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Simulation of a solar collector array consisting of two types of solar collectors, with and without convection barrier

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Abstract

The installed area of solar collectors in solar heating fields is rapidly increasing in Denmark. In this scenario even relatively small performance improvements may lead to a large increase in the overall energy production. Both collectors with and without polymer foil, functioning as convection barrier, can be found on the Danish market. Depending on the temperature level at which the two types of collectors operate, one can perform better than the other. This project aimed to study the behavior of a 14 solar collector row made of these two different kinds of collectors, in order to optimize the composition of the row. Actual solar collectors available on the Danish market (models HT-SA and HT-A 35-10 manufactured by ARCON Solar A/S) were used for this analysis. To perform the study, a simulation model in TRNSYS was developed based on the Danish solar collector field in Braedstrup. A parametric analysis was carried out by modifying the composition of the row, in order to find both the energy and economy optimum.

Keywords: solar collector; flat plate collector; solar heating field; FEP foil; TRNSYS; collector row; row composition; economic analysis

1. Introduction

At the end of 2013 Denmark had already installed around 350,000 square meters of thermal solar collectors in solar heating plants in district heating areas, with further 250,000 square meters planned for 2014 [1,2] . In a scenario still characterized by a strong growth in the installed solar collector capacity, even relatively small improvements may lead to a large increase in the overall energy production in absolute terms. For this reason

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research and development into the optimization of the collector characteristics and solar field design play key roles. Solar collectors in Denmark have seen a significant enhancement in performance in the last years [3] and efforts are still being made for further improvement, as new collector models prove [4,5]. Nevertheless, efficient components do not always guarantee the best performance possible, unless the overall system is well designed and operated.

Collectors installed in Danish solar collector fields for district heating applications are usually large flat plate collectors, connected in rows having between 10 and 25 modules each [1]. These collectors are either produced by ARCON Solar A/S or SUNMARK Solutions A/S, and may have a polymer foil between absorber and glass, functioning as a convection barrier to decrease the heat losses (in ARCON collectors only). On the other hand, as the polymer foil is not completely transparent, it slightly reduces the solar irradiance reaching the absorber. Consequently, if two collectors differ only for the presence of the convection barrier, there is a certain temperature below which the model without foil performs better than the other. For this reason, the choice of a collector with convection barrier over one without is strongly influenced by the temperature the collector operates at. In large solar fields, where the temperature rise within the same row is usually very high (from 40 °C up to 85 °C), both types of collectors may be used together to maximize the energy output. Collectors without foil may be used in the first part of the row, where the fluid temperature is still relatively low, to provide the first temperature increase. On the other hand, collectors with foil may be best exploited in the second part of the string, where higher temperatures are reached. Nevertheless, also the higher cost of collectors with foil must be taken into account, to verify whether the improved efficiency is worth the extra investment.

Nomenclature

a_1	first order heat loss coefficient, ($W\ m^{-2}\ K^{-1}$)
a_2	second order heat loss coefficient, ($W\ m^{-2}\ K^{-2}$)
b_0	first order IAM coefficient, (-)
b_1	second order IAM coefficient, (-)
FEP	fluorinated ethylene propylene
G	total irradiance on the collector plane, ($W\ m^{-2}$)
IAM	incidence angle modifier = $1 - b_0 \cdot (1/\cos\theta - 1) - b_1 \cdot (1/\cos\theta - 1)^2$, (-)
NPV	net present value, (Danish crown, DKK)
T_a	ambient temperature, (°C)
T_m	fluid mean temperature, (°C)
T^*_m	reduced temperature difference = $(T_m - T_a)/G$, ($K\ m^2\ W^{-1}$)
η_0	zero-loss efficiency, (-)
η	efficiency of solar collector = $\eta_0 - a_1 \cdot T^*_m - a_2 \cdot G \cdot (T^*_m)^2$, (-)
θ	incidence angle, (°)

2. Method

To carry out the optimization analysis on the collector row composition, a TRNSYS simulation model was developed based on the design and control strategy of an actual solar collector field, more specifically the field in Braedstrup (Denmark), installed by the Danish company ARCON Solar A/S. Design of the field and 1-year (June 2013-May 2014) measured data of solar radiation, flow rate and inlet and outlet temperature were kindly made available by ARCON Solar and PlanEnergi, and then used as input for the TRNSYS model.

