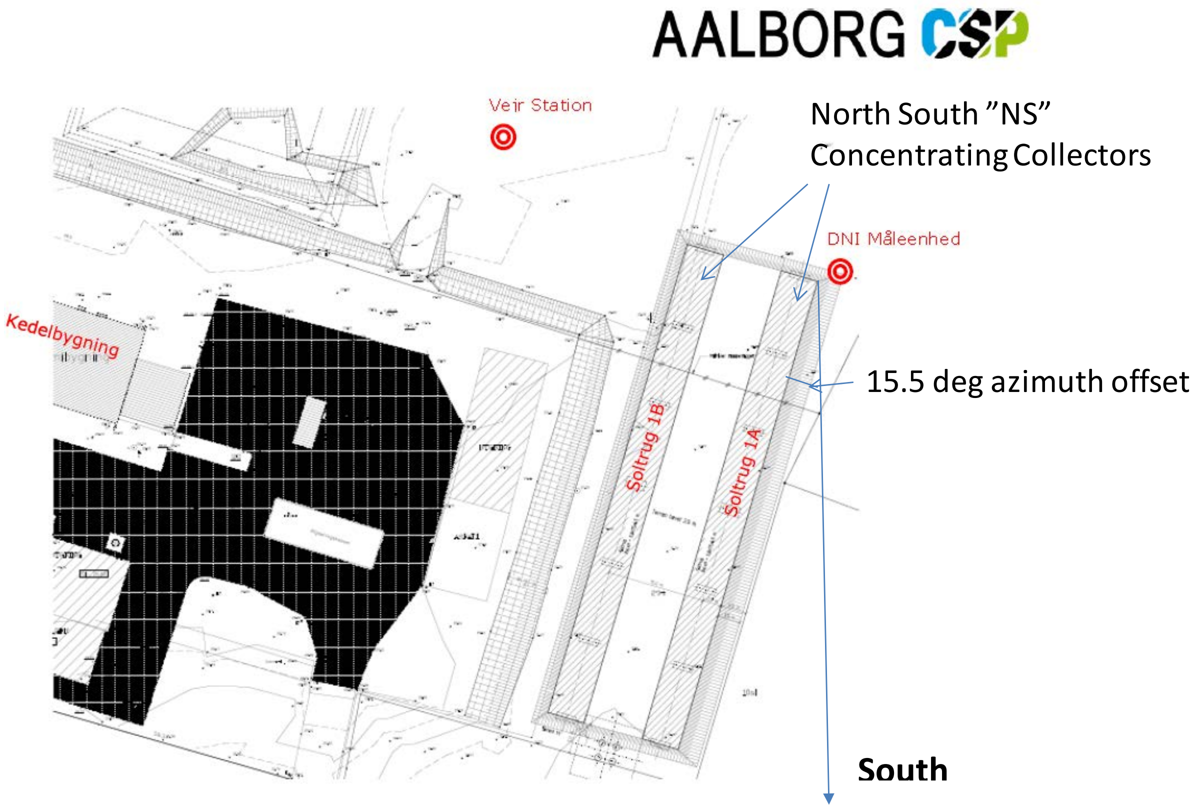

Figure 4. Overview drawing of the Thisted plant from Ref [1]

The operation of the plant has been almost continous and as close to a production situation as possible. As it is a prototype, some adjustments and replacement of components have been necessary during the period. This has been noted in a log file. These periods are excluded from the performance evaluation. Normally the plant was shut down or at least defocused during maintenance giving a clear separation between prototype adjustment work and normal operation.

The need for cleaning of mirrors, vacuum tube glass on the absorber and the direct solar irradiation (DNI) instrument, also have been identified more exactly during the operating period. Only representative data for normal operation have been chosen for evaluation. *Construction work nearby the plant, probably enhanced this problem significantly during the monitoring period. This problem with dust, was also the case in one of the first CSP collector tests in Sweden [11] This problem would probably also affect performance significantly, for a flat plate collector array. During certified testing regular cleaing is of solar collectors and solar radiation insturments is very important too.*

The representative data periods chosen have been used to validate a whole collector array performance model. The collector array model then was programmed and used in a specially developed Excel tool for annual performance estimation [2]. In the Excel tool one old and 6 different new reference climates for Denmark were used, see figure 5 [3]. The model match against measured data was optimised for lowest error in power output. This will result in the most accurate annual performance calculations with the model.

The total solar radiation and the direct radiation from the sun disk, are higher for the new reference years, than for the old Danish reference year. Most solar radiation appear in the new reference year for Bornholm.

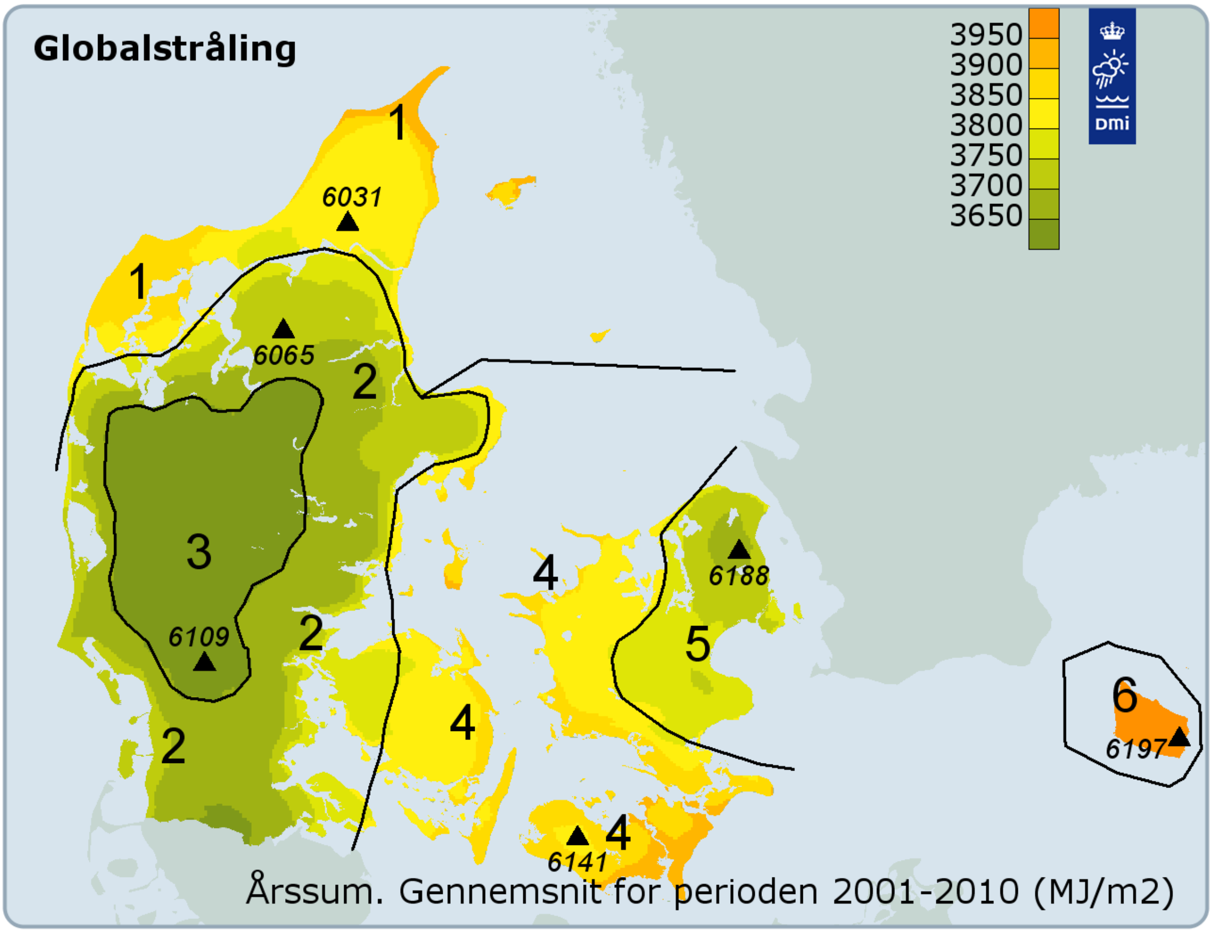

Figure 5. Climate data locations expecially for Solar radiation [3] used in the excel tool.

