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1 **Thermo-economic optimization of a hybrid solar district heating plant with flat plate**
2 **collectors and parabolic trough collectors in series**

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5 **Denmark**

6 **Abstract**

7 Large-scale solar heating plants for district heating networks have gained great success in Europe,
8 particularly in Denmark. A hybrid solar district heating plant with 5960 m² flat plate collectors and 4039 m²
9 parabolic trough collectors in series was built in Taars, Denmark in 2015. The solar heating plant was used
10 as a reference case in this study. A validated TRNSYS-GenOpt model was set up to optimize the key design
11 parameters of the plant, including areas of both collector types, storage size, orientation of the parabolic
12 trough collectors and so on. This study introduces a generic method to optimize the hybrid solar district
13 heating systems based on levelized cost of heat. It is found that the lowest net levelized cost of heat of hybrid
14 solar heating plants is 0.367 DKK/kWh. The system levelized cost of heat can be reduced by 5% - 9% by use
15 of solar collectors in the district heating network. The results also show that parabolic trough collectors are
16 economically feasible for district heating networks in Denmark. The generic and multivariable levelized cost
17 of heat method can guide engineers and designers on the design, construction and control of large-scale solar
18 heating plants.

19 **Keywords**

20 Hybrid solar district heating plants; LCOH optimization; Parabolic trough collector; Flat plate collector;
21 TRNSYS-GenOpt.

22 **1 Introduction**

23 Solar energy is widely used in the building sector to supply space heating and cooling. Rad et al. [1]
24 reviewed solar community heating and cooling systems with borehole thermal energy storage and gave
25 suggestions about the development of borehole storage. Hazami et al. [2] simulated two domestic hot water
26 systems with flat plate collectors and evacuated tube collectors separately and compared two systems by
27 means of TRNSYS. Deng et al. [3] investigated a solar space heating system coupled with air source heat
28 pump in TRNSYS. Kemal et al. [4] revealed the influence of the size of the storage tank on the performance
29 and usability of solar water heating systems. Kaçan et al. [5] found that the actual optimum values for
30 independent parameters have a vital importance for design engineer with respect to select the proper system
31 component for solar heating system. Li et al. [6] discussed the operational strategy of a combined solar and
32 ground source heat pump system for an office building in TRNSYS. Bellos et al. [7] did energetic and
33 financial evaluation of solar assisted heat pump space heating systems with TRNSYS. Pardo García et al. [8]
34 studied district heating configurations with photovoltaic thermal hybrid solar collectors for a central
35 European multi-family house. Ramos et al. [9] also used TRNSYS to study a combined heating, cooling and
36 power provision in the urban environment. Bava et al. [10] developed a numerical model to investigate the
37 flow distribution in different operation conditions for solar district heating plants in Denmark. Bava et al. [11]
38 also investigated pressure drop and flow distribution in a solar collector with horizontal U-connected pipes
39 with this numerical model. Bava et al. [12] developed a detailed TRNSYS-Matlab model to simulate the
40 thermal performance of large solar collector fields for district heating applications based on developed
41 numerical model. Wang et al. [13] carried out energy, exergy and environmental analysis of a hybrid
42 combined cooling heating and power system utilizing biomass and solar energy. The vision of the Solar
43 Heating and Cooling Programme of the International Energy Agency is "By 2050 a worldwide capacity of 5
44 kW_{th} per capita of solar thermal energy systems is installed and significant reductions in energy consumption
45 are achieved by using passive solar and daylighting: thus solar thermal energy meeting 50% of low
46 temperature heating and cooling demand (heat up to 250 °C)" [14]. Large-scale solar heating plants for

47 district heating networks have developed fast in the last decades, and are one of the most successful
48 applications of solar energy for the building sector.

49 **1.1 Solar district heating plants**

50 In the northern European countries, district heating networks have supplied both space heating and
51 domestic hot water to many residents for many years. In the early 1980s, several large solar heating plants
52 were installed in Sweden, which is the first country to apply large solar collector arrays into district heating
53 networks [15]. Recently, the number of large solar district heating plants has increased very fast in Denmark,
54 Germany and Austria [16]. Fisch et al. [17] reviewed all the large-scale solar heating plants in Europe in
55 1998. IEA-SHC Task 9, 45 and 55 have focused on the application of large solar heating plants in district
56 heating networks [14].

57 De Guadalfajara et al. [18] evaluated the potential of large solar heating systems with seasonal storage for
58 5 typical climate conditions in Spain. The system included a 2854 m² solar collector field. It was found that
59 the estimated cost of the heat produced in large solar heating systems with seasonal storage with a solar
60 fraction of 50% can be competitive with the heat cost of traditional domestic heat boilers in Spain. Bauer et
61 al. [19] reviewed central solar heating plants with seasonal heat storage in Germany. Experiences from
62 construction and operation of the research and pilot plants has led to technical improvement, higher
63 efficiencies and cost reduction. Olsthoorn et al. [20] reviewed optimization methods on integration of
64 renewable energy into district heating. The optimization method consists of a multi-objective method,
65 sensitivity analysis, thermodynamic-economic analysis, and genetic algorithm. Tulus et al. [21] did multi-
66 objective optimizations on central solar heating plants with seasonal storage in Spain. The results showed
67 that central solar heating plants with seasonal storage led to significant environmental and economic
68 improvements compared to the use of conventional natural gas heating systems. Life cycle assessment for
69 economy and environment was carried out to optimize central solar heating plants. Guerreiro et al. [22]
70 carried out the investigations on efficiency improvement and potential levelized cost of energy reduction
71 with a linear Fresnel concentrator plant with storage. LCOEs showed that there was an enormous potential
72 for the investigated plant. Sartor et al. [23] did simulations and optimizations of a CHP biomass plant and

73 district heating network. The contribution presented a synthetic way to achieve such a task using only simple
74 models on thermodynamic, combustion process, heat transfer and finance. The solar district heating system
75 combined with borehole thermal energy storage (BTES) in Drake Landing Solar Community in Canada has
76 managed to provide 96% of the community's annual space heating demand with solar heat for the period
77 2012-2016 [24].

78 Large solar district heating plants have gained great success in Denmark recently [25]. More than 1.3
79 million m² collectors are in operation in solar heating plants in Denmark by the end of 2016 [26]. Flat plate
80 collectors have been used in the large-scale solar district heating plants in Denmark. Flat plate collectors
81 have a bit lower efficiency at high temperature levels compared to evacuated tube collectors [27], Fresnel
82 collectors and parabolic trough collectors [28]. Parabolic trough collectors are the more cost-effective at high
83 temperature ranges such as 80-200°C during these collectors [28]. Parabolic trough collectors are mainly
84 used for solar power plants with oil or molten salt as heat transfer fluid. Parabolic trough collector with water
85 as heat transfer fluid for direct steam generation also is an attractive option in electricity generation or
86 industrial process [29]. Leiva-Illanes et al. [30] analyzed a solar poly-generation plant with parabolic trough
87 collectors for electricity, water, cooling and heating in high direct normal irradiation conditions. More and
88 more small-scale parabolic trough collectors are optimized to supply heat to industrial process [31] and hot
89 water production. A preliminary case study of parabolic trough collectors for district heating networks at
90 high latitudes with low solar radiation resources was first carried out in 2000 [32]. The economic comparison
91 indicated that parabolic trough collector systems could be competitive with flat plate collectors. But few
92 practical projects with parabolic trough collectors for district heating are found during the last decades. The
93 Danish company Aalborg CSP A/S [33] and Technical University of Denmark (DTU) [34] started in 2013 to
94 investigate the feasibility of parabolic trough collectors for district heating networks in large solar heating
95 plants supported by the Danish Energy Agency through the Energy Technology Development and
96 Demonstration Program (EUDP). A hybrid solar heating field with both flat plate collectors and parabolic
97 trough collectors in series has been constructed and connected to the existing district heating network in
98 Taars [35]. It was found that the flat plate collector field was oversized. To avoid too high temperature in the

99 system, the parabolic trough collectors therefore was often defocused in the summer [36]. This reduces the
100 cost efficiency of the plant dramatically. All the potential benefits of the hybrid plant can only be
101 experienced if the design, size and operation of the whole integrated system is consistently optimized [37].
102 The optimization of such hybrid solar district heating plants with different solar collector technologies is a
103 major issue for large solar heating plants.