2.1. Description of the solar collector field

The solar collector field in Braedstrup was built in 2007, with an overall transparent area of 8,000 m^2. An extension of 10,608 m^2 was added in 2012 and is investigated in the current study. This new solar field consists of 847 collectors with convection barrier (model HT-SA 28-10), arranged in 72 rows spaced by 5.5 m. Most of the collectors (60%) are arranged in 14 module rows, while the remaining 40% is installed in shorter rows (Fig. 1).

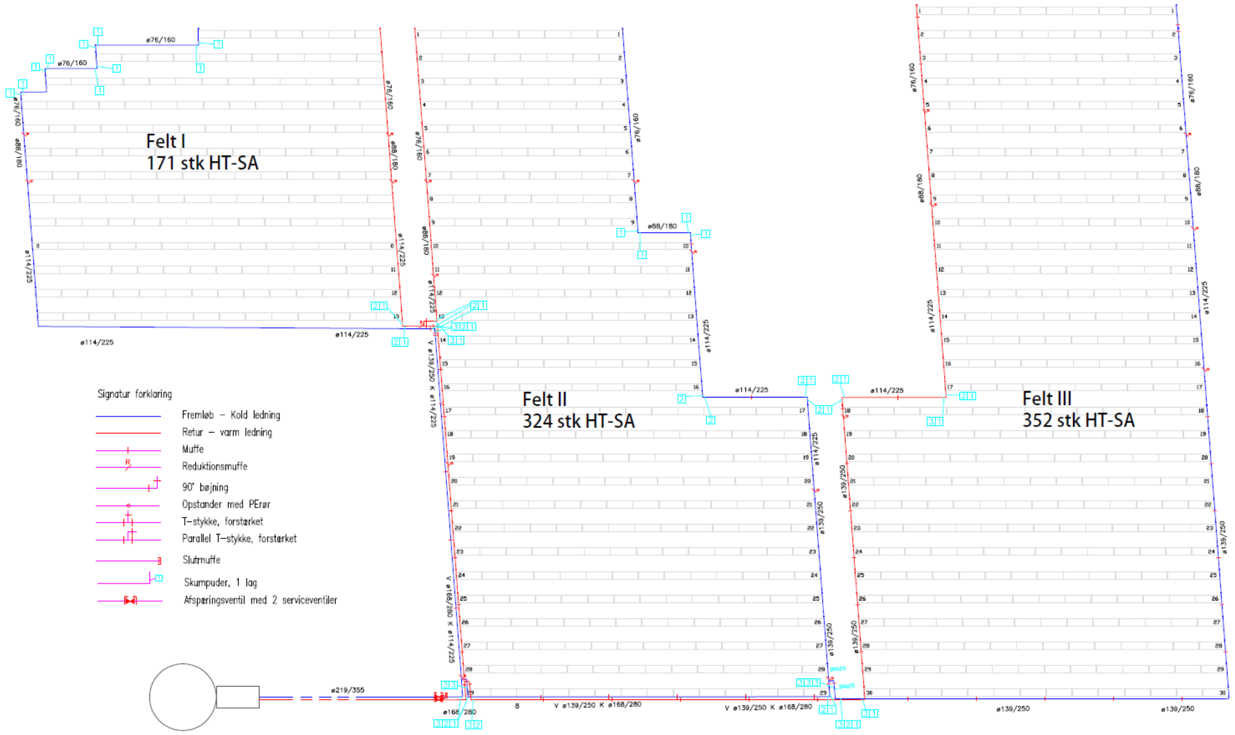

Fig. 1. Layout of the 10,608 m^2 collector field in Braedstrup (source: ARCON Solar A/S).