The Thisted plant is located in a windy location close to the North Sea. In this way the mechanical stability of the design during operation can be checked.

The Thisted collector array is connected to a boiler plant and it has been operated at relatively high temperatures in the range of 100°C inlet and 120°C outlet. The solar collector fluid is pure water. Freeze protection is done by circulation in the night at moderate overtemperatures. The heat losses per m^2 collector area are extremely low, as it is a high concentrating collector with vaccum tube insulated selective absorber. Therefore the absorber tube will be kept warm by diffuse radiation between the beam radiation periods. This is an interesting observation from the plant monitoring that also lead to easier modelling of all day performance. No detailed analysis of this was possible in the project though.

2. Performance evaluation of the Thisted Prototype CSP plant

A large amount of high resolution plant and climate data from Thisted have been collected and analyzed. A simplified collector field model including relevant parameters for the Thisted CSP plant has been validated against measurements.

In a second step the same model and parameters determined from measurements are used together with the mentioned new reference climate data for Denmark. Representative annual performances for Plat Plate and CSP collector fields are calculated.

Figure 6 shows an example of how good the collector array model, can predict the measured thermal output power over the whole day for different weather situations. The collector model includes all optical losses, as incidence angle cosine effects, incidence angle modifier and also internal shading in the array between the troughs at low solar altitudes in the morning and evening. The heat losses are also modeled, but they are extremely low due to the very high concentration ratio, a selective absorber and transparent vacuum tube insulation. (very small absorber area that only loose very little heat by radiation).

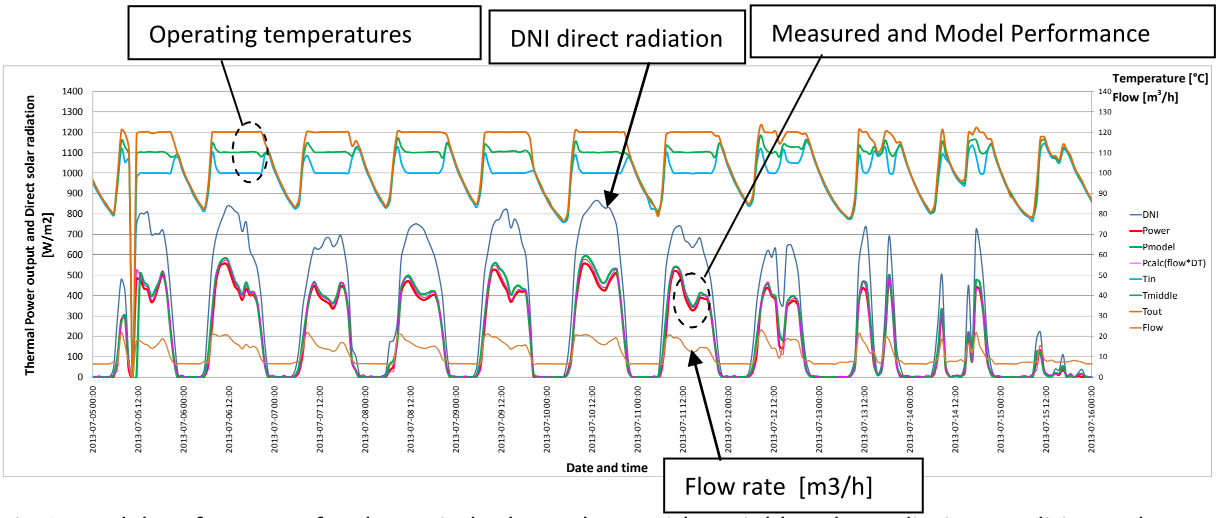

Fig 6. Model performance for the period July 5-July 14 with variable solar radiation conditions. The thick red curve is measured (with a Kamstrup Multical 801 energy meter). The green curve is the collector model output power. The match is very good (the curves overlap mostly). For this period the collectors and DNI sensor are clean, so the results are representative for normal operation. The uppermost curves are Tin, Tm and Tout. The orange curve is the fluid flow rate trough the collector. The flow rate is modulated to give a constant outlet temperature in spite of varying solar radiation input. The DNI beam radiation, measured with the pyrheliometer is also shown, as a thin blue curve.

A zero loss efficiency of $\eta_0 = 0.75$ for beam radiation was used and a heat loss coefficient, $a_1 = 0.04$ W/m2/K were used in the model. The temperature dependence of the heat losses a_2 was assumed to be zero. This extremely low collector heat loss level can be benchmarked from receiver test data in [4]. See also Appendix E for this calculation.

Only beam radiation is considered for the CSP in this simplified modeling. But also diffuse radiation directly onto the vacuum tube insulated absorber, will contribute marginally. Most importantly diffuse radiation will help to keep the vacuum tube absorber warm between the operating periods.

The tracking accuracy, mirror accuracy/adjustment and absorber alignment, is very critical for the collector array performance. Bad tracking accuracy has been one reason for disappointing results for prototype concentrating technologies in the past. During the evaluation of the Thisted plant the rotation position of the troughs have been compared with a theoretical angular position. The match has been better than 0.5° for both CSP troughs in full operation which is completely within the calculation and measurement accuracy, see figure 7. (The sun disk angular size is 0.5° across)

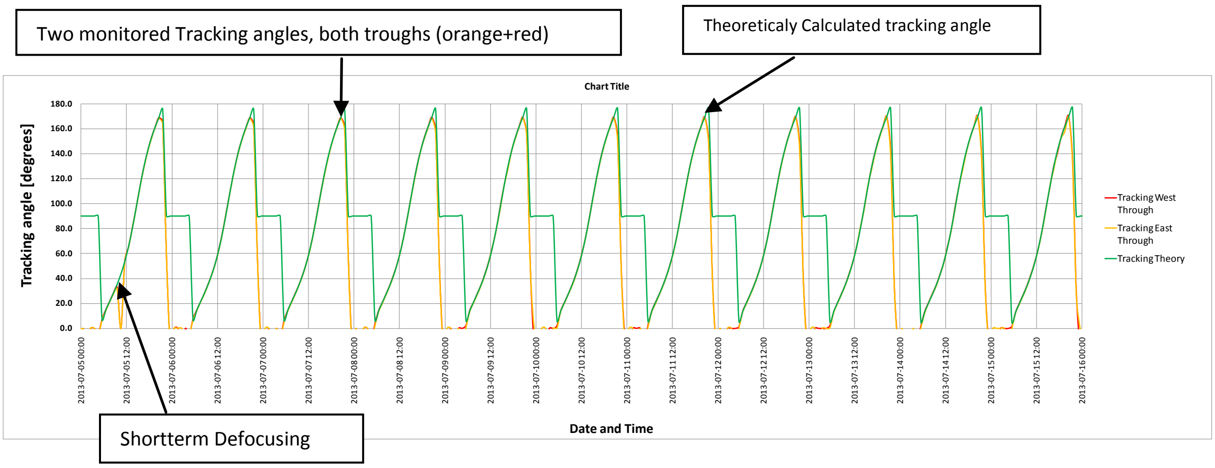

Figure 7. Check of tracking accuracy for both troughs and comparison to theoretical tracking angle based on time of day/year and solar position and geometry using the theory in ref [5] and [6]. The match is almost perfect within 0.5°, except the first day when some maintenance was done. Same period as for the performance in Figure 6.