104 **1.2 Levelized cost of heat**

105 Designing solar heating plants is a multivariable optimization task because many design parameters
106 should be varied and optimized on a project-specific basis, especially the area of the collectors and storage
107 size. Cost of application of solar energy systems in district heating networks has been discussed for a long
108 time. The levelized cost of energy (LCOE) has become the most popular and common criteria to identify the
109 most cost-effective energy production technologies on a consistent basis [38]. The LCOE not only considers
110 the cost of the energy systems, but also depends on the energy production of the investigated system
111 simultaneously. Levelized cost of heat (LCOH), derived from LCOE, is used to evaluate the solar heat from
112 the solar district heating plants in this study. The LCOH concept can be used as a tool to help to make
113 decisions on systems planning and design based on the optimization routine [39].

114 **1.3 Scope**

115 Based on a comprehensive literature survey and data collected from detailed country reports from IEA-
116 SHC over the past decades, the previous literatures were mainly focused on small solar heating systems [16],
117 [40], including domestic hot water systems for single-family homes and multi-family homes, small combined
118 hot water and space heating systems. Only a limited number of publications on both energy and economic
119 optimizations of large-scale solar district heating plants including natural gas boilers simultaneously in detail
120 were found [41].

121 The novelty of this study is summarized as followed: 1. The optimized objective is a hybrid 9999 m²
122 solar district heating plant with both flat plate collector and parabolic trough collector technologies, which is
123 a novel design concept for solar district heating systems; 2. Two kinds of boundary conditions for LCOH

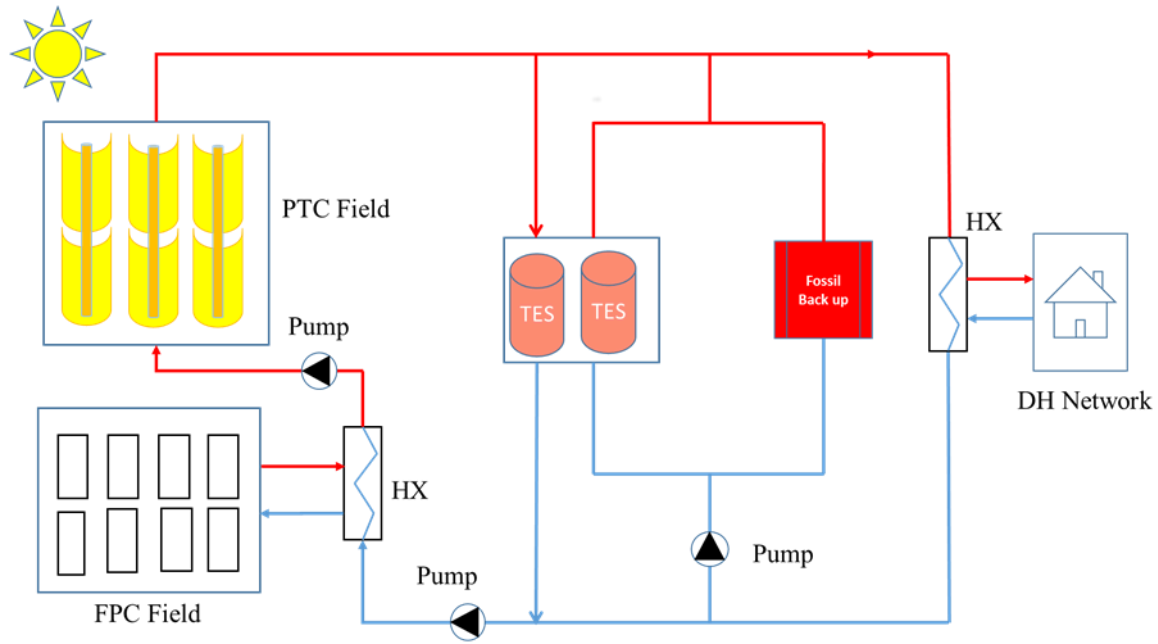
124 optimization are compared in this study. The main goal of this study is to investigate ways to reduce the cost
125 of the installation and increase the thermal performance of large solar heating plants simultaneously. Optimal
126 area of different collectors for hybrid solar district heating plants in this study were figured out. Sensitivity
127 analysis on storage size, orientation of PTC, different heat demands, fuel price trend and PTC price trend in
128 the nearby future, are also investigated. This study could provide information on the optimal design of such
129 combined solar district heating plants with both flat plate collectors and parabolic trough collectors.

130 **2 Method**

131 TRNSYS-GenOpt model, objective functions and cost investigations are introduced in this section.

132 **2.1 TRNSYS-GenOpt model**

133 A TRNSYS model on hybrid solar district heating plants has been developed in the TRNSYS 17 and
134 validated [42]. Dynamic simulated daily (typical cloudy and sunny days) and monthly energy outputs of the
135 hybrid solar heating plants have good agreements with the measured data. The TRNSYS model includes flat
136 plate collectors, parabolic trough collectors, the storage tanks, natural gas boilers and so on. The quasi-
137 dynamic model was used to simulate the energy output of both collector fields. Fig.1 shows the basic process
138 flow of the investigated plant in TRNSYS 17. GenOpt, developed by Lawrence Berkeley National
139 Laboratory [39], was used to carry out the multivariable optimization. The general methodology of
140 TRNSYS-GenOpt is summarized in Fig. 2. When the simulation results reach maximum or minimum aim
141 value, the model will stop, such as minimum LCOH or maximum energy output. The flat plate collector field
142 consists of two types of flat plate collectors without/with foils in series. The main components in the
143 TRNSYS model can be found in the Table 1.



144

145

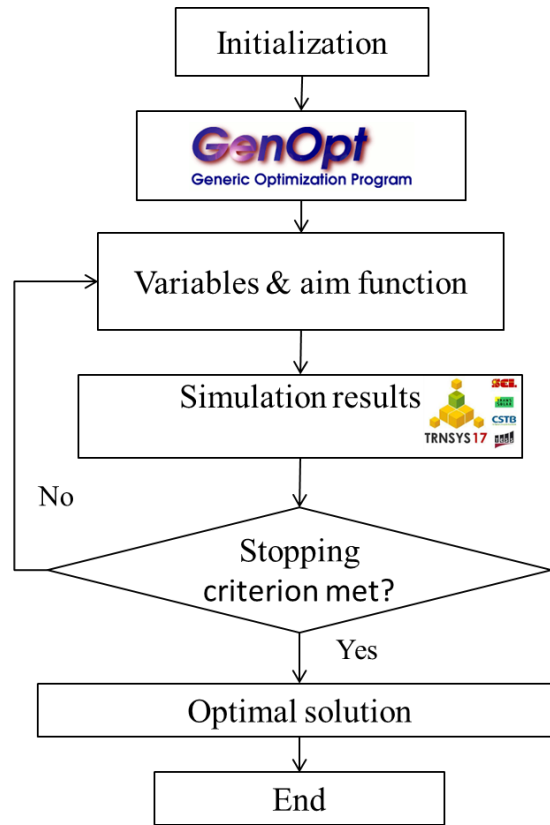
Fig.1 Simplified process flow diagram of the hybrid solar heating plant model.

146

Table 1. Main TRNSYS components and parameter settings (default condition) [43].