The collectors are tilted by 35° and are south oriented. For space reasons, the building containing the heat exchanger between solar collector loop and the water loop is shown in the bottom left corner of Fig. 1, relatively close to the solar collector field, while it is actually located approximately 500 m away. The field uses a mixture of propylene glycol and water with a 30% weight concentration as solar collector fluid. The inlet temperature is about 40 °C while the outlet temperature is about 90 °C.

2.2. Description of the TRNSYS model

One-year measured data (June 2013-May 2014) of total radiation on the collector plane, ambient temperature, flow rate through the entire collector field and supply temperature were given to TRNSYS as input, while the outlet temperature was used only as basis of comparison to check the correct operation of the model.

As the purpose of this study is to optimize the composition of a single row, the developed TRNSYS model simulates the behaviour of one row only, consisting of 14 collectors, which represents the most common configuration in Braedstrup field (Fig. 1). Because only the total field flow rate was measured, the ratio between the row flow rate and the field flow rate was assumed equal to the ratio between row area and field collector area, which guarantees approximately the same outlet temperature from each row.

Although the field is made of solar collectors of type HT-SA 28-10, manufactured by ARCON Solar, two other ARCON models (HT-A and HT-SA 35-10) were used in this study, as they are similar to the original model and more detailed information were available from previous studies [6]. The two HT 35-10 collectors are mostly identical in terms of design and technical specifications, with an aperture area of 12.56 m^2 and 18 horizontal copper tubes connecting two manifolds [7,8]. The only relevant difference between the two collectors is a 0.025 mm thick fluorinated ethylene propylene (FEP) foil interposed between the absorber and cover in the model HT-SA (Fig. 2), in order to decrease the convection losses.

The two collectors were tested between 2012 and 2013 [6], according to the standard norm EN 12975-2 and their efficiency was calculated for a 45° tilt angle, 25 litres per minute flow rate and using a mixture of water and propylene glycol with a 40% weight concentration as solar collector fluid.

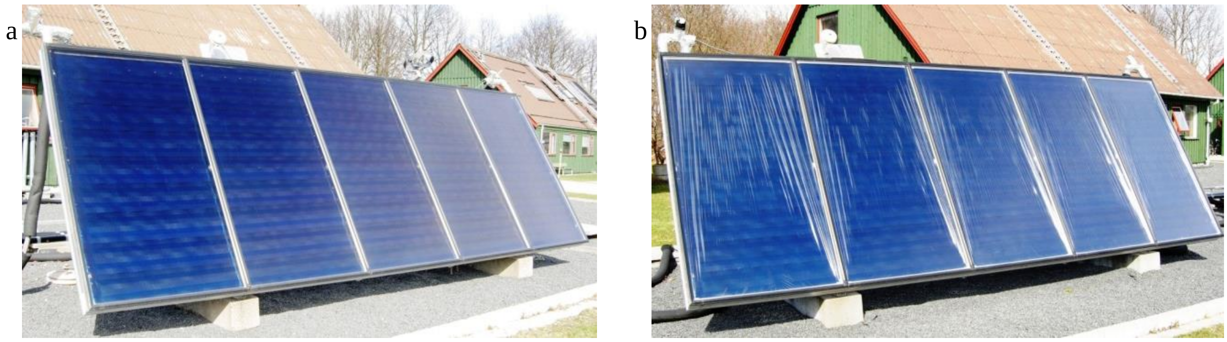

Fig. 2. Solar collector HT-A (a) and HT-SA (b) at Department of Civil Engineering at Technical University of Denmark.

As the operating conditions used in Braedstrup plant differ from those used in the efficiency tests in [6], a simulation model was created in Soleff, software developed at the Technical University of Denmark [9]. This model was first validated against the experimental results from [6], and then used to predict the efficiency parameters for a 30% glycol/water mixture and 35° tilt angle, which were then used as input for the collector Type 539 in the TRNSYS model [10]. The collector parameters given as input to Type 539 are listed in Table 1, while the collector efficiency curves are shown in Fig. 3 for a solar irradiance of 800 W m^{-2}. In the diagram it is possible to appreciate the effect of the FEP foil on the zero-loss efficiency and convection losses, as described in Section 1.