3. Annual calculation model validation for Thisted

The second step in model validation was to use the Excel tool with the validated model and to compare daily sums of modeled and measured thermal output. As can be seen in figure 8 the match is good for clean mirrors. July 2013 was extremely dry and needed more frequent cleaning. A concentrating collector is sensitive to dirt and dust, as the particles on the surface scatter the beam solar radiation and less radiation will reach the absorber and be converted to useful heat.

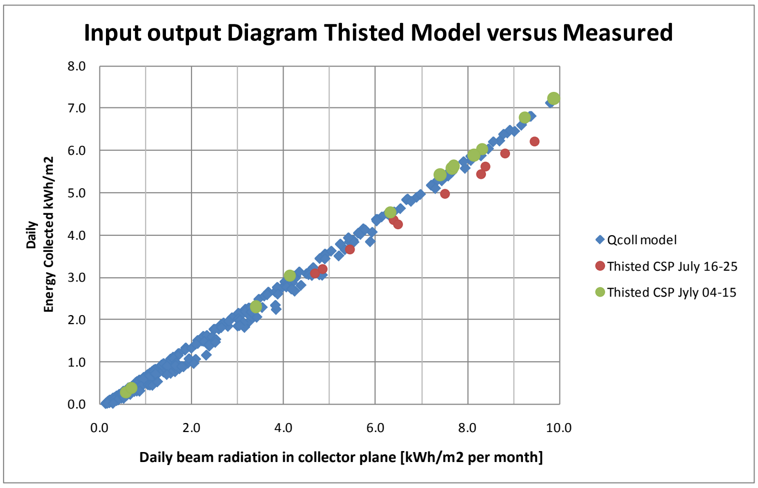

Fig 8. The blue points are from an annual calculation with the model and parameters as for evaluation of Thisted data. Operating mean temperature Tm= 110°C. The green points are just after

cleaning of the DNI instrument and the CSP collector and mirrors (cleaning of the glass tubes is equally important). Red points are later in July until July 25 with probably more and more dust on the mirrors in the dry weather.

4. Model check for flat pate collector fields

For this work no detailed performance measurements were available for flat plate collector fields of the same quality as for the Thisted plant. Therefore data from the homepage www.solvarmedata.dk [7] was downloaded and compared with the Excel tool developed and used in this work. The Input output method [8] was used. It is well validated since 30 years back, but seldom used today, in spite of its simplicity for approximate performance check when complete data sets are not available for scientific level evaluation.

Monthly values from three locations in Denmark are plotted in figure 9. The Excel tool was then used to calculate monthly results for a flat plate collector field. Parameters for Arcon collectors with ETFE foil was used in the calculations according to the homepage. Results for two mean operating temperatures 50°C and 70°C, typical for district heating are shown, as there is no information available about operation temperatures.

It can be seen that the match is very reasonable all over the year for all three plants. A certain scatter is always there as every month is different in climate variable details and also shorter periods with operating problems can be present in the measured data. Also the accuracy and installation of the solar radiation sensors at the collector fields have an influence. It should also be mentioned that the Excel tool does not take pipe losses or thermal capacitance effects in the field into account in the present version. This can be added in the next step of collector field model development.

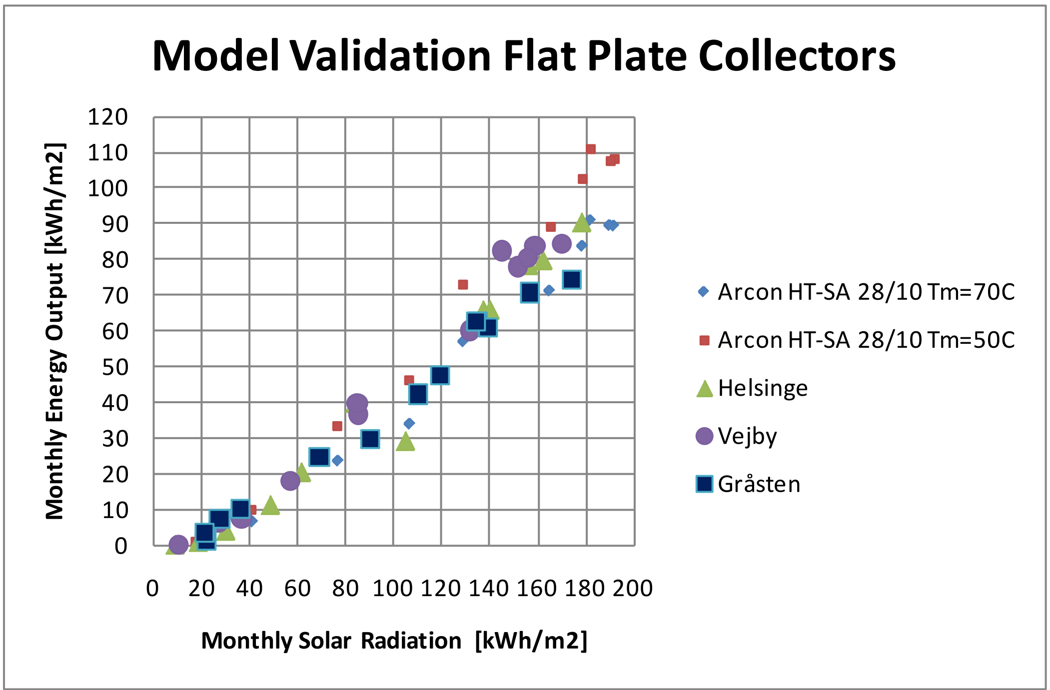

Figure 9. Input output diagram for flat plate collector fields measured and modeled. This is a first step validation as individual operating temperatures of the plants are not available.

5. Annual Performance calculation tool

After validation of the Excel tool results can be calculated for comparison of thermal performance and later economy for typical CSP and Flat Plate collector fields.

The Excel tool is prepared for 3 different flat plate collector fields and one CSP field. The energy output is calculated for 5 temperatures at the same time. Figure 10 shows the front page of the tool. Detailed hourly or monthly data can be derived in subfolders in Excel. Only input parameters for the collector field and annual kWh performance output are shown on the front page.

The tool is designed so that all input parameters can be copied and stored together with the results for later check and changes. Climate data, location, collector parameters and field parameters have to be specified. Input data can be stored for later reuse.