Name	Component type	Main Parameters	Descriptions
Weather data	Type 15	North Jutland of Denmark, Design Reference Year	Tracking model 1: fixed surface for FPC; Tracking model 2: the surface rotates about a fixed (user-defined) axis for PTC
FPC	Type 1290	5960 m ²	Flat plate collectors without/with FEP foils
PTC	Type 1290	4039 m ²	Parabolic trough collectors
Shadow	Type 30	Model 1: row distance : 5.67 m Model 2: row distance: 12.6 m	Model 1: flat plate collectors; Model 2: Parabolic trough collectors.
Tank	Type 4	2430 m ³	Short-term storage.
Boilers	Type 659	9100 kW	Natural gas boiler systems
Pump	Type 3	Varied parameters	-
Heat load	Type 9	Return temperature and Heat load	Measured return temperature and heat load from the district heating system (approximately 850 buildings with about 1900 residents).

147



148

149

Fig.2 Flow-chart of the TRNSYS-GenOpt model.

150 **2.2 Objective functions**

151 Two different kind of objective functions for optimizations are shown. In addition, two different boundary
 152 conditions of levelized cost of heat are also discussed.

153 **2.2.1 Energy output**

154 The energy output of the hybrid solar heating plant is expressed as Equation 1. The maximum energy
 155 output per square meter of the plant can be used to determine the most efficient solar heating plant during the
 156 optimization. The energy output of the solar heating plant per m² aperture area in this study is the solar heat
 157 generated by the hybrid solar collector field minus heat loss from pipe loops and heat storages.

158
$$Q_0 = (Q_{ptc} \times A_{ptc} + Q_{fpc} \times A_{fpc} - Q_{loss}) / (A_{ptc} + A_{fpc}) \quad (1)$$

159 2.2.2 Levelized cost of heat

160 Levelized cost of heat (LCOH) was used in this study. For end-use consumers, the final and optimal heat
161 price which consumers would pay for the district heating is interesting for the commercial market. LCOH is
162 a fair index to use both for parabolic trough and flat plate collectors in large solar heating plants for district
163 heating networks. The general Equation of LCOH can be found in Equation 2 [44].

$$164 \text{LCOH} = \frac{I_0 - S_0 + \sum_{t=1}^T \frac{C_t \cdot (1 - TR) - DEP_t \cdot TR}{(1+r)^t} \cdot RV \cdot (1+r)^{-T}}{\sum_{t=1}^T E_t \cdot (1+r)^{-t}} \quad (2)$$

165 Two boundary conditions are applied for calculations of LCOH for the solar district heating plants in this
166 study. One boundary condition is elaborated only for the solar collector fields and heat storage. The other
167 boundary condition not only includes the solar collector fields and heat storage, but also takes conventional
168 heat supply into consideration at the same time. The former is called by net LCOH and the latter is called by
169 system LCOH respectively in this study. The DEP_t and TR are regarded as zero in the residential sector
170 [39]. The simplified approach (Equations 3 and 4) is derived from the exhaustive approach (Equation 2), by
171 making a series of assumptions in the optimization; There is no residual value; There are no incentives;
172 Operation and maintenance costs do not change from year to year; The yearly heat generation remains
173 constant throughout the lifetime of the system [45].

174

175 1. Net LCOH ($nLCOH$)

176 Equation 3 can be used to determine $nLCOH$. The lifetimes of both flat plate collector and parabolic
177 trough collector field in Denmark are assumed as 30 years. Assumption of calculation discount rate is 3%
178 [41]. With the increase or decrease of discount rate, the LCOH will increase or decrease slowly.

$$179 \text{nLCOH} = \frac{I_s + C_{storage} + \sum_{t=1}^T P_s \cdot (1+r)^{-t}}{\sum_{t=1}^T SE \cdot (1+r)^{-t}} \quad (3)$$

180 2. System LCOH ($sLCOH$)

181 The conventional natural gas boiler system is existing and quite common in Denmark. The integration of
 182 solar heating plants in existing district heating networks is a more and more common practice in Denmark.
 183 The system LCOH including the natural gas boiler system is expressed as Equation 4. The lifetime of natural
 184 gas boilers is assumed as 30 years. The main operation cost of the backup boiler systems is regarded as the
 185 operation cost of the fuel consumption.

$$186 \quad sLCOH = \frac{I_s + C_{storage} + I_b + \sum_{t=1}^T (P_s + P_b) \cdot (1+r)^{-t}}{\sum_{t=1}^T (SE + NE) \cdot (1+r)^{-t}} \quad (4)$$

187 2.3 Cost investigations

188 The heat price from the natural gas boiler system is assumed to be 0.57 DKK/kWh in this study. The
 189 assumed cost of the flat plate collector field with collectors without FEP foils is shown by Equation 5. The
 190 cost of the flat plate collector field with collectors with FEP foils is assumed to be 7.6% higher than that of
 191 the flat plate collector field with collectors without FEP foils. The cost of the parabolic trough collector field
 192 and the storage tank is expressed by Equation 6 [46] and 7 [40] respectively. The cost of parabolic trough
 193 collector field is 40%-70% higher than the cost of flat plate collector field regarding of the size. The
 194 operation and maintenance cost of the flat plate collector field every year is assumed as follows: a) 2
 195 DKK/MWh heat produced for maintenance fee [47]; b) 1.5 kWh electricity/100kWh heat produced for
 196 operation (2.3 DKK/kWh electricity) [40]. The operation and maintenance cost of the parabolic trough
 197 collector field every year is assumed to be 0.8% of the initial cost [33].

$$198 \quad C_{fp} = \begin{cases} 240 \text{ DKK/m}^2 & \text{for } 50 \text{ m}^2 < A_{fp} \leq 100 \text{ m}^2 \\ 230 \text{ DKK/m}^2 & \text{for } 100 \text{ m}^2 < A_{fp} \leq 300 \text{ m}^2 \\ 218 \text{ DKK/m}^2 & \text{for } 300 \text{ m}^2 < A_{fp} \leq 1000 \text{ m}^2 \end{cases} \quad (5)$$

199 The cost function of the parabolic trough collector field is as Equation 6 [46]

$$200 \quad C_{ptc} = 13925 \times A_{ptc}^{-0.17} \quad (6)$$

201 The cost function of the tank is assumed as Equation 7 [40]

202 $C_{storage} = (11680 \times V_{storage}^{-0.5545} + 130) \times 7.44$ (7)

203 **3. Case study**

204 A hybrid solar district heating plant with flat plate collectors and parabolic trough collectors is used as the
205 reference case in the optimization. Details about the hybrid solar heating plants, climate data and heat
206 demand are shown in the section 3.1 and 3.2.

207 **3.1 Taars solar heating plant**

208 Taars plant with flat plate collectors and parabolic trough collector was constructed in August 2015. The
209 hybrid plant is supported by the Danish Energy Agency through the Energy Technology Development and
210 Demonstration Program (EUDP). The flat plate collector field preheats the return water from the district
211 heating networks to about 75 °C. Then the preheated water from the flat plate collector field is heated by the
212 parabolic trough collector field to about 95 °C. Main design and technical parameters for the plant can be
213 found in Table 2 and Table 3 respectively. The solar collector field consists of flat plate collectors and
214 parabolic trough collectors in series. In the flat plate collector subfield, half of the collectors are without FEP
215 foils (HTHEATboost 35/10) and the other half of the collectors are with FEP foils (HTHEATstore 35/10).
216 The flat plate collectors are delivered by Arcon-Sunmark A/S [48]. The collectors without the foils are
217 placed first in the rows, while the collectors with the foils are placed last in the rows. The tilt of flat plate
218 collectors is 50°. The return water from the district heating network is preheated by the flat plate collector
219 field. Then the preheated water is heated up to a required temperature by the parabolic trough collectors. The
220 parabolic trough collectors were delivered by Aalborg CSP A/S [33]. The orientation of parabolic trough
221 collectors is N-S orientation with 13.4° towards west. The existing natural gas boilers are the backup systems
222 for the district heating network. The efficiency parameters of the investigated solar collectors based on the
223 aperture area can be found in Table 4.