Table 1. Collector parameters used as input for the collector Type 539 in the TRNSYS model.

Collector characteristic	HT-A 35-10	HT-SA 35-10
Zero-loss efficiency η_0, (-)	0.850	0.816
First order heat loss coefficient a_1, (W m^{-2} K^{-1})	3.093	2.418
Second order heat loss coefficient a_2, (W m^{-2} K^{-2})	0.0111	0.0085
First order IAM coefficient b_0, (-)	0.045	0.070
Second order IAM coefficient b_1, (-)	0.089	0.080
Collector thermal capacity, (kJ/K)	78.5	78.5

Because the diffuse radiation was not measured in the solar collector field in Braedstrup, Type 546 was used to evaluate the diffuse component according to Erbs correlation [11], given the total radiation on the collector plane, horizontal extraterrestrial radiation and position of the sun in the sky. Shadow effect from other rows was considered by using Type 30a. Given the significant length of the supply pipes (560 m and 474 m for forward and return pipe respectively), these were taken into account by Type 604b, which modelled plug flow, thermal losses and pipe thermal capacity.

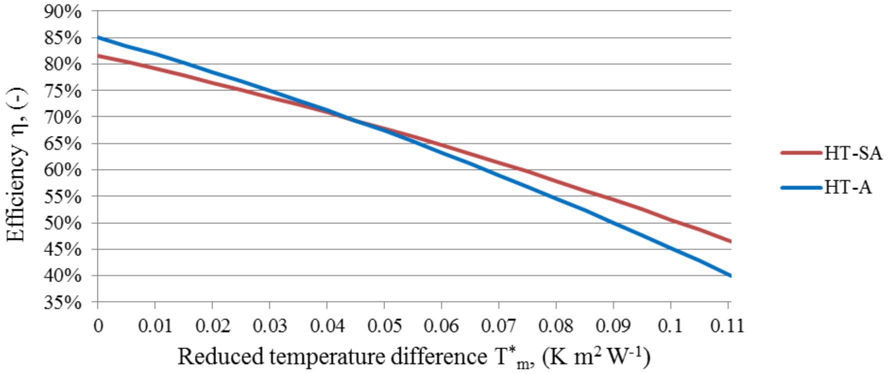

Fig. 3. Efficiency of the HT-A and HT-SA collector for a solar irradiance G=800 W m^{-2}.

After verifying the correct operation of the model, this was used to carry out a parametric analysis, varying the composition of the row by increasing the number of HT-A collectors. Computing and comparing the useful energy outputs in the different cases, it was possible to determine the best row composition from an energy point of view.

2.3. Economic analysis

The most efficient solution from an energy point of view may not be the most effective from an economic point of view. For this reason a simple economic analysis, based on the Net Present Value (NPV) method, was carried out as well. In this way the most cost-effective solution could be identified.

In order to carry out this analysis, the parameters listed in Table 2 were used. The cost of the solar collectors, their maintenance and their lifetime were communicated by ARCON Solar. The costs of the solar collectors include also installation and piping. The maintenance cost was said to be the same for both collector models, as no need of replacement of the FEP foil is expected during the collector lifetime, and, even if the FEP foil breaks, this is replaced by the collector manufacturer at their own expense. The lifetime of 20 years is meant as the period during which the collectors are supposed to maintain their original efficiency. This kind of solar collectors are usually kept in operation for longer than 20 years, but the same performance is not guaranteed afterwards.

The interest rate was assumed equal to 6%, as in similar project studies in Denmark [12], and the energy price was read from [13] as energy price for the customer without the 25% VAT.

The collector efficiency, and therefore the yearly energy production, was assumed constant throughout the expected lifetime of the solar collector field. Energy losses from the district heating network were neglected.