Input Data Flat Plate Collector	Collector Field (1)	Collector Field (2)	Collector Field (3)		Flat Plate Collector Field	Flat Plate Collector Field	Flat Plate Collector Field	CSP Collector Field
	Arcon Teflon HT	Arcon HT-A 28	Sunmark GJ 14	Units	Output Results	Output Results	Output Results	Output Results
IAM coef. Beam rad. p	4.51	4.51	5.3	[-]	Climate data location no:	Climate data location no:	Climate data location no:	Climate data location no:
a_1	2.205	3.2	2.3	[W/m^{2}K]	1	1	1	1
a_2	0.0135	0.0137	0.029	[W/m^{2}K^2]	Collector Field (1)	Collector Field (2)	Collector Field (3)	
IAM diffuse rad. K_θ (60°)	0.916	0.916	0.946	[-]	Arcon Teflon HT-SA 28/10	Arcon HT-A 28/10 (no ETFE foil)	Sunmark GJ 140D (No teflon)	*Horisontal NS axis Tracking*
η_0	0.817	0.839	0.85	[-]	*Yearly thermal performance kWh/(year*m^2) Collector Field Performance*	*Yearly thermal performance kWh/(year*m^2) Collector Field Performance*	*Yearly thermal performance kWh/(year*m^2) Collector Field Performance*	*Yearly thermal performance kWh/(year*m^2) Collector Field Performance*
T_{m_1}	30	30	30	[°C]	727	701	751	576
T_{m_2}	50	50	50	[°C]	578	525	566	573
T_{m_3}	70	70	70	[°C]	447	378	396	570
T_{m_4}	90	90	90	[°C]	328	254	245	568
T_{m_5}	110	110	110	[°C]	224	153	125	565
FP Collector tilt	35	35	35	[°]	*Relative performance*	*Relative performance*	*Relative performance*	*Relative performance*
FP Coll. Surface azimuth	0	0	0	[°]	1.00	1.00	1.00	0.79
Ground reflection	0.2	0.2	0.2	[-]	1.00	1.00	1.00	0.99
Climate number or location	1	1	1	[-]	1.00	1.00	1.00	1.28
Latitude climate data	57.18	57.18	57.18	[°]	1.00	1.00	1.00	1.73
Longitude climate data	9.95	9.95	9.95	[deg]	1.00	1.00	1.00	2.52
Longitude time zone	15	15	15	[deg]	*Solar radiation kWh/(year*m^2)*	*Solar radiation kWh/(year*m^2)*	*Solar radiation kWh/(year*m^2)*	*Solar radiation kWh/(year*m^2)*
Collector width (height along glass)	2	2	2	[m]	1186	1186	1186	1322
Row distance in coll field	5	5	5	[m]	*Utilization of solar radiation %*	*Utilization of solar radiation %*	*Utilization of solar radiation %*	*Utilization of solar radiation %*
Number of rows in coll field	40	40	40	[no#]	61.3	59.1	63.3	43.6
Diffuse rad. in field correction	0.5	0.5	0.5	[-]	48.8	44.2	47.7	43.4
Input Data NS Tracking collector: Axis Azim	15	0	0	[°]	37.7	31.9	33.4	43.2
p	2.4	2.4	2.4	[-]	27.7	21.4	20.7	43.0
a_1	0.04	0.04	0.04	[W/m^{2}K]	18.9	12.9	10.6	42.8
a_2	0	0	0	[W/m^{2}K^2]				*Direct rad in collectorplane kWh/(year*m^2)*
K_θ diffuse	0.010	0.010	0.010	[-]				872
$\eta_{0\ beam}$	0.75	0.75	0.75	[-]				*Utilization of Direct radiation onto collector %*
Wa=Width of Through	5.77	5.77	5.77	[m]				66.0
Da=Tracking Axis CC distance	15	15	15	[m]				65.7
Nr=Number of rows in collector field	2	40	40	[-]				65.4
								65.1
								64.8
								DNI in direction to the sun kWh/(year*m2)
								1124.5

Figure 10. View from the highest level folder of the Excel collector field calculation tool, further developed and validated in this project.

6. Annual Performance comparison between CSP and Flat plate collector fields

The models for flat plate collector fields and CSP collector fields in the Excel tool have been used to calculate the annual performance for different collector mean operating temperatures. The influence of shading from nearby collector rows, for beam and diffuse radiation, in the collector field, is also taken into account in a realistic but slightly simplified way.

Annual results with the Excel tool assuming a constant solar collector fluid temperature throughout the year, are given in figure 11 and 12. At high temperatures, the CSP delivers more energy than a flat plate collector per m^2. At low temperatures the flat plate collectors have a higher thermal performance than the CSP collector.

For both climates shown in the figure 11 and 12, the performance cross over temperature 45-55C is similar. A tendency to lower cross over temperature for Bornholm due to the increased direct radiation to total radiation ratio can be seen.

The thermal performance for both collector types, are also much higher at Bornholm, due to the increased solar radiation.

The collector parameters used are taken from certified test data sheets, see table 1, [9] and [10]. Flat plate collectors have been improved strongly in the past and most likely they will be further improved in the future therefore figure 11 and 12 should only be seen as indicative that CSP technology can be competitive, performance wise in Denmark.

Table 1. Collector Parameters used in this report with references. *The choosen parameters should only be seen as indicative of the technologies as improvements are possible with time.*

Parameter=>	η_0	K_{diff}	a_1	a_2	p	Reference
Collector type / Unit=>	[-]	[-]	[W/m^2/K]	[W/m^2/K^2]	[-]	
Aalborg CSP	0.75	0.0	0.04	0.0	2.40	This report
Arcon HT-SA 28/10 (with ETFE foil)	0.817	0.916	2.205	0.0135	4.51	[9]
Arcon HT-A 28/10 (no ETFE foil)	0.839	0.916	3.200	0.0137	4.51	[9]
Sunmark GJ 140V (without Teflon)	0.850	0.946	2.300	0.0290	5.30	[10]

The collector field input parameters taken into account so far, in this pre-study, are shown in the columns to the left in figure 10 and magnified in appendix F. *These field parameters are meant to be adapted from case to case. Representative average values are used in this report to limit the number of calculations and diagrams.*

Pipe losses outside the collectors and thermal capacitance in the collector field are not explicitly included in the present Excel calculations, using hourly time step, as this is a second order factor *for the comparison* between technologies in well designed collector fields. A rough estimation of the influence of pipe losses on the annual performance, in a well designed collector field is given in appendix B. These variables are still important to include in the modeling, in coming project steps, for optimization of design and control of a whole collector field, as the marginal savings can be very significant. Long transit pipes, between the collector array and district heating network, are outside the considerations here too, but they have very little influence on the comparison of collector technologies.

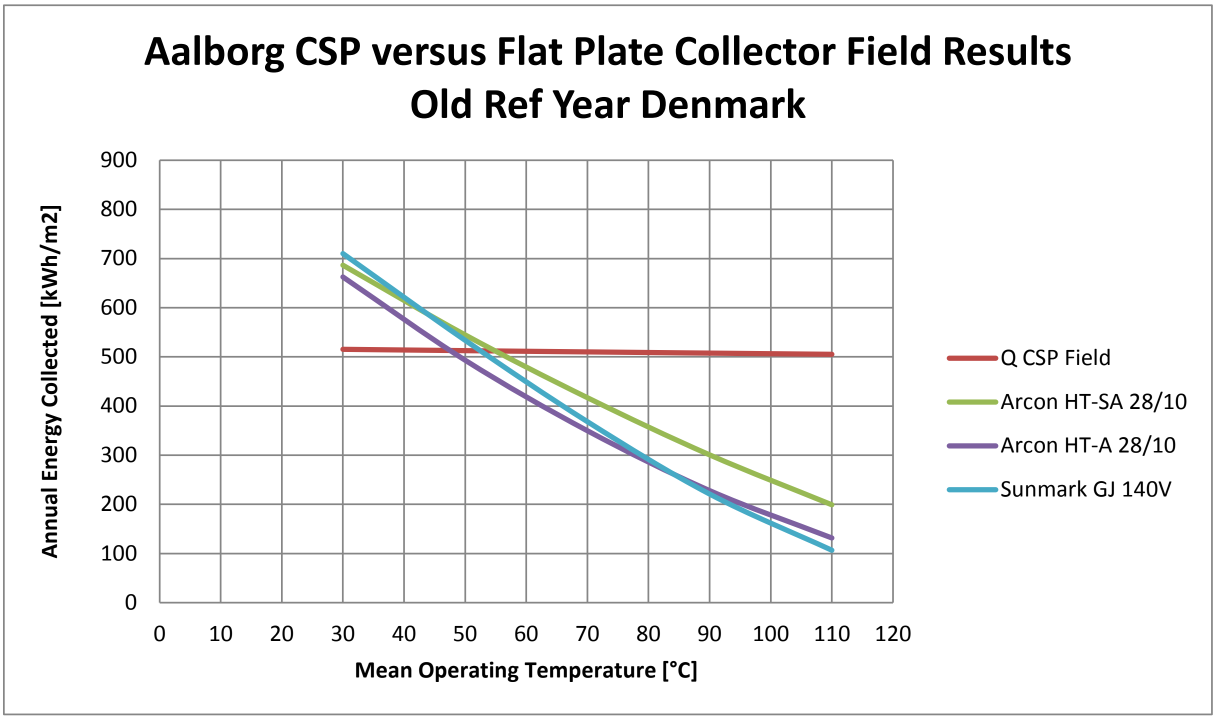

Fig 11. Annual performance for Flat Plate and CSP collector fields. "Old" Danish Reference year.