224

225

226

Table 2. Main design parameters of the Taars plant.

Parameters	Taars (Denmark)
Latitude	57.39 °N
Longitude	10.11 °E
Altitude	48 m
Parabolic trough collector field (Aperture area)	4039 m ²
Flat plate collector field (Aperture area)	5960 m ²
Fossil backup -Natural gas boilers	9.1 MW
Storage tank (2)	2430 m ³

227

228

Table 3. Main technical parameters of the collector fields.

Parameters	PTC	FPC
Solar collector fluid	Water	35% propylene glycol/water
Collector row distance, m	12.6	5.67
Azimuth, °	-13.4	0
Tilt, °	-	50

229

230

Table 4. Parameters of the investigated solar collectors.

η_0	b_0	b_1	$K_{\theta d}$	c_1 , [W/(m ² ·K)]	c_2 , [W/(m ² ·K ²)]	c_3 , [kJ/(m ² ·K)]	
0.839	0.1	0	0.98	2.596	0.016	7.321	HEATboost 35/10
0.802	0.1	0	0.93	2.226	0.010	7.876	HEATstore 35/10
0.75	0.27	0	0.038	0.04	0	4.00	PTC

231

$$\frac{Q}{A} = \eta_0 K_{\theta b}(\theta) G_b + \eta_0 K_{\theta a}(\theta) G_a - c_1(T_m - T_a) - c_2(T_m - T_a)^2 - c_3 \frac{dT_m}{dt} \quad (08)$$

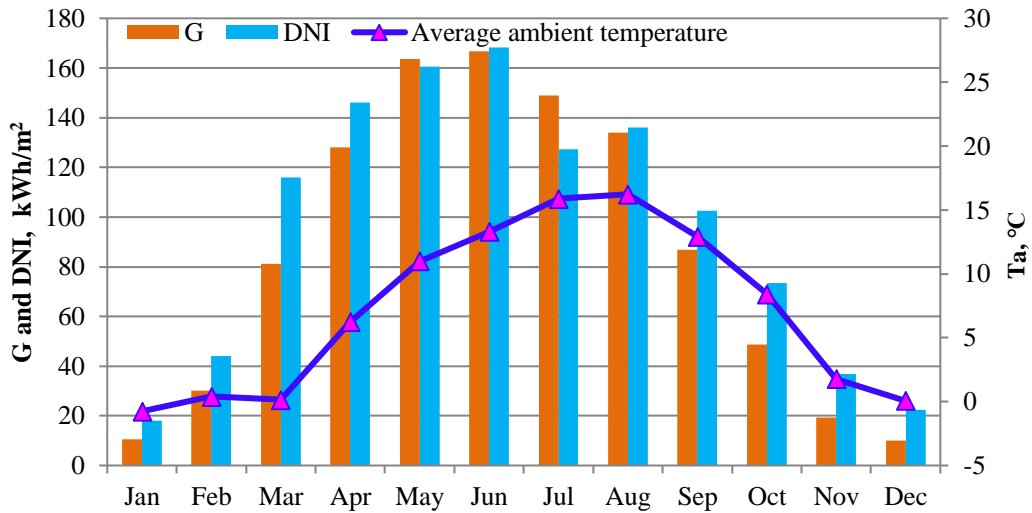
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233
$$K_{\theta b}(\theta) = 1 - b_0 \left(\frac{1}{\cos\theta} - 1 \right) - b_1 \left(\frac{1}{\cos\theta} - 1 \right)^2, \theta \leq 60^\circ \quad (09)$$

234 When $\theta > 60^\circ$, the IAM is linearized from the value at 60° to a value of zero at 90° .

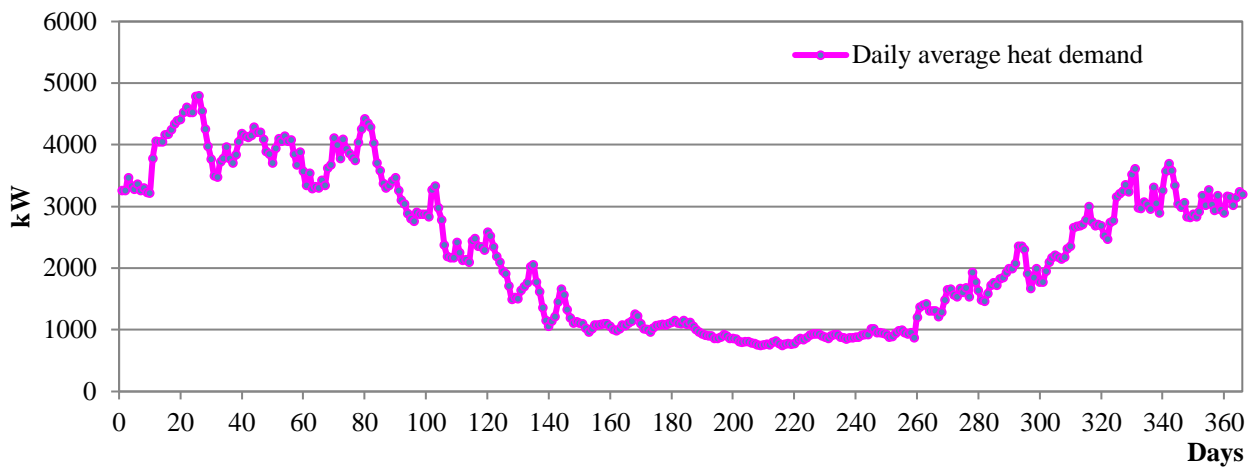
235 **3.2 Climate data and heat demand**

236 Fig. 3 shows the monthly global radiation, DNI and average ambient temperature in the Design Reference
 237 Year (DRY) of Northern Jutland of Denmark [49]. Yearly DNI and global radiation in the DRY are 1150 and
 238 1030 kWh/m² respectively. The district heating network consists of approximate 850 buildings with about
 239 1900 consumers. The typical design heat demand of the district heating network is shown in Fig.4. The heat
 240 demand was measured from the district heating network as the typical design parameter for the hybrid solar
 241 heating plant. The total heat demand is 20167 MWh per year. The heat demand is quite low in the summer
 242 and high in the winter.



243

244 Fig.3 Monthly global radiation, DNI and average ambient temperature in the DRY (Northern Jutland,
 245 Denmark).



246

247

Fig.4 Typical daily average heat demand of the district heating network [33].