Table 2. Parameters used in the economic analysis

Economic parameter	Value
Turnkey price of a HT-A 35-10 collector, (DKK/m^2)	1750
Turnkey price of a HT-SA 35-10 collector, (DKK/m^2)	1850
Energy price, (DKK/MWh)	574.50
Maintenance cost, (DKK/MWh)	2.00
Minimum expected lifetime of the solar collector field, (years)	20
Interest rate, (%)	6%

3. Results

3.1. Comparison between TRNSYS model and measurements

To check the correct operation of the TRNSYS model, its results were compared against the measured data from Braedstrup, both in terms of return temperature from the solar collector field and useful energy delivered to the heat exchanger. As in Braedstrup all collectors are equipped with FEP foil, the row configuration used as comparison consisted of 14 HT-SA collectors.

In the considered year (June 2013-May 2014), the energy transferred to the heat exchanger in the TRNSYS simulation was approximately 72.8 MWh, only 1.2% higher than the measured one. Nevertheless, on a seasonal basis the deviations had higher values and opposite trend. In fact, the periods June-December 2013 and January-May 2014 were characterized by average deviations of +7% and -8%, weighted on the monthly transferred energy. As the flow rate and the inlet temperature used in the TRNSYS model were the measured ones, the difference was caused by the different outlet temperature at the end of the return pipe, before the solar collector fluid entered the heat exchanger. The comparison between measured and simulated return temperatures is shown in Fig. 4. The outlet temperature computed by the model followed the measured temperature profile, despite some deviations for high irradiance values. It can be seen how the return temperature calculated by the TRNSYS model was lower than the measured one, if data from 2014 were used (Fig. 4.a). On the other hand, the TRNSYS return temperature was higher, when data from 2013 were considered (Fig. 4.b). No significant intervention was done on the field in the winter 2013-2014, so the abrupt change in the performance of the solar collector field was unexpected.

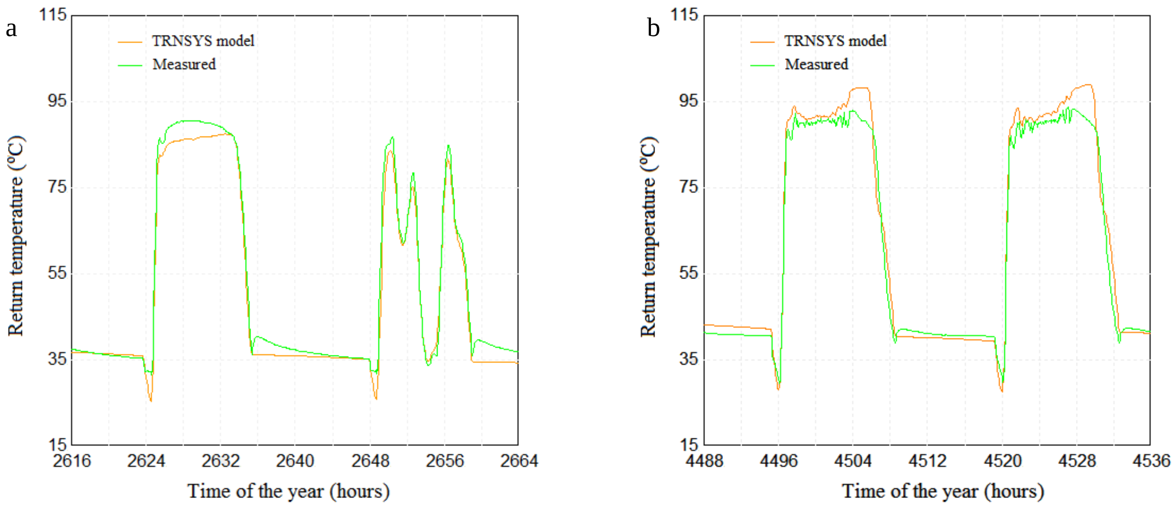

Fig. 4. Comparison between simulated and measured return temperature from the solar collector field: (a) April 20th and 21st, 2014; (b) July 7th and 8th, 2013.