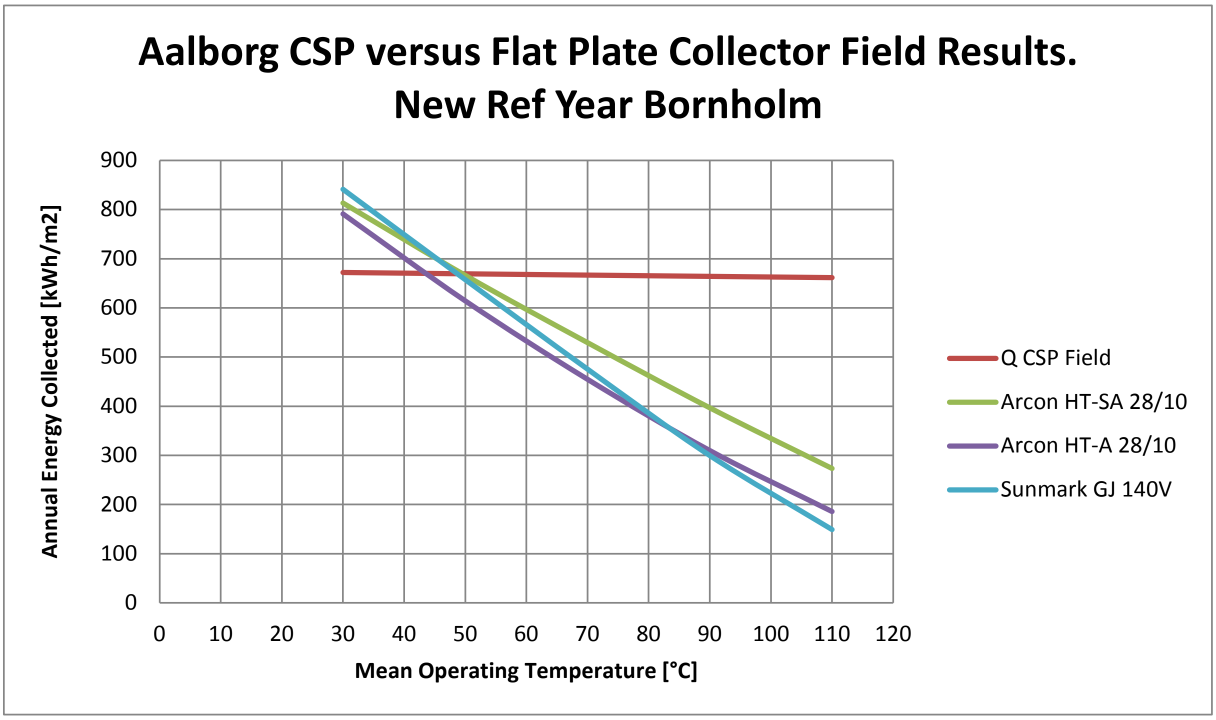

Fig 12. Annual performance for Flat Plate and CSP collector fields. New Reference year for Bornholm.

7. Energy Cost comparison between CSP and Flat Plate Collector Fields

Comparable energy cost estimates are shown in figure 13 and 14. Results are given with operating temperature and collector field investment cost per m^2 collector area, as variables. An annuity of 0.0574 is assumed equivalent to 25 years depreciation time and 3% interest rate. Operating and maintenance costs are assumed equal for both technologies in this step.

Weather data for the "old" Danish Reference year and the best reference year location in Denmark, Bornholm, of the new climate data sets are used.

An investment cost range from 1000 to 3000 DKK/m^2 for both Flat Plate and the new CSP Aalborg technology is assumed. *The reader should find out by himself the relevant price level for the different technologies, to get the exact economic comparison result, from case to case. Also the collector parameters in Table 1 should be remembered as indicative, as they are the basis for the result. They can be improved with time, as in the past and for new products on the market. The Excel tool developed in this project, can be used to give more specific updated results from case to case.*

The costs are assumed to be for an equal "turn key" delivery of the collector field including all costs, also ground area cost. The best performing Flat Plate collector, at higher operating temperatures in Table 1, Arcon HT SA-28/10 with ETFE foil, is chosen in this case. An example of a cross over economic point is indicated in both figure 13 and 14. The costs chosen for the point are just examples.

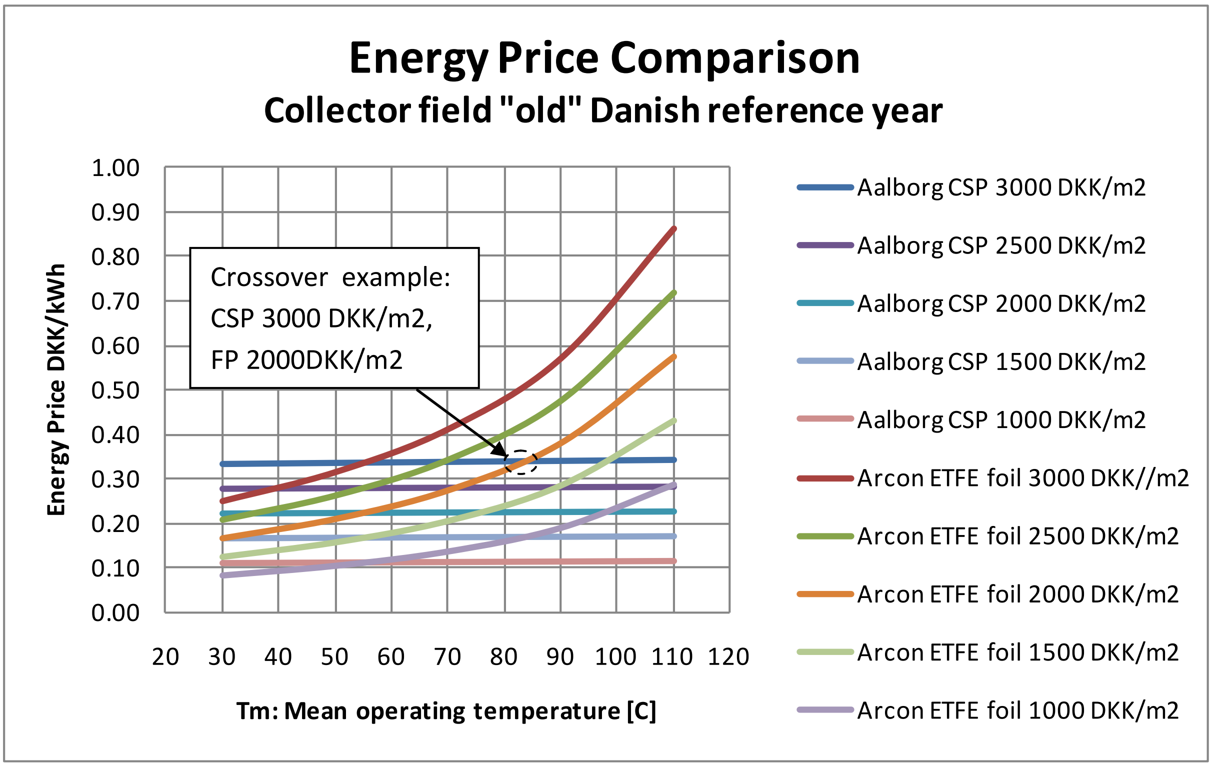

Figure 13. Energy Price for CSP and Flat Plate solar collector fields for the old Danish Reference year. Parameters for an Arcon collector with ETFE foil and Aalborg CSP collector from table 1, is used to be more precise about the product data. The cost of the collector field is shown as a range, as this will vary from plant to plant. An example is given for CSP cost 3000 DKK/m^2 and FP collector field cost 2000 DKK/m^2.