248

4. Results

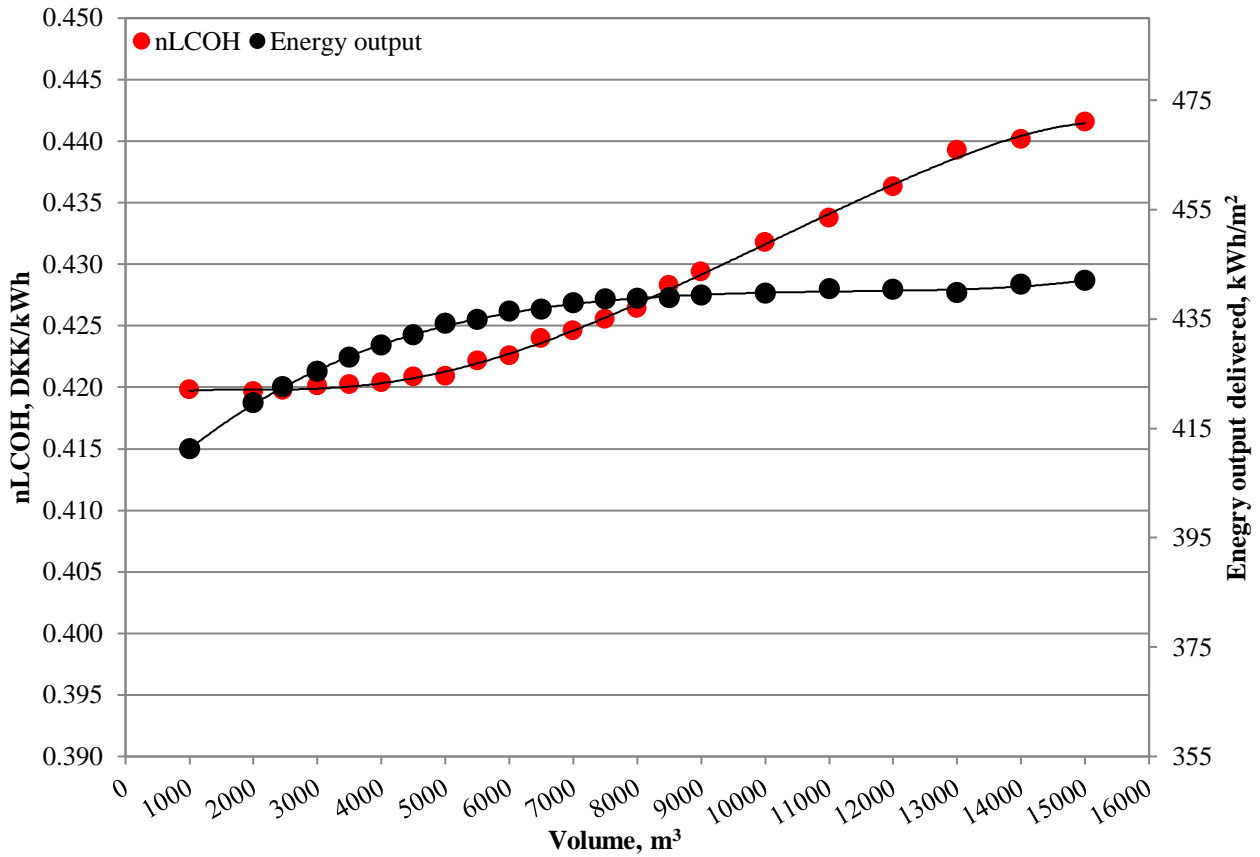
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Influence of storage size, orientation of PTC, different heat demands, fuel price trend and PTC price trend

250

in the nearby future, are investigated and analyzed in this section.

251 **4.1 The influence of storage volume**



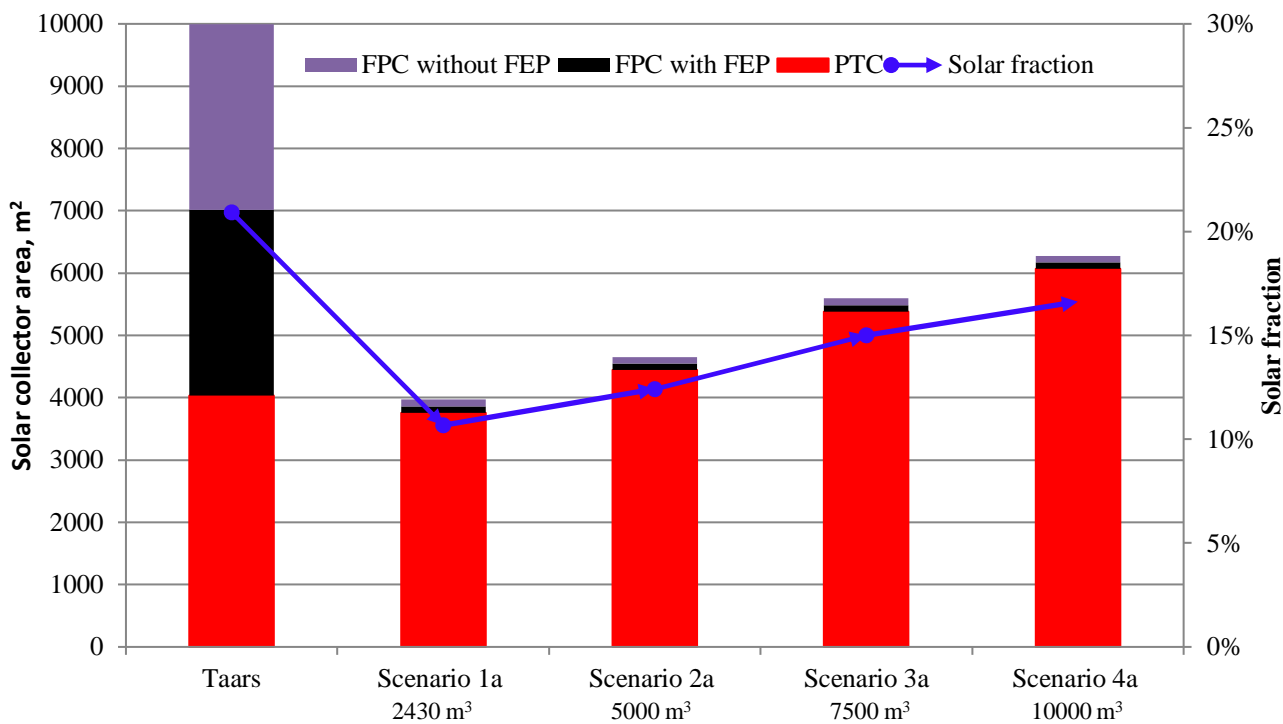
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253 Fig.5 The influence of the storage volume on net LCOH and yearly solar energy output of the Taars
 254 plant (All the other variables are kept constant as in the Taars plant).

255 Areas of both collector fields and volume of the storage tanks are important design parameters for the
 256 hybrid solar heating plant. The optimal storage volume and solar collector areas of the solar collector fields
 257 depend strongly on each other. Fig.5 shows the influence of the storage volume on the *nLCOH* and solar
 258 energy output in the reference case. The *nLCOH* of the Taars plant is 0.420 DKK/kWh. The *nLCOH* almost
 259 has the same level of 0.420 DKK/kWh when the storage volume varies between 2430 m³ and 5000 m³. The
 260 energy output of the plant delivered to the district heating network can increase from 422 kWh/m² to 434
 261 kWh/m². When the heat storage volume is 7000 m³, the energy output delivered to the district heating
 262 network almost peaks at 438 kWh/m². For further increased storage volumes, the thermal performance is not
 263 much increased. 5000-7000 m³ could be the reasonable storage volume for the Taars plant.