On the basis of the available information, only some hypothesises could be made. The higher energy output of the TRNSYS model in 2013 was most likely due to the fact that the model assumed perfectly uniform flow distribution in the different rows, which might not be the case. Additionally, the heat losses from pipes were slightly underestimated, as only one collector row was modelled. Finally, pollen and dust on the collector cover or presence of moisture on the inner surface of the glass might reduce the actual performance of the collectors in real-world operation. Regarding the lower energy output in the first half of 2014, this seemed to be caused by underestimated irradiance measured by the silicon pyranometer Soldata 80spc, manufactured by SolData Instruments and installed in Braedstrup field. The irradiance measured in Braedstrup was compared to the horizontal irradiance from a DMI (Danish Meteorological Institute) climate station in Horsens, 20 km away from the solar collector field, where a NovaLynx 8101 Star pyranometer (first class according to ISO 9060) was installed. The comparison was done between the days May 29th-30th 2014 and June 2nd-3rd 2013, as they were characterized by clear sky conditions and almost identical solar declination. Considering an interval of a couple of hours around midday, the ratio between the irradiance in Braedstrup and that in Horsens in late May 2014 was about 7 % lower than the same ratio calculated for early June 2013, thus supporting the hypothesis that the silicon pyranometer underestimated the actual solar irradiance reaching the solar collector field, maybe because of dirt on the pyranometer cover or due to aging.

3.2. Useful energy output

After this comparison, calculations were carried out increasing the number of HT-A collectors placed in the first part of the row. Fig. 5 shows the monthly solar radiation reaching a unit area of solar collector during operation of the pumps, and the utilization factor of solar radiation for differently composed rows. The utilization factor is defined as the ratio between the row useful energy output and the collected radiation defined above.

For the sake of clarity, not all the utilization factor curves are shown in Fig. 5, as it would be difficult to distinguish them, but only those with a relevant difference between each other are displayed.

On the other hand, results for all the possible row combinations are listed in Table 3 in terms of yearly energy output and relative difference with respect to a composition consisting of 14 HT-SA collectors. From the values listed in Table 3, it is possible to see that the best performance was achieved by a row consisting of HT-SA collectors only. Nevertheless, introducing up to five HT-A collectors in the first part of the row did not significantly decrease the energy output, as the relative difference with respect to the row composed by 14 HT-SA collectors was lower than 1%. Further replacement of HT-SA collectors with HT-A models increasingly deteriorated the row performance, up to a 7% reduction in the case where only HT-A modules were used.