Figure 14 shows the energy price for CSP and Flat Plate solar collector fields for the new reference year for Bornholm, the best solar climate in Denmark. The crossover temperature is slightly lower (5°K lower) in Bornholm due to the slightly better climate for CSP. The energy price level is also lower in Bornholm due to the higher energy output.

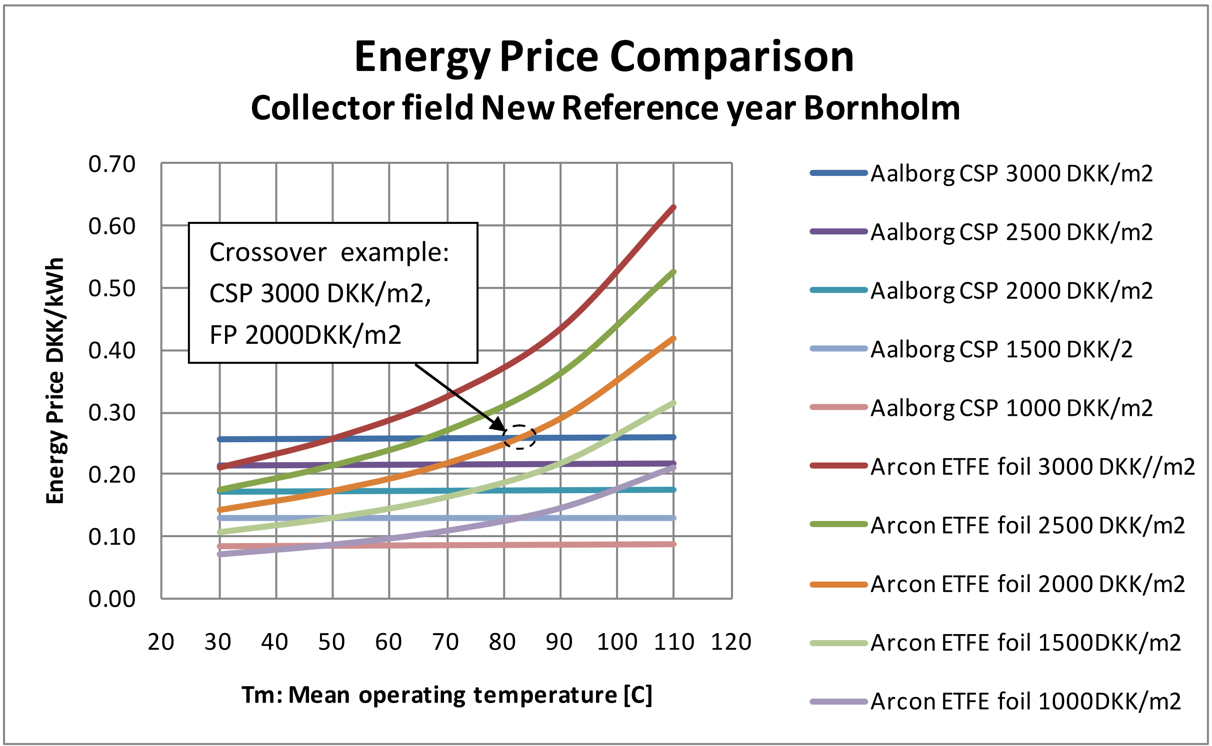

Figure 14. Energy Price for CSP and Flat Plate solar collector fields for the new Reference year for Bornholm. Parameters for an Arcon collector with ETFE foil and Aalborg CSP from table 1, is used to be more precise about the product data. The cost of the collector field is shown as a range, as this will vary from plant to plant. An example is given for CSP cost 3000 DKK/m^2 and FP collector field cost 2000 DKK/m^2.

It can be seen that there is a cross over between the technologies, so that CSP is best at high temperatures and Flat Plate is better at lower temperatures. This is as expected. The cross over temperature depends on the costs of the collector fields from case to case.

The investment cost per m^2 should be treated as including land cost, typically 50 DKK/m^2 land area. Both collector designs use a ground area that is 2.5 times the collector aperture area in these calculations, to have similar collector field internal row to row shading conditions. Then the land cost is 2.5*50 = 125 DKK/m^2 aperture area. A very small contribution/addition to the total cost.

8. Annual Distribution Comparison between CSP and Flat plate collector fields

Figure 15 shows the month by month distribution over the year, of thermal performance for CSP collector fields with tracking axis oriented North-South and East-West, as well as for a Flat Plate collector field with collectors facing south with a tilt 45 deg. East-West orientation of the CSP collector tracking axis can result in relatively high thermal performance in the winter. As a future possibility a green curve with an intermediate axis orientation of SW-NE is given that shows that the annual distribution of energy output can be evened out to match a load or a seasonal storage capacity.

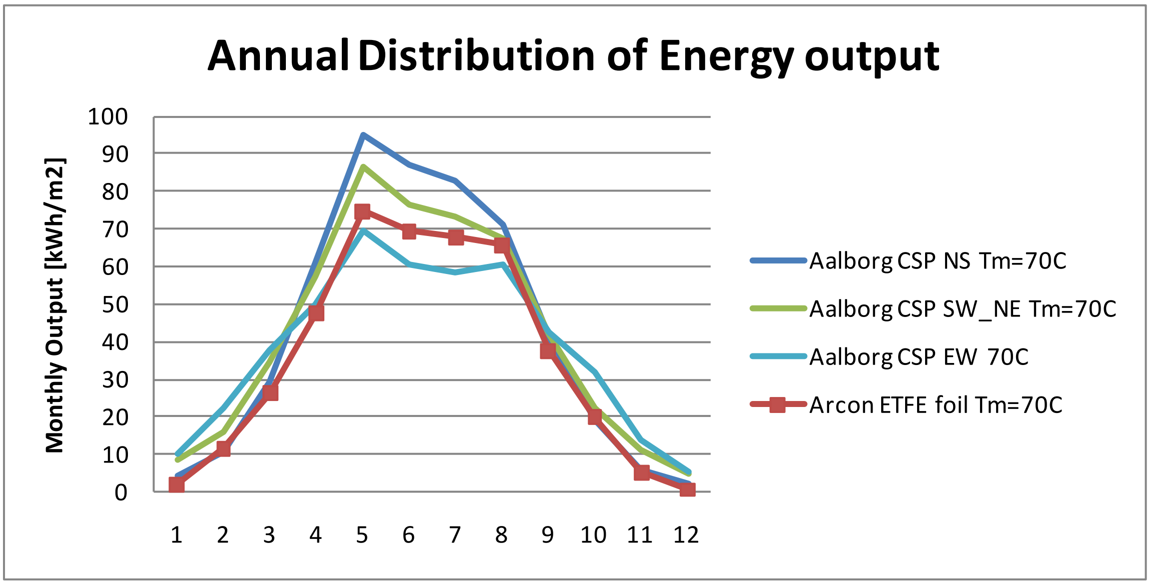

Figure 15. Annual distribution month by month of collector field output for CSP and Flat Plate collector fields. Climate data from Bornholm is used here. Note the possibility to have an axis orientation between NS and EW (green curve) giving a different annual distribution of energy output.

To investigate if a concentrating collector field can work as good as a flat plate collector field, in climates with high diffuse solar radiation ratios, figure 16 is given as one example. Here the daily energy output for a Flat Plate and CSP collector field is plotted over a whole year. The operating temperature is Tm=70°C and the solar radiation data from area 1, north Jutland on the climate station map, see figure 5.