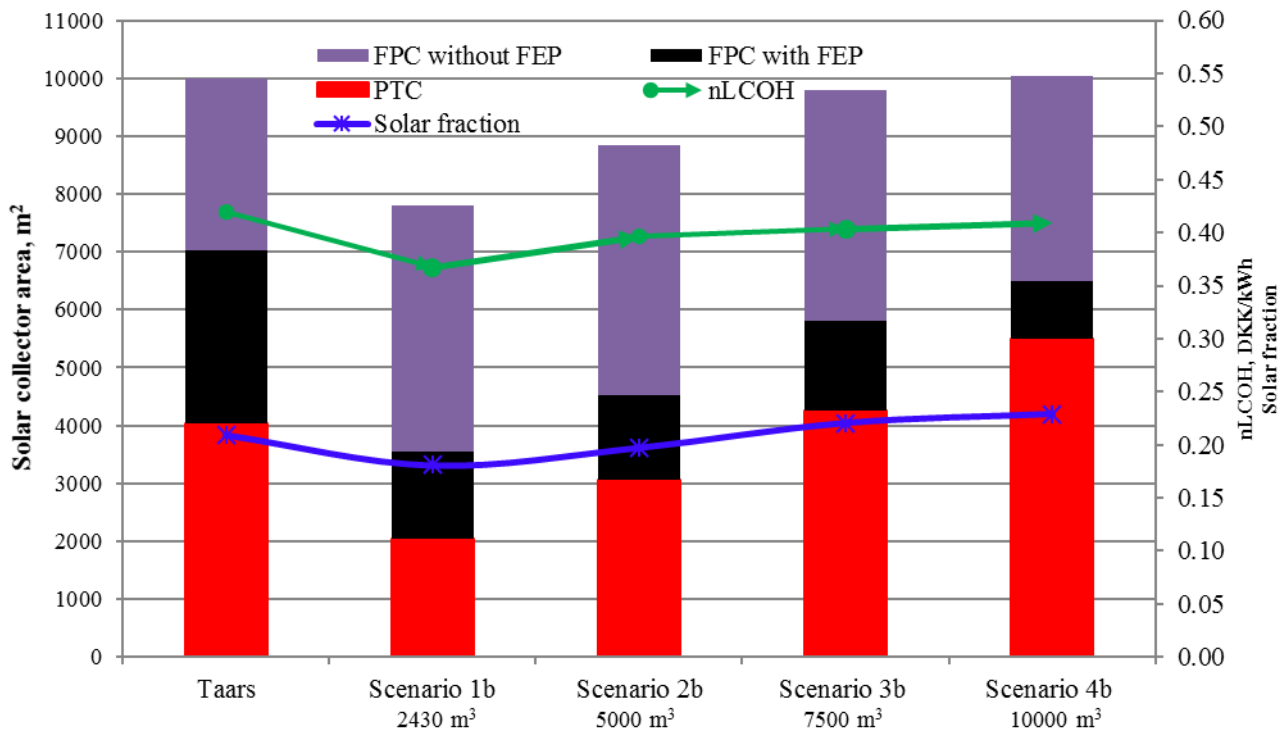
264 4.2 Area of both collector fields

265 It appears from Fig. 5 that a larger storage tank not only can increase the energy output of the plant, but
266 also keeps the *nLCOH* at a low constant level. So optimal areas of the collector fields based on four heat
267 storage scenarios, including 2430 m³ – scenario 1a/b, 5000 m³ – scenario 2 a/b, 7500 m³ – scenario 3a/b and
268 10000 m³ – scenario 4a/b, are investigated and compared to the reference case. In the whole scenarios, the
269 tilt of the flat plate collectors and the orientation of the parabolic trough collectors are also optimized to
270 reach the minimum *nLCOH*. The optimal tilt of the flat plate collectors is 35° and the optimal orientation of
271 the parabolic trough collectors is E-W orientation in the scenarios 1a-4a and 1b-4b. The areas of both flat
272 plate collector field and parabolic trough collectors are between 100 and 10000 m² in the optimizations. Fig.
273 6 shows the optimal collector areas of different collectors based on the aim function of maximum energy
274 output delivered to the consumers. It is suggested that the optimal collector field should consist of mainly
275 parabolic trough collectors without flat plate collectors for four scenarios. Fig. 7 shows the optimal collector
276 areas of different collectors based on the aim function of minimum *nLCOH*. It is suggested that the optimal
277 collector field should integrate flat plate collectors and parabolic trough collectors in series to reach
278 minimum *nLCOH* points with the range 0.367 - 0.400 DKK/kWh. The solar fraction of the Taars plant is
279 21.6%. The solar fractions of the investigated four scenarios 1b-4b in Fig. 7 are placed in the interval from
280 18% to 23%. The comparison of Taars plant and scenario 1b in Fig.7 shows that the solar collector fields was
281 oversized during the design phase, which causes that the net LCOH of the Taars plant is higher than that of
282 scenario 1b. But the net LCOH of Taars plant is still lower than the price for natural gas boiler systems. In
283 addition, the comparison of Taars plant and scenario 4b in Fig.7 shows that if there were a 10000 m³ large
284 storage volume, the optimal solar fraction could have increased to 23% with lower heat price, then the cost
285 performance of such large-scale solar heating plants increases a lot.



286

287 Fig.6 Optimal solar collector area and solar fraction of the investigated scenarios 1a-4a based on the aim
 288 function of maximum energy output (All the other variables are kept constant as the Taars plant).



289

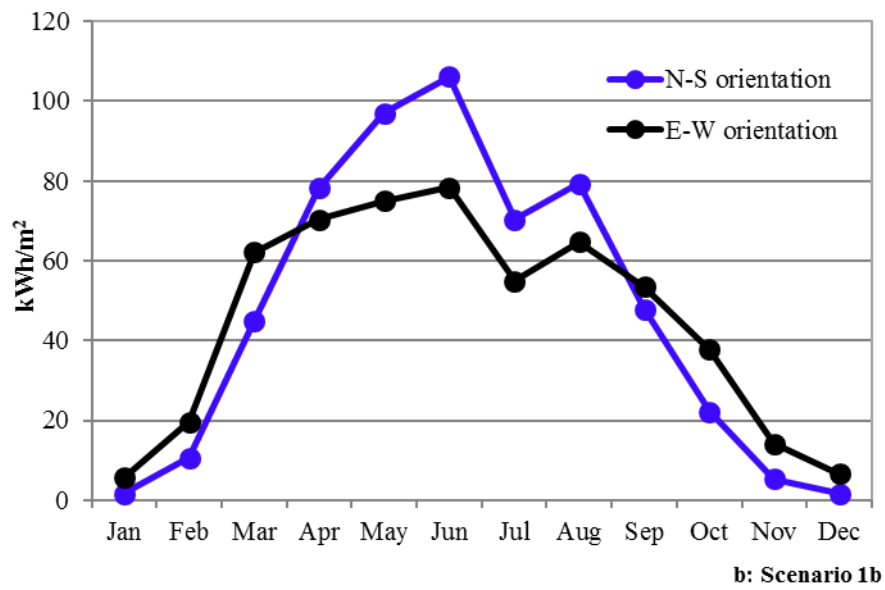
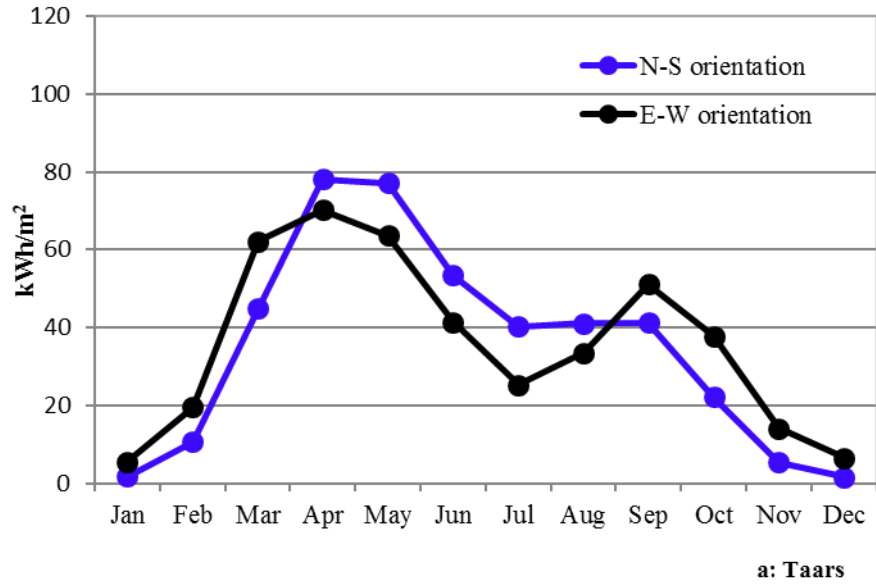
290 Fig.7 Optimal solar collector area, *net LCOH* and solar fraction of the investigated scenarios 1b-4b based on
291 the aim function of minimum *nLCOH* (All the other variables are kept constant as in the Taars plant).

292 Based on the results in Figs. 6 and 7, it is seen that quite different conclusions appear from different aim
293 functions for the 4 scenarios. Various target groups would use different aim functions to benefit from the
294 results. On the one hand, parabolic trough collectors are more efficient than flat plate collectors for high
295 temperature levels. On the other hand, the price of parabolic trough collectors is higher than the price of flat
296 plate collectors for high temperature levels. From the scenarios 1-4 in Fig. 7, it is shown that the combination
297 of flat plate collectors and parabolic trough collectors in series can increase the cost-performance of the solar
298 district heating plants, which is interesting for the commercial market and end-use consumers.