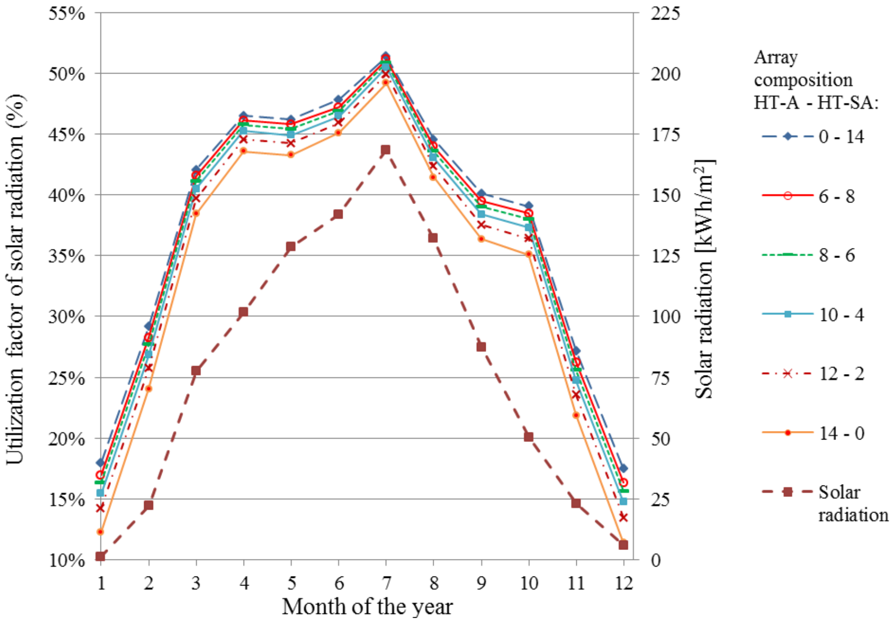

Fig. 5. Monthly utilization factor of solar radiation for different row compositions (left axis) and monthly solar radiation per unit area of collector (right axis), using weather data measured at Braedstrup field between June 2013 and May 2014.

Table 3. Yearly energy output from the collector row and relative difference with respect to a 14 HT-SA composition, using weather data measured at Braedstrup field between June 2013 and May 2014.

Row composition HT-A - HT-SA:	Yearly energy output, (MWh)	Relative difference, (%)
0 - 14	74.0	0%
1 - 13	74.0	-0.1%
2 - 12	73.9	-0.1%
3 - 11	73.8	-0.3%
4 - 10	73.7	-0.5%
5 - 9	73.5	-0.7%
6 - 8	73.2	-1.1%
7 - 7	72.9	-1.5%
8 - 6	72.6	-2.0%
9 - 5	72.2	-2.5%
10 - 4	71.7	-3.1%
11 - 3	71.2	-3.9%
12 - 2	70.5	-4.7%
13 - 1	69.8	-5.7%
0 - 14	68.9	-6.9%

3.3. Economic assessment

Under the assumptions made in Section 2.3, an investment analysis was carried out and its results are reported graphically in Fig. 6, both in terms of net present value of the installation after 20 years and payback time of the investment. It can be seen that the net present value of the row had a maximum (approximately 164,000 DKK) for the configuration consisting of five HT-A and nine HT-SA collectors.

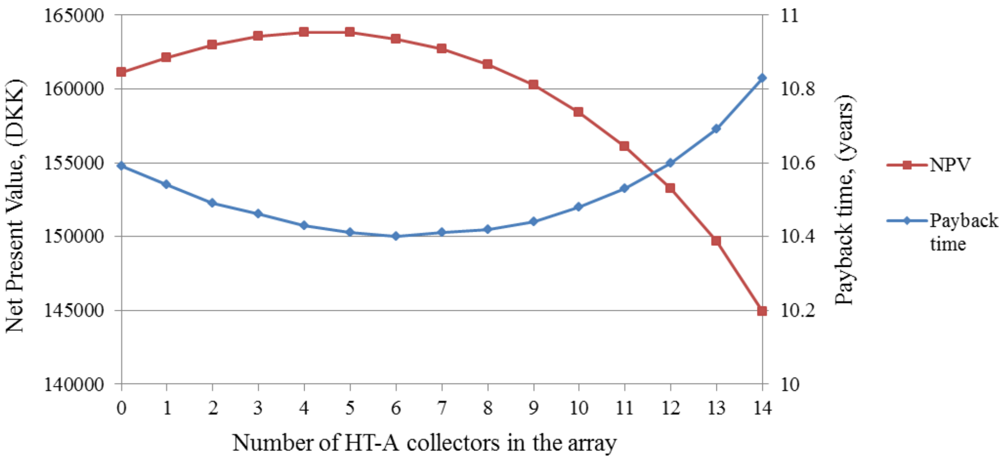

Fig. 6. Net Present Value (NPV) of the row at 20 years (left axis) and payback time of the investment (right axis).

Row configurations with a number of HT-A collector between two and seven presented very similar net present values (relative difference lower than 1%), while for an increasing presence of the HT-A model in the row this value decreased to a minimum value of approximately 145,000 DKK (-11.5% with respect to the highest NPV).