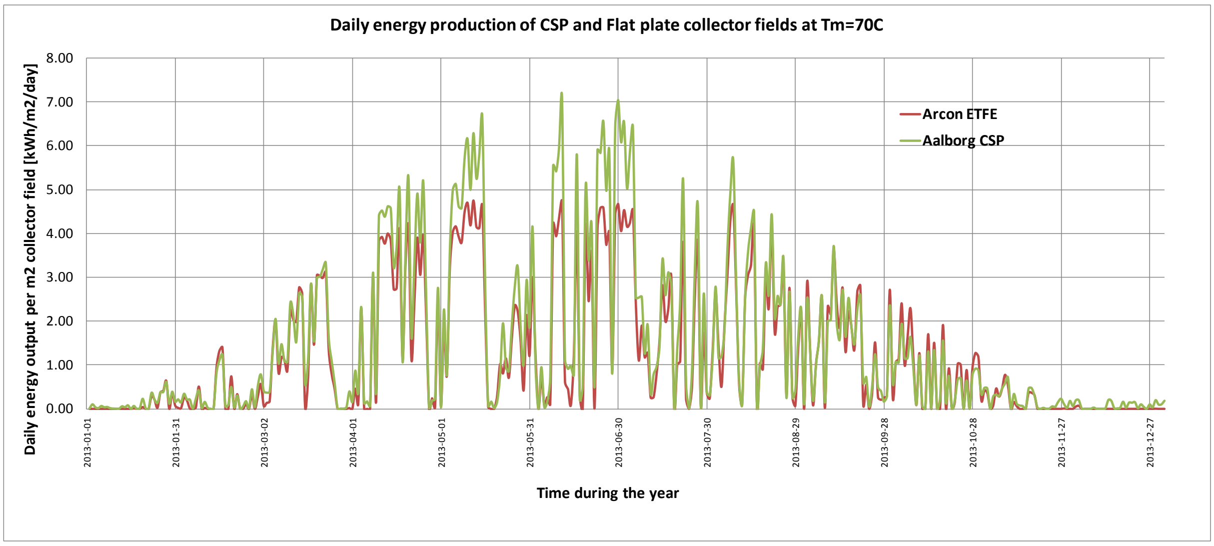

Figure 16. Daily energy output for a Flat Plate and CSP collector field over a whole year. The operating temperature is Tm=70°C and the location is area 1, north Jutland.

It can be seen that no single day with only flat plate collector operation can be found in this example. At much lower operating temperatures it is possible to have collectors operate under pure diffuse sky conditions as for example together with a heat pump system to recharge the ground source.

9. Ground area use for CSP versus Flat plate collector fields

Figure 17 shows the annual energy output related to collector aperture area and ground area for a collector field. The closer the distance between the collector rows, the lower performance per m^2 collector as expected, but higher performance per m^2 ground area.

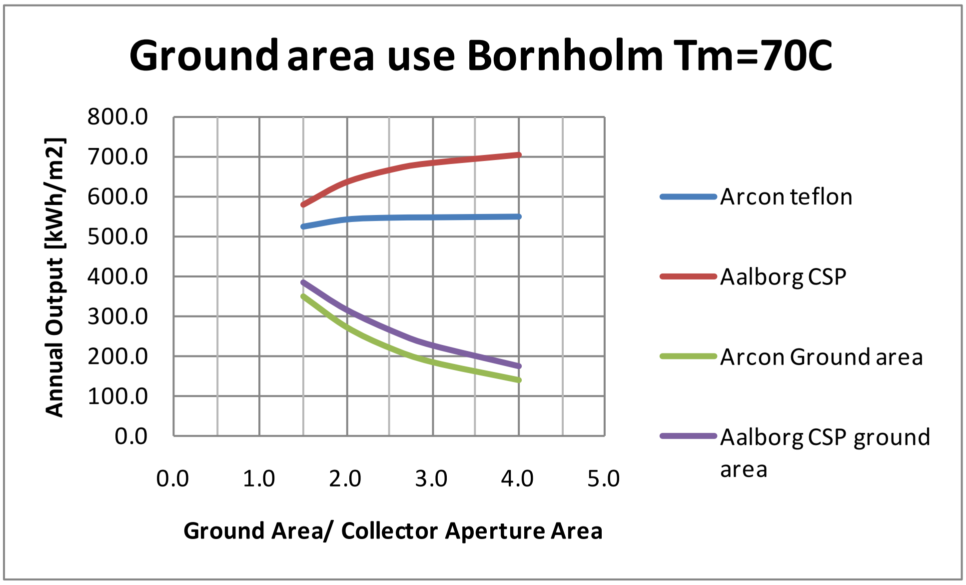

Figure 17. Performance variation with density of collectors in a collector field. Both performance per Collector- and Ground area is shown. In most of the report a ground to aperture area ration of 2.5 is used.

In the main results a ground area to collector area of 2.5 is used as the cost of collector area is much higher than land area, roughly a factor of 40-60 (ground cost 50 DKK/m^2 and collector array cost 2000-3000 DKK/m^2) Therefore it is better to spread out the collectors and get more energy if land area is available. Closer to a city with higher ground area prices a slightly denser optimum can be found most likely.

Due to the North South tracking and more operation time at low solar altitudes in morning and evening the CSP suffer more from short distance between the collector rows, as can be seen from the upper two curves.

A mean operating temperature of 70°C, has been chosen here, typical for district heating. The Flat Plate collector tilt can be optimized/fine tuned for each row distance to collector height = ground to collector area ratio. Fig 16 gives a good indication for a collector tilt range from approximately 35° to 45° tilt. This can be further elaborated in a coming project.

10. Conclusions

- A simplified collector field model and Excel calculation tool for CSP and Flat Plate collector fields has been developed and validated based on measurements in Denmark.

- The model for the CSP solar Collector field is validated by means of measurements in Thisted, during July 2013.

- CSP collector fields can in theory, at higher temperature levels (from Tm = 50-55°C, see figure 11 and 12), perform better than the present flat plate collector designs and field technology, for all locations in Denmark.

- The advantage of a CSP collector field compared to a flat plate solar collector field increase with increasing annual solar radiation.

- Concentrating collectors are very insensitive to operating temperature opposed to flat plate collector fields. The analysis shows Concentrating Collectors are more suitable for higher temperature District Heating and Industry Applications. At temperatures higher than 50-55°C, Concentrating Collector arrays perform consistently better than Flat Plate collector fields (annual collected kWh/m2). At a temperature of 100°C the Concentrating Collector arrays collects approximately double the energy (kWh/m2) compared to Flat Plate collector fields.

- The economical comparison indicates that Concentrating Collector arrays are competitive (rentable) at higher temperature networks and industry loads . Two diagrams are given for comparison from case to case depending on real turn key investment costs in DKK per m^2 of collector field.

- Reference Climate data are now available for estimation of performance from case to case with the new calculation tool.

11. Future work

The thermal performances of solar collector fields are first of all influenced by the temperature level of the solar collector fluid in the collectors and by the weather, especially the solar radiation. For most solar collectors the split between beam and diffuse radiation has a large influence on performance.

Further, the solar collector type and design, the design of solar collector field, the operation strategy inclusive different flow rates and uneven flow distributions in the solar collector field, the choice of solar collector fluid, the heat loss from the pipes in the solar collector loop and conditions related to shadows between collector rows and dirt and snow on the glazing, influence the thermal performance.

Furthermore, for flat plate collectors the collector tilt and moisture conditions in the solar collector influence the thermal performance. For CSP collectors the energy used to avoid freezing damages in cold periods if water is used as heat transfer medium, influence the thermal performance.

For CSP collectors the thermal performance is strongly influenced by the ratio between the direct radiation and the total radiation. Detailed solar radiation measurements inclusive measurements of diffuse radiation at different locations in Denmark and detailed investigations on both flat plate solar collector fields and CSP collector fields are needed before it is possible to quantify the importance of the above mentioned points for the thermal performance of the systems. It is recommended to start work in these fields so that it in the future will be possible to optimize solar collector fields for different applications.