299 **4.3 Orientation of the parabolic trough collectors**

300 The orientation of the PTC fields affects the way of tracking and the received beam radiation. The N-S
301 orientation is always regarded as the optimal orientation of concentrating solar power plants [50]. The typical
302 E-W and N-S orientations are compared in Fig.8. Fig. 8a and Fig. 8b show the reference case (the Taars
303 plant) and the optimal case of scenario 1 with both typical orientations in Fig. 7 respectively. The
304 comparison between Figs. 8a and 8b indicates that the parabolic trough collectors are defocused a lot from
305 May to August in the reference case. The defocus of the parabolic trough collector field causes a low heat
306 production of the plant and a high *nLCOH*. Furthermore, Fig.8 shows that the PTC field with N-S orientation
307 produces higher heat in the summer months than the PTC field with E-W orientation. As shown in Fig.4, the
308 heat demand of the district heating network in the summer is very low. The PTC field with N-S orientation
309 may cause excess heat production if the PTC works normally in the summer. It can be seen that in Fig.8b
310 that the monthly energy output of the PTC field with N-S orientation can be higher than 100 kWh/m². So the
311 PTC field with N-S orientation has to be defocused a lot in sunny days in the summer. On the contrary, the
312 PTC field with E-W orientation produces lower heat in the summer due to large incidence angle losses. In
313 addition, the PTC field with E-W orientation produces more solar heat in the spring, autumn and winter
314 seasons while the heat demand is also high. In order to avoid the heat overproduction of the PTCs in the

315 summer and harvest the thermal performance of the PTC in spring and autumn, E-W orientation is the
 316 suggested orientation for the PTC field for the district heating network in this study.



317

318 Fig.8 The influence of typical orientation on the energy output of the parabolic trough field (a: the reference
 319 Taars plant; b: Scenario 1b- optimal case for Taars plant).

320 **4.4 Heat demand**

321 The heat demand of the district heating network influences the operation strategy of the solar heating plant
 322 directly, especially in the summer. Larger heat demand could improve the operation of parabolic trough
 323 collectors in the summer. Seven heat demand scenarios varying from 0% to 60% extra demand compared to
 324 the demand in Taars are shown in Table 5. All the other variables are kept constant as in the Taars plant.
 325 Compared to existing flat plate collector plants in Denmark, the energy output of the flat plate collector field
 326 in Taars produces higher solar heat. That is due to the fact that the flat plate collectors work at relatively low
 327 operation temperature in the hybrid solar heating plant. With the increase of the heat demand, the energy
 328 output of the flat plate collector field increases slowly. But the energy output of the parabolic trough
 329 collector field increases sharply with larger heat demand. That is because the parabolic trough collector field
 330 is defocused and not used fully in the summer in the reference case. When the heat demand increases by 60%,
 331 the yearly output of the PTC field can increase from 418 kWh/m² to 528 kWh/m² and the *nLCOH* can be
 332 reduced from 0.420 to 0.363 DKK/kWh. So the collector field is oversized and should be smaller based on
 333 the heat demand in Taars. Another solution for the reference case is that a larger storage tank should be used,
 334 as indicated in Fig.5.

335 Table 5. *nLCOH* based on different heat demands.

Heat demand	Annual energy output, kWh/m ²			<i>nLCOH</i> , DKK/kWh
	FPC field	PTC field	The whole plant excluding heat loss	
0 (Taars)	449	418	422	0.420
+10%	454	447	437	0.405
+20%	458	472	449	0.395
+30%	460	487	457	0.388
+40%	463	506	466	0.380
+50%	465	521	474	0.374
+60%	467	528	478	0.363

336

337 **4.5 Fuel price trend**

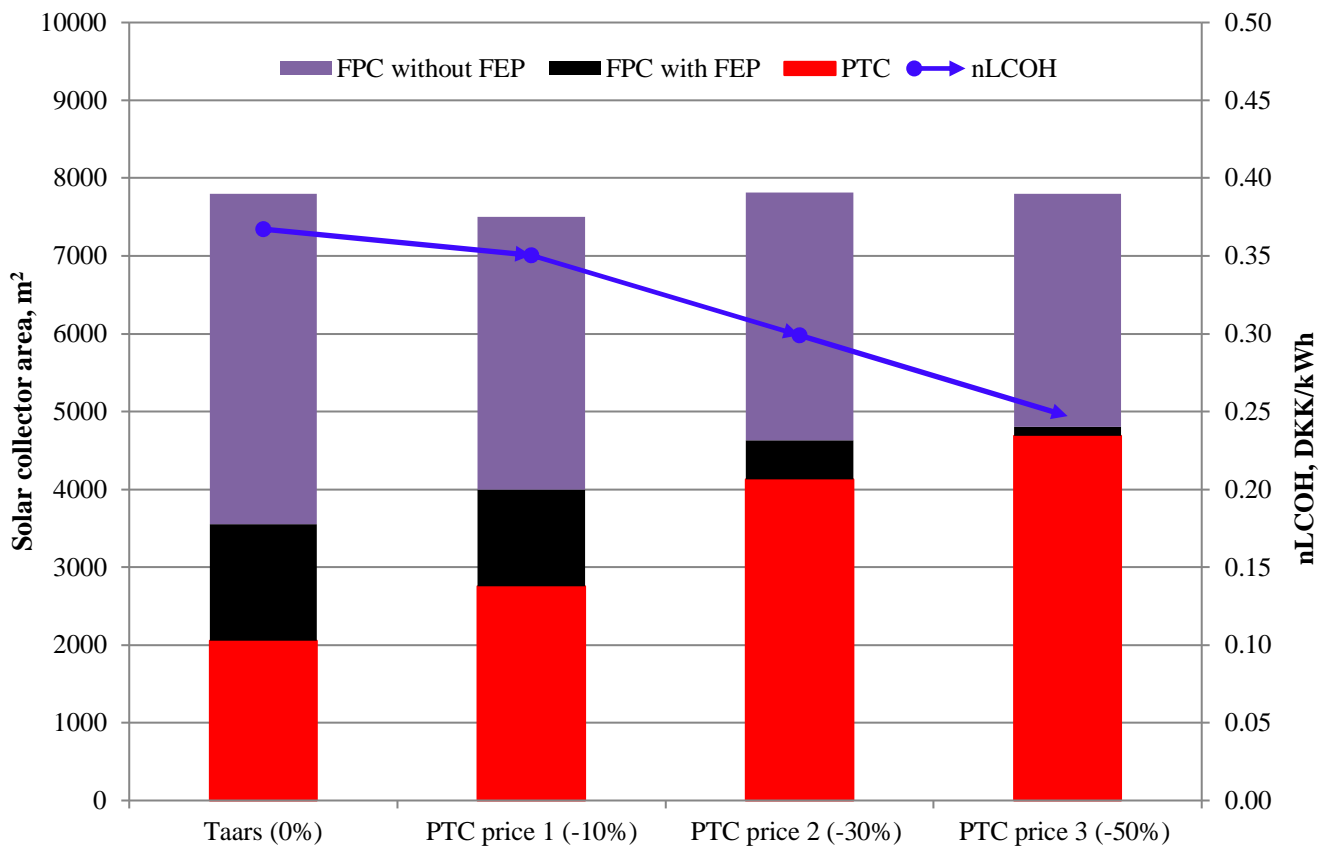
338 The price of natural gas for household consumers in Denmark fluctuates a lot year by year, even month by
339 month [25], [26]. Four increased fuel price scenarios varying from 0% to 30% price increase are shown in
340 Table 6 to determine the system LCOH. The system LCOH of the Taars plant is 0.54 DKK/kWh. The system
341 LCOH is 5% - 9% lower than traditional natural gas boiler systems because of the application of the solar
342 heating collectors in Table 6.