Regarding the payback time of the investment, this was found almost independent of the row configuration and with an average value of approximately ten years and a half (maximum value of 10.8 years for a 14 HT-A collector row and minimum value of 10.4 years for a 6 HT-A collector row). This value is in good agreement with the payback times usually estimated for solar collector fields in Denmark [14].

4. Discussion and conclusions

A TRNSYS model was developed in this study, in order to analyse the performance of differently composed solar collector rows, consisting of 14 collectors, both with and without polymer foil as convection barrier. The model was built based on measured data from the Danish solar collector field in Braedstrup and using two different solar collectors available on the Danish market.

The results returned by the model were compared to measurements coming from the plant. The model returned a value of useful energy output 7% higher than the measured one in the period June-December 2013, and then 8% lower in the period January-May 2014. As no significant intervention was done on the field in the winter 2013-2014, only some hypothesises about the reason of such a change in performance could be made. The higher energy output of the TRNSYS model in 2013 was most likely a consequence of some assumptions made in the model, such as uniform flow distribution in the different rows, clean and moisture-free collector cover throughout the year and slightly underestimated heat losses from supply and return pipes. The lower energy output in the first half of 2014 seemed to be caused by underestimated irradiance measured by the silicon pyranometer installed in Braedstrup field. Comparison between the irradiance measured in Braedstrup and the horizontal irradiance from a nearby DMI climate station supported this hypothesis. The reason for such an underestimation might be accumulated dirt on the flat cover of the silicon pyranometer, as this was not regularly cleaned.

The parametric analysis carried out on the row composition proved that the best performance in terms of yearly useful energy output was given by a row consisting of HT-SA modules only (74 MWh), assuming weather conditions as those recorded between June 2013 and May 2014. Nevertheless, rows with up to five HT-A collectors, installed in the first part of the row, presented very similar energy outputs, less than 1% different (Table 3). Although the replacement of HT-SA collectors with HT-A models reduced the performance, the effect was not so significant, as the collectors were replaced at the very beginning of the row, where the fluid temperature was not so high and hence the difference in efficiency between the two collector models was small. Nevertheless, when additional HT-A collectors were introduced, the performance of the row increasingly deteriorated, with a 7%

reduction in the case where only HT-A collectors were used. This was in agreement with the expectations, as in this case HT-A collectors were used also in a relatively hot part of the row, where thermal losses were more important than the transmittance of the cover.

From Fig. 5 it can be seen that the presence of the FEP foil played a more or less significant role depending on the season. Comparing the row with only HT-SA collectors to the case where only HT-A collectors were used, the additional gain in the first case was more important in winter months, when the temperature difference between collector operating temperature and ambient temperature is larger. In this case convection losses play a significant role, which the FEP foil helps reduce. So, the highest deviation occurred in December, with 6 percentage point difference in utilization factor of solar radiation, and the lowest in July, with 2 percentage point difference.

The economic analysis, carried out according to the method of the net present value and in a 20 year lifetime scenario, showed that the most cost-effective solution was given by a row consisting of five HT-A and nine HT-SA collectors. This is due to the fact that this configuration yielded a yearly energy output slightly lower (-0.7%) than the best case scenario, but also required a lower initial investment cost (-2%). The payback time was approximately the same in all scenarios, so it could not be used as a significant parameter to identify the best solution.

Since the solar collectors are expected to last more than 20 years, a longer lifetime could be assumed. In this case, the most cost-effective solution in terms of net present value would shift toward row compositions consisting of a larger number of HT-SA collectors. In fact, the additional yearly energy production would have a longer timespan to pay back the extra investment. Nevertheless, the collector efficiency after 20 year operation is not guaranteed to be the same as for brand new collectors, which makes it difficult to make forecast. Information about how the efficiency curves of the two different collector change over time are needed, if an analysis in the longer term is desired. Additionally, it must be noted that measured data from a specific year (June 2013-May 2014) were used in this study. Different yearly weather conditions influence the useful energy output of the solar collector field and thus affecting the results of the economic analysis.

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