Further for evaluation of the CSP technology under Danish conditions it is important to get long term experience on the operation and thermal performance of the latest technology for CSP solar collector fields. It is also recommended to develop a more detailed simulation tool for whole CSP solar collector fields.

An accurate collector field model can also be used for control and on-line check of a solar plant, if applied in the normal computer system for the collector field in a district heating plant.

Furthermore it is recommended to demonstrate the performance and economy of a full scale Aalborg CSP plant with seasonal thermal storage in one location in Denmark. Preferably as a side by side test with a Flat Plate collector field at the same location and the same district heating system. In this way a fair and convincing comparisons between the two technologies can be made.

12. References

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Appendix A: Aperture area calculation

The aperture area in this report is defined by the active mirror area (cross section of mirrors as seen from the sun). As the same area is used all trough the report from performance evaluation to annual simulation up to economy calculations, the exact value on the last decimal is not critical for the results and conclusions.

From the drawing below one can calculate: Effective area of one mirror section = (L-V-S)*B

(B = 1.7 m length of one mirror in the direction parallel to the absorber.)

This is the effective area of one set of mirrors. There are 7 mirror sections on each of the two sides and 12 such trough sections in the plant, so the total area for Thisted is:

Effective Aperture area =((2,887-0,04-0,0165)*1,7)*7*2*12 = 808 m²

The gross area can be calculated as trough mirror width * trough total mirror length * no of troughs = 5.77m * 72 *2 = 831 m^2.

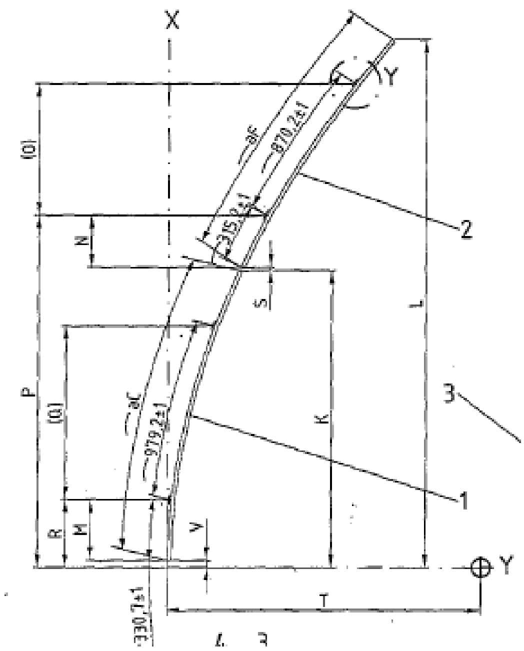

Fig A1. Cross section of a one set of mirrors in the troughs used in the Thisted plant.

Appendix B: Estimation of importance of Pipe heat losses in a well designed collector field

To estimate the significance of pipe losses in a collector array one can assume a heat loss from the pipes of 50 W/m pipe (typical district heating level). If 800 m pipes are assumed in a 10000 m2 collector array and operating time 1500 hours: This will give an annual pipe loss of 800*50*1500/10000 = 6 kWh/m2 per year. With an annual thermal output of 500 kWh/m2 this corresponds to 6/500 = 1.2 %. This may be an ideal figure, but indicates that pipe losses in a collector field are not a first order effect, when comparing CPS with flat plate collector fields. Marginally it is still of course important to optimize pipe size, pipe lengths, hydraulic layout and pipe insulation. This is connected to the pumping power optimization too.

Appendix C: Estimation of Pumping Power and Electrical Energy use in a well designed Flat plate collector field.

The Collector flow rate is typically 0.2 l/min/m2 giving 50 deg maximum temperature rize from inlet to outlet at maximum irradiation. If 10 collectors of 15 m2 each are series connected the maximum flow rate is 10*15*0.2 = 30 l/min => 30/1000 * 60 m3/h = 1.8 m3/h. At this flow the pressure drop per module is 6 kPa. The total pressure drop will then be 10*6= 60 kPa. The pumping power need with 50% pump efficiency will be: 60*1000*30/1000/60 * 0.5 = 15 W ! This is for 150m2 of collectors corresponding to 0.1 W/m2 completely neglectable compared to the thermal power output !

The pipe pressure losses can be designed to a low level by choosing appropriate pipe diameters within reasonable cost limits. If we assume a total pipe pressure loss of 1 bar in the array outside the collectors and a flow of 0.2 l/min/m2 and 50% pump total efficiency the pipe pumping power per m2 will be 0.2/1000/60*100000 *0.5=0.33 W/m2 also this a very small value less than 1 % of the thermal collector output.

These are very rough numbers that of course can be elaborated and optimized for each plant but it motivates not to include this in a simplified cost estimation and comparison between different collector designs. The CSP collector field will probably have lower pumping power as the concentration gives less pipe work in an array.

Appendix D: Estimation of night time heat losses for frost protection of a CSP collector array

With a heat loss coefficient a_1 of 0.04 W/m2/K and 50°C temperature difference to ambient (very large marginal to freezing) and 2000 hours operation during cold nights, the heat loss will be 0.04*50*2000 = 4 kWh /m^2. This is less than 1% of the annual thermal collector output per m2 presented in this report. Additional losses can occur if also transit pipes above ground need freeze protection.

Appendix E: Estimation of heat loss coefficient for the Aalborg CSP collector.

Measured Data from ref [4] and data from the Thisted plant are used here:

Overtemperature	DT deg C	107
Heat loss per m absorber	W/m	23
Mirror width * 1 m	Area/m	5.77
Heat loss coef a1	W/m2/K	0.04

Numerical Calculation: 23 / 5.77 / 107 = <u>0.04 W/m2/K</u>

Appendix F: Collector Field input parameters used in this report in the Excel tool for annual performance

Input Data Flat Plate Collector	Collector Field (1) Arcon Teflon HT	Collector Field (2) Arcon HT-A 28	Collector Field (3) Sunmark GJ 14	Units
IAM coef. Beam rad. p	4.51	4.51	5.3	[-]
a_1	2.205	3.2	2.3	[W/m^{2}K]
a_2	0.0135	0.0137	0.029	[W/m^{2}K^2]
IAM diffuse rad. K_θ (60°)	0.916	0.916	0.946	[-]
η_0	0.817	0.839	0.85	[-]
T_{m_1}	30	30	30	[°C]
T_{m_2}	50	50	50	[°C]
T_{m_3}	70	70	70	[°C]
T_{m_4}	90	90	90	[°C]
T_{m_5}	110	110	110	[°C]
FP Collector tilt	35	35	35	[°]
FP Coll. Surface azimuth	0	0	0	[°]
Ground reflection	0.2	0.2	0.2	[-]
Climate number or location	1	1	1	[-]
Latitude climate data	57.18	57.18	57.18	[°]
Longitude climate data	9.95	9.95	9.95	[deg]
Longitude time zone	15	15	15	[deg]
Collector width (height along glass)	2	2	2	[m]
Row distance in coll field	5	5	5	[m]
Number of rows in coll field	40	40	40	[no#]
Diffuse rad. in field correction	0.5	0.5	0.5	[-]
Input Data NS Tracking collector: Axis Azim	0	0	0	[°]
p	2.4	2.4	2.4	[-]
a_1	0.04	0.04	0.04	[W/m^{2}K]
a_2	0	0	0	[W/m^{2}K^2]
K_θ diffuse	0.010	0.010	0.010	[-]
$\eta_{0\ beam}$	0.75	0.75	0.75	[-]
Wa=Width of Through	5.77	5.77	5.77	[m]
Da=Tracking Axis CC distance	15	15	15	[m]
Nr=Number of rows in collector field	40	40	40	[-]

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ISBN 9788778773784