343 Table 6. *sLCOH* based on different fuel fees.

Price of the fuel, DKK/kWh	<i>sLCOH</i> , DKK/kWh
0.57 (Taars)	0.54
0.63	0.59
0.68	0.63
0.74	0.67

344 **4.6 Price trend of parabolic trough collectors**

345 The high price is the main barrier for the parabolic trough collectors to be applied widely in the market
346 compared to the flat plate collectors. With the commercial development of PTC just started in 1970s [51],
347 there is huge decrease potential of the cost of PTC. So four PTC price scenarios varying from 0% to -50%
348 reduction in price were investigated to obtain an overview of the development for PTC technology in district
349 heating networks in the future. Areas of the collectors, tilt of the FPC and orientation of the PTC were
350 optimized simultaneously to reach minimum *nLCOH*. Fig.9 shows the optimal design points for all the PTC
351 price scenarios. The optimal tilt of flat plate collectors is 35°. The optimal orientation of parabolic trough
352 collectors is E – W orientation. All the other variables are kept as in the Taars plant. When the price of PTC
353 decreases by 50%, the optimal *nLCOH* of the plant can be reduced from 0.367 DKK/kWh to 0.247
354 DKK/kWh. It can be found that the design strategy of flat plate collectors and parabolic trough collectors in
355 series is feasible and optimal in order to reach minimum net LCOH in all the scenarios.



356

357 Fig.9 Minimum $nLCOH$ and optimal design collector areas based on different prices of the PTC.

358 5. Discussion

359 The studied plant is the first pilot large-scale solar heating plant with flat plate collectors and parabolic
 360 trough collectors in series for district heating networks in Europe, even worldwide. The boiling problem for
 361 solar district heating plants in the summer is one of main factors to limit the size of plants, if there are not
 362 seasonal storage. On the one hand, the application of parabolic trough collectors can easily be defocused to
 363 avoid the overheat production, which can increase the flexibility of solar heating plants in the whole energy
 364 system, compared to evacuated tube collectors and compound parabolic collectors. On the other hand, the
 365 defocus of the parabolic trough collector reduces the cost-effective competitiveness of the hybrid solar
 366 heating plants. The integration of parabolic trough collectors can also guarantee that flat plate collectors

367 work at relatively low operation temperature and produce more than the normal solar heating plants. The
368 investigations in this study figure out the optimal solar collector areas for the Taars plant.

369 In addition, Fresnel collectors is another line-focusing collector, which arouses increasing interests in the
370 last decade. Fresnel collectors have cheaper price and higher land use efficiency than parabolic trough
371 collectors, while it has lower solar-to-power efficiency. If the advantages of Fresnel collectors were enough
372 strong to the low efficiency, the Fresnel collectors could be an optional alternative collector type to parabolic
373 trough collectors for such hybrid solar district heating plants. All in all, the integration of evacuated tube
374 collectors, compound parabolic collectors, or Fresnel collectors with flat plate collectors due to the cheaper
375 price could also be interesting to investigate for large-scale hybrid solar district heating plants in the future
376 work.

377 **6. Conclusions and future work**

378 Analyses based on levelized cost of heat for large scale solar district heating plants have been carried out.
379 An optimization approach based on TRNSYS-GenOpt was introduced. Multi variable and function
380 optimizations of a hybrid solar heating plant were carried out. The LCOH of hybrid solar heating plants for
381 different scenarios in the near future was also figured out. The following conclusions can be drawn:

382 The net LCOH of the Taars plant is 0.42 DKK/kWh. The lowest net LCOH of the optimized hybrid solar
383 heating plant (0.367 DKK/kWh) is much lower than the average price of heat from the natural gas boilers
384 (0.57 DKK/kWh). The use of parabolic trough collector in the solar district heating systems is cost effective.

385 The system LCOH of the Taars plant can be reduced by about 5-9% by using solar collectors in district
386 heating networks in this study.

387 For the investigated district heating network, parabolic trough collectors with E-W orientation are more
388 suitable than that with N-S orientation due to the high solar fraction during the summer. The low heat
389 demand/collector area ratio limits the potential of parabolic trough collectors as long as the plant is not

390 equipped with large heat stores. Heat stores with large volumes are needed in order to fully utilize the
391 parabolic trough collectors.

392 The concept with flat plate collectors and parabolic trough collectors in series for district heating networks
393 is technical-economic feasible in Denmark compared to the heat price of conventional natural gas boiler
394 systems. The optimization of area of the collectors and storage size based on the heat demand should be
395 addressed in the planning and design phase of hybrid solar heating plants. The results not only can provide
396 useful recommendations to designers, but also result in the lowest heat price for the end-use domestic
397 consumers.

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411	Nomenclature	
412	Abbreviations	
413	<i>DH</i>	district heating
414	<i>DKK</i>	Danish Krone
415	<i>DRY</i>	design reference year
416	<i>DNI</i>	monthly direct normal irradiance, kWh/m ²
417	<i>E-W</i>	East-west
418	<i>FEP</i>	fluorinated ethylene propylene
419	<i>FPC</i>	flat plate collector
420	<i>HX</i>	heat exchanger
421	<i>IEA</i>	International Energy Agency
422	<i>LCOH</i>	levelized cost of heat, DKK/kWh
423	<i>LCOE</i>	levelized cost of energy, DKK/kWh
424	<i>nLCOH</i>	net levelized cost of heat, DKK/kWh
425	<i>N-S</i>	North-south
426	<i>PTC</i>	parabolic trough collector
427	<i>SHC</i>	solar heating and cooling
428	<i>sLCOH</i>	system levelized cost of heat, DKK/kWh
429	<i>TES</i>	Thermal energy storage

430 Latin Symbols

431	A_{ptc}	aperture area of the parabolic trough collector field, m ²
432	A_{fpc}	aperture area of the flat plate collector field, m ²
433	C_{ptc}	cost of the parabolic trough collector field, DKK/m ²
434	C_{fpc}	cost of the flat plate collector field, DKK/m ²
435	c_1	heat loss coefficient at (T _m -T _a)=0, W/(m ² ·K)
436	c_2	temperature dependence of the heat loss coefficient, W/(m ² ·K ²)
437	c_3	effective thermal capacity, J/(m ² ·K)
438	C_t	operation and maintenance costs (year t), DKK
439	$C_{storage}$	specific costs of the tanks incl. installation (excl. VAT and subsidies), DKK/m ³
440	DEP_t	asset depreciation (year t), DKK
441	E_t	Energy generated (year t), kWh
442	G	monthly global radiation, kWh/m ²
443	I_s	specific solar thermal system costs incl. installation (excl. VAT and subsidies), DKK/m ²
444	I_b	specific boiler system costs incl. installation (excl. VAT and subsidies), DKK
445	NE	heat from the natural gas boiler system, kWh
446	P_s	operation & maintenance expenditures of the solar plant in the year t, DKK
447	P_b	operation & maintenance expenditures of the natural gas boiler system in the year t, DKK
448	Q_{ptc}	yearly energy output of the parabolic trough collector field, kWh/m ²

449	Q_{fpc}	yearly energy output of the flat plate collector field, kWh/m ²
450	Q_{loss}	yearly heat loss in solar loop pipe and thermal energy storage, kWh
451	Q_0	yearly energy output of the whole collector field, kWh/m ²
452	r	discount rate , %
453	RV	residual value, DKK
454	SE	specific useful energy delivered by the solar thermal system in the year t (thermal losses in pipe
455		loop and thermal storage considered), kWh
456	S_0	subsidies and incentives, DKK
457	T_a	ambient temperture, °C
458	I_0	initial investment, DKK
459	TR	corporate tax rate, %
460	T	period of use (solar thermal system life time in years), a
461	t	year within the period of use (1,2,... T)
462	Greek Symbols	
463	η_0	optical efficiency,-
464	Subscripts	
465	th	thermal
466		